

Development of a Free-Swimming Acoustic Tool for Liquid Pipeline Leak Detection Including Evaluation for Natural Gas Pipeline Applications

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TABLE OF CONTENTS

1.0	Introduction/Project Background	7
2.0	SmartBall Applications	8
2.1	Introduction	8
2.2	Insertion	9
2.3	SmartBall Capture and Extraction	10
2.4	Tracking the Position of the SmartBall	10
2.5	Leak Rate Calibration	12
3.0	Task 1 – Literature Review of Existing Technologies	13
3.1	Introduction	13
3.2	Internal Leak Detection Systems	14
3.2.1	Computational Pipeline Monitoring	14
3.2.2	Pressure Testing	14
3.2.3	In-Line Inspection	15
3.3	External Leak Detection Systems	15
3.3.1	Optical Remote Sensor Methods (Gas Detection Only)	15
3.3.2	Acoustic Emissions	16
3.3.3	Fiber Optic Sensing	16
3.3.4	Liquid Sensing	16
3.3.5	Vapor Sensing	16
3.4	Patent Search	17
4.0	Task 2 – Production of Oil and Gas Balls	18
4.1	Electronic and Mechanical Design	18
5.0	Task 3 – Laboratory Testing	20
5.1	Inclined Line Propulsion Test	21
5.2	External Pressure Test	22
5.3	Temperature Test	23
6.0	Task 4 – Software Development	24
6.1	SmartBall Analyst Software	24
7.0	Task 5 – Field Testing in Operational Lines	27
7.1	CLH Loesch-Villaverde Line – Madrid, Spain	27

7.2	MOL Szajol to Tiszaujvaros Line – Siofok, Hungary	28
7.3	Plains Midstream Senlac to Unity Line – Unity, Saskatchewan	29
7.4	Plains Midstream Manitou Line – Calgary, Alberta	30
7.5	EnCana Pipeline Severn to Crowfoot Gas Line – Calgary, Alberta	31
8.0	Conclusions and Recommendations	35
8.1	SmartBall Benefits	35
8.2	SmartBall Limitations	36
9.0	References	37

APPENDIX A – Operating Protocol

APPENDIX B – SmartBall Dimensions

LIST OF FIGURES

Figure 1. Typical SmartBall Survey	9
Figure 2. Insertion of SmartBall Tool in Standard Pig Launcher	9
Figure 3. Extraction of the SmartBall Tool	10
Figure 4. Leak indication Power	11
Figure 5. Accelerometer Profile	11
Figure 6. Frequency Spectrum	12
Figure 7. CPM System	14
Figure 8. Traditional In-Line Inspection Tool	15
Figure 9. Helicopter Deployment of Remote Sensing Technology	15
Figure 10. Acoustic Emission Array	16
Figure 11. Electronic Design Package	19
Figure 12. SmartBall Docking Station for Direct Uploading of Captured Data	20
Figure 13. Internal Components (L) and Outer Polyurethane Shell (R)	20
Figure 14. OilBall with Polyurethane Shell (L) and GasBall with Foam Shell (R)	20
Figure 15. CFD Software Model Results	21
Figure 16. Inclined Line Propulsion Test Apparatus	22
Figure 17. Pressure Vessel Closed (L) and Open (R)	23
Figure 18. Sonic Tracking of SmartBall	26
Figure 19. Acoustic Summarization	26
Figure 20. Loeches to Villaverde Pipeline	27
Figure 21. The 10" OilBall Removed from Pipeline	29
Figure 22. Senlac to Unity Pipeline	29
Figure 23. Section of Manitou Pipeline	30
Figure 24. Acoustic Profile of the OilBall vs. Distance Traveled	31
Figure 25. Severn to Crowfoot Natural Gas Pipeline	32
Figure 26. Measuring Gas Leak Flow Rate	33

LIST OF TABLES

Table 1. Overview of Currently Available Leak Detection Systems	17
Table 2. Velocity Required by Degree of Incline	22
Table 3. Temperature Test Results	24
Table 4. Leak Rate Results for GasBall Run	33
Table 5. List of Field Test Results of OilBall in Live Lines	34
Table 6. List of field Test Results of GasBall in Live Lines	35

ABSTRACT

Significant financial and environmental consequences often result from line leakage of oil product pipelines. Product can escape into the surrounding soil as even the smallest leak can lead to rupture of the pipeline. From a health perspective, water supplies may be tainted by oil migrating into aquifers. A joint academic-industry research initiative funded by the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) has led to the development and refinement of a free-swimming tool called SmartBall, which is capable of detecting leaks as small as 0.028 GPM in oil product pipelines and has proven to record leaks in natural gas pipelines. The tool swims through the pipeline being assessed and produces results at significantly reduced cost to the end user compared to current leak detection methods. GPS synchronized GIS-based above ground loggers capture low frequency acoustic signatures and digitally log the passage of the tool through a pipeline. This report presents the development, laboratory and field validation testing of the SmartBall for oil and gas pipeline integrity.

1.0 INTRODUCTION

The objective of this joint academic-industry project was to develop a sensitive leak detection system that can economically and reliably detect very small leaks (i.e. less than 1 GPM) and accurately locate 8 leaks (within 10 ft.) in hazardous gas and liquids pipelines.

Primarily used for operational pipelines, the technology may be also used to locate leaks that occur during a pre-commissioning pipeline hydrotest. The project involved the development of a prototype free-swimming acoustic leak detection tool that will resolve some of the shortcomings of the existing leak detection technologies available to pipeline operators. Furthermore, a side benefit of the tool is gained through the detection of loss of product due to illegal taps in a system caused by third party entities. Although not a major issue in the U.S., this loss of product is a concern for pipeline operators of some foreign systems.

When pressurized product leaks from a pipe, it creates a distinctive acoustic signal that is transmitted through the product flowing in the pipeline. Acoustic leak detection equipment identifies the resulting sound or vibration (Klein 1993). Such systems have proven to be one of the most effective and reliable means for identifying leaks in pipelines; however, fixed sensors have limited range due to the rapid attenuation of sound. A free-swimming, un-tethered acoustic leak detection tool avoids this limitation by passing directly by any leak, regardless of its location along the pipeline. By operating inside the pipe, the device is not affected by ground cover or environmental conditions, and there is never any concern that sections of the line could be missed.

Recognizing the value offered by acoustic technology, but also the range limitations for a fixed sensor system, a research and development program was undertaken to develop a free-swimming acoustic leak detection device. The broad goal of the program was to develop a technology that would provide operators with the ability to detect small leaks at an early stage and determine the location with sufficient precision to enable remedial work to be performed without additional surveying. It also had to be available at an affordable cost without the need for major changes in pipeline construction or operation.

The resulting system, named SmartBall[®], was initially developed in 2005 for water transmission pipelines because of the magnitude of the leak problems in the water industry and the lack of alternative solutions (Moncrief et al. 2009; Dancer et al. 2009). Because the SmartBall principle was equally applicable to oil and gas pipelines, the research and development program was extended in 2007 to modify the technology for use in the hydrocarbons industry. This led to a two year research project funded by the U.S. DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA) in collaboration with Arizona State University and Pure Technologies Limited.

The SmartBall device diverges from the traditional cylindrical shape of in-line equipment or "pigs". The spherical shape greatly reduces the noise produced by the device as it passes along the pipe, thus permitting the sensitive acoustic sensor to operate free of external interference. The net result is a tool that is sensitive to very small acoustic events and therefore, very small leaks.

An additional benefit of the spherical design is that it allows much greater flexibility in the methods of deployment and retrieval compared to a cylindrical tool, and it is able to negotiate a much wider range of bore changes, small radius bends and other obstacles that may exist within the pipe. SmartBall can

run in lines without pig traps, and in a wide range of traditionally unpiggable locations. Both liquid and gas pipelines can be inspected. With the current series of tools, any pipeline size of 4" diameter or greater is accessible.

The device is inserted into an operational pipeline in the same manner as a smart pig and can monitor many miles of pipeline during a single deployment. The SmartBall's position is logged internally by on-board accelerometers and the ball can also be tracked by GPS synchronized surface sensors in the same way as a conventional pig. This combination of tracking systems allows the location of any leak to be determined within ± 3 ft (± 1 m) under ideal conditions.

The SmartBall is fully sealed with no electronic components exposed to the pipeline environment. This allows the achievement of high levels of reliability in a wide range of hostile conditions, and ensures that the device is intrinsically safe for use in flammable products such as oil and natural gas.

2.0 SMARTBALL APPLICATIONS

2.1 Introduction

SmartBall is an acoustic based technology that detects anomalous acoustic activity associated with leaks in pressurized pipelines at the time of inspection. The tool is composed of a liquid-tight, aluminum alloy core that contains a power source, electronic components and instrumentation (including an acoustic sensor, accelerometer, magnetometer, GPS synchronized ultrasonic transmitter, and temperature sensor). The core is encapsulated inside either a protective outer foam shell or a polyurethane coating. The outer foam shell or polyurethane coating provides additional surface area to propel the device while reducing the low frequency ambient noise present in the pipeline. The SmartBall assembly is deployed into the flow of a pipeline and traverses the pipeline – propelled by the hydraulic flow - and is captured at a pig receptor further downstream (Ariaratnam and Chandrasekaran 2010).

While traversing the pipeline, it acquires high quality acoustic data that is evaluated to identify leaks. Since the SmartBall acoustic sensor passes no further than a pipe diameter from an acoustic anomaly of interest, three significant advantages are recognized:

1. Medium and Large Diameter Pipe: SmartBall can be used to detect leaks on medium and large diameter pipe (4" and greater in diameter). Many conventional leak detection technologies (e.g. correlators) have limitations that preclude their use on medium and large diameter pipe.
2. Pipe Material: SmartBall can be used on pipes manufactured of any pipe material including steel, plastic, concrete, etc.
3. Sensitivity: SmartBall has detected leaks as low as 0.028 gallons per minute under ideal conditions.

Once a suspected leak is identified during the data analysis, the positional data for SmartBall is reviewed to determine its location. To track the position of the SmartBall device as it traverses the pipeline, SmartBall Receivers (SBR's) and Above Ground Markers (AGM's) are positioned periodically along the pipeline. The SBR's detect ultrasonic pulses that are periodically emitted by the SmartBall. The SBR

devices measure the duration that it takes for the pulse to travel from the ball to the SBR. This duration is used to calculate an approximate location of the ball, which is used to track the ball during the survey. However, more importantly, as the ball passes the SBR, it provides a discrete point where the location of the ball is known at any moment in time.

To develop an accurate plot of SmartBall position, the device has an on-board three-dimensional accelerometer. The accelerometer data is used to best fit a curve between the discrete points from when the ball passed an SBR or AGM. This provides an accurate plot of distance versus time that is used to report the location of leaks. A schematic of a typical SmartBall survey is shown in Figure 1.

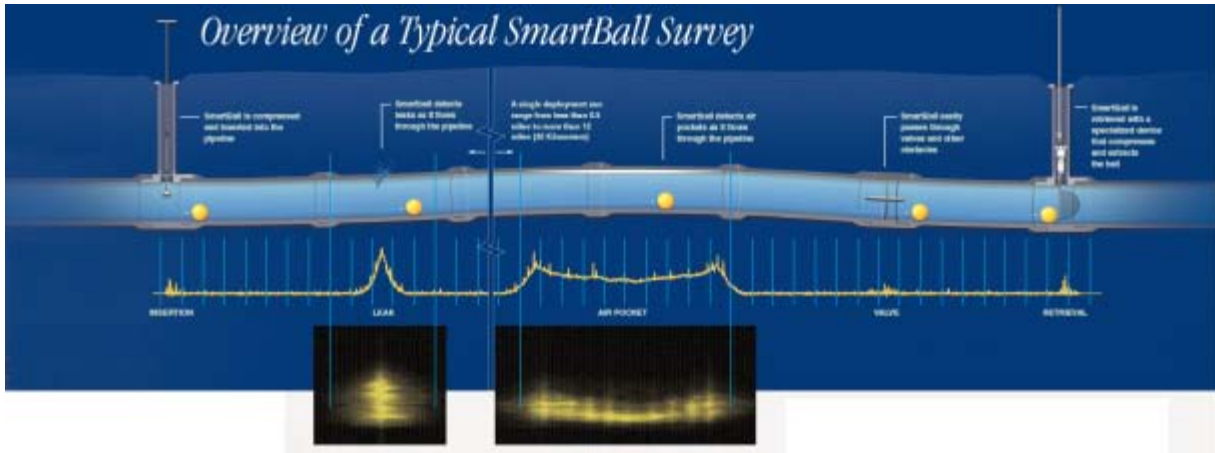


Figure 1. Typical SmartBall Survey

2.2 Insertion

Insertion of the SmartBall tool is conducted through use of a standard pig launcher as illustrated in Figure 2. This provides an excellent access point for commencing the leak survey.



Figure 2. Insertion of SmartBall Tool in Standard Pig Launcher

2.3 SmartBall Capture and Extraction

The SmartBall is then tracked into the pig receive trap at the end of the line and removed from the pipeline as shown in Figure 3. A custom made strainer device is used to prevent the SmartBall tool from passing through the bypass line coming off the barrel of the pig receiver.



Figure 3. Extraction of the SmartBall Tool

The SmartBall operating protocol may be found in Appendix A. This provides step-by-step guidance on how to best deploy the tool and capture leak data.

2.4 Tracking the Position of the SmartBall

Knowledge of the position of the SmartBall within a pipeline is critical for locating important features, such as leaks. The methodology used to track the tool involves obtaining a velocity profile using data obtained from the accelerometers and magnetometers on board the SmartBall. Then, absolute position reference points obtained from the SBRs are applied to time stamped data. Individual SBRs are able to track the ball's progress through the pipeline for up to 500 ft (150m). The result of the rotation profile and SBR tracking is a position versus time relationship for the entire run of the tool.

To assist in identifying the approximate leak rate of any identified leak, an end-user can compare the leak indication power of a detected leak with that of a known leak rate. Known leak rates and corresponding leak indication power (in dB), shown in Figure 4, are developed by holding the SmartBall in the launch trap at the start of the survey run. The acoustic analysis of the calibration leaks can then be compared with the leak rate of each leak detected during the inspection of the pipeline. Subsequently, the leak indication power is the single most important indicator of a leak's presence and size.

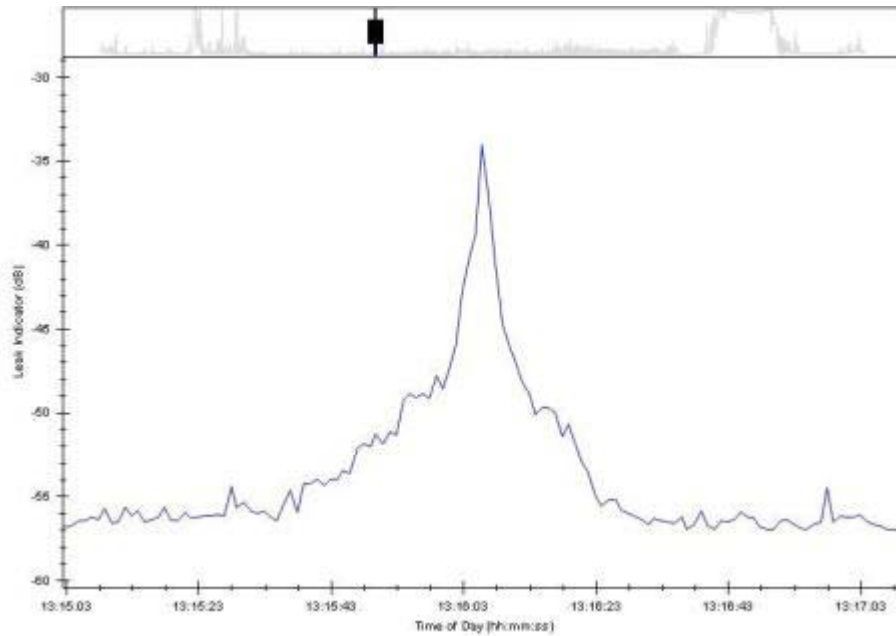


Figure 4. Leak Indication Power

Because the simulated leaks are controlled and released through a threaded outlet, the comparison to actual field condition leaks may vary. This is because the acoustic frequency and power indication of any leak may vary with several factors including pressure, pipe diameter, size and configuration (i.e. pin-hole, rolled gasket, split pipe, etc.); however, a leak calibration curve provides a useful tool in approximating leak rates for identified leaks. The leak calibration curve increases in accuracy as more data points and calibration leaks are added.

A three-dimensional accelerometer also aids in locating the position of the SmartBall tool within the pipeline as well as providing an indication of motion of the ball as it travels through the pipeline (i.e. uniform rotation, slipping/skidding, etc). Figure 5 illustrates a typical accelerometer profile. This enables the user to identify locations where flow was interrupted or the exact time the ball departs and arrives at the pigging facilities.

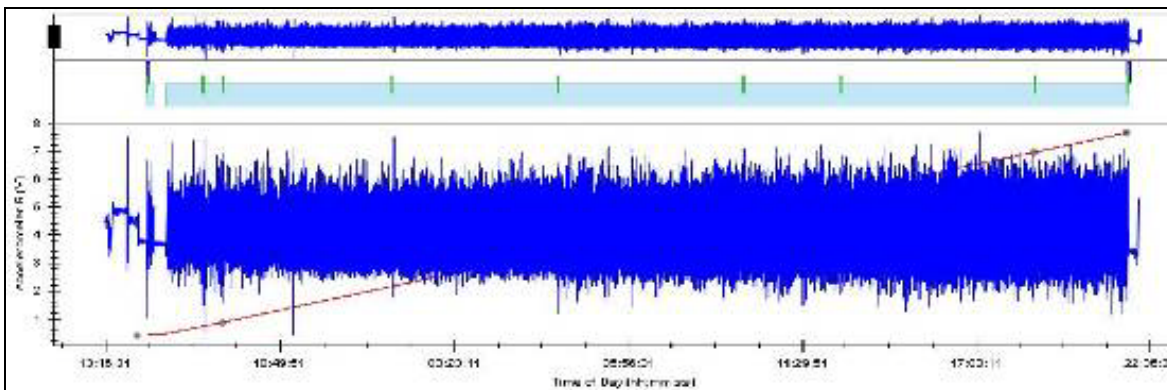


Figure 5. Accelerometer Profile

A leak signature via a frequency spectrum provides the user with an indication of the location and magnitude of a given leak. Figure 6 illustrates a typical frequency spectrum from a SmartBall run.

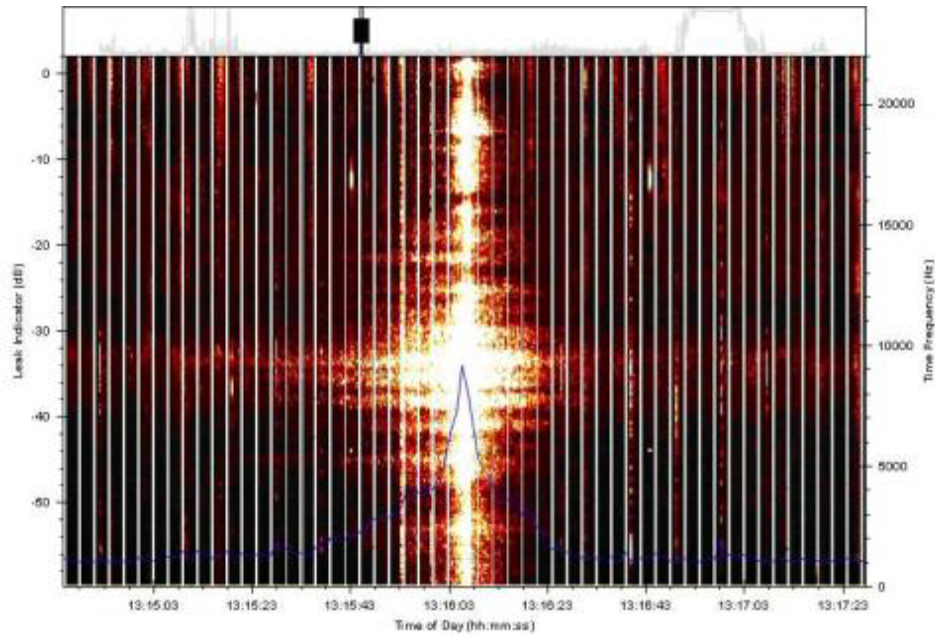


Figure 6. Frequency Spectrum

2.5 Leak Rate Calibration

To identify the magnitude of a leak, it is necessary to compare the leak indication power of a detected leak with that of a known leak rate. Known leak rates and their leak indication power (in dB's) are developed by holding the SmartBall in the receive trap at the end of the survey and simulating leaks of varying sizes. The leak indication power is the single most important indicator of a leak's size and presence.

Leaks of varying rates are produced using an existing tap at the receive trap and a graduated vessel is used to collect and measure the product collected by each of the leaks over a measured period. The simulated leaks are controlled and released through a threaded outlet and therefore, the comparison to natural leaks may vary. However, the leak calibration curve provides a useful tool in providing a general estimate of the magnitude of leak rates for identified leaks.

Based on this calibration process Pure Technologies Limited categorizes leaks into three categories: small, medium and large. Small leaks are estimated to be in the range of 0-2 GPM (0-7.5 LPM), medium leaks are estimated to be in the range of 2-10 GPM (7.5 to 37.5 LPM), and large leaks are estimated to be greater than 10 GPM (37.5 LPM).

3.0 TASK #1 – LITERATURE REVIEW OF EXISTING TECHNOLOGIES

3.1 Introduction

There are a variety of methods that can detect leaks in natural gas and petroleum product pipelines, ranging from manual inspection to advanced satellite based hyper-spectral imaging (Carlson, 1993). The various methods can be classified into internal and external systems. Internal systems include: 1) computational pipeline modeling; 2) pressure testing; and 3) inline inspection. External systems include: 1) optical remote sensor methods; 2) acoustic emissions; 3) fiber optic sensing; 4) liquid sensing; and 5) vapor sensing. No single system is universally accepted as the preferred method as all have strengths and weaknesses, though some are far more commonly used than others. Typically, most operators opt for a combination of Computational Pipeline Modeling (CPM) and direct observation methodologies including aerial or ground patrols. Permanent monitoring sensors based on acoustic or other technologies are also available; however, these methods can be costly and none can reliably detect small leaks regardless of their location in the pipeline.

Most pipeline operators also employ in-line inspection (ILI) programs using “smart pigs” that detect cracking, wall thinning, and other anomalies (Turner 1991). However, a majority of pipelines are typically only inspected at intervals of several years, and all ILI technologies have limits on the minimum cross-sectional area of the defects that they can detect. Furthermore, they are unable to differentiate between a deep defect and a leak. Through-wall pinhole leaks resulting from aggressive corrosion mechanisms such as microbiologically influenced corrosion are not typically detected. Also many lines, particularly in the gathering and distribution sectors, are never pigged.

The desirable attributes of a leak detection system as defined by API are as follows. The requirements are primarily applicable to computational pipeline modeling (CPM) systems:

- Possesses accurate product release alarming;
- Possesses high sensitivity to product release;
- Allows for timely detection of product release;
- Offers efficient field and control center support;
- Requires minimum software configuration and tuning;
- Requires minimum impact from communication outages;
- Accommodates complex operating conditions;
- Is available during transients;
- Is configurable to a complex pipeline network;
- Performs accurate imbalance calculations on flow meters;
- Is redundant;
- Possesses dynamic alarm thresholds;
- Possesses dynamic line pack constant;
- Accommodates product blending;
- Accounts for heat transfer;
- Provides the pipeline system’s real time pressure profile;
- Accommodates slack-line and multiphase flow conditions;
- Accommodates all types of liquids;
- Identifies leak location;
- Identifies leak rate;

- Accommodates product measurement and inventory compensation for various corrections (i.e., temperature, pressure, and density); and
- Accounts for effects of drag reducing agent.

3.2 Internal Leak Detection Systems

3.2.1 Computational Pipeline Modeling

The Department of Transportation (USDOT) regulates the “Transportation of Hazardous Liquids by Pipeline” under federal regulations in 49 CFR Part 195. Part 195 recognizes computational pipeline monitoring (CPM) as the acceptable standard for leak detection systems on hazardous liquid pipelines, and that each CPM system must comply with American Petroleum Institute (API) Standard 1130. CPM systems (Figure 7) employ software modeling that dynamically evaluates flow monitoring devices measuring the rate of change of pressure or the mass flow at different sections of the pipeline. If the rate of change of pressure or the mass flow at two locations in the pipe differs significantly, it could indicate a potential leak. The major advantages of the system include its ability to monitor continuously, as well as non-interference with the operation of the pipeline. Two disadvantages of the system include the inability to pinpoint the leak location, and the high rate of false alarms. These systems are also very expensive for monitoring a large network of pipes.

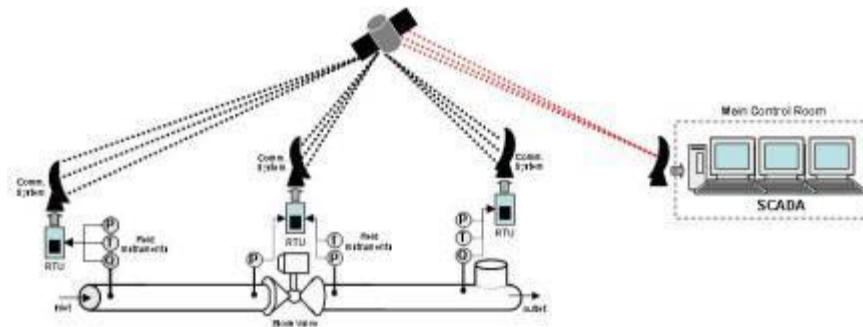


Figure 7. CPM System

API recognizes that detectable limits using CPM are difficult to quantify because of the unique characteristics presented by each pipeline (API 1130 Document Information, Nov. 1, 2002). The Alaska Department of Environmental Conservation has expanded on 49 CFR Part 195 and API 1130 by establishing a 1% of daily throughput leak detection standard. For example, this means that a 24” diameter pipeline transporting refined or crude oil at 8 ft/sec, would require a leak rate of more than 100 GPM to occur before the CPM system would detect the leak at the 1% detection limit. Given the high rate of false alarms associated with CPM systems, many pipeline operators do not initiate action until an even higher detection limit is discovered.

3.2.2 Pressure Testing

Leak detection is also an objective of the mandatory pressure test required for new pipelines, and also required under some specific other circumstances. When the pressure test does reveal a leak, but the line does not rupture, locating the leak can be a lengthy and expensive operation. Existing location methods include the use of ice plugs to isolate the length containing the leak or the use of odorizers or other trace elements in the test fluid. None of these methods are considered to be fully satisfactory.

3.2.3 In-Line Inspection

In-line inspection or “smart pigging” is a well established method for inspecting pipelines for corrosion, dents, cracking and a variety of other defects. While it is true that a pipeline containing a defect large enough to cause a leak will likely be detected by a smart pig, they are not designed to differentiate between leaks and deep, but not through-wall, defects. Furthermore, all smart pig technologies have certain limitations. For example, magnetic flux leakage, the most commonly used technology, cannot detect long axial defects or small pinhole defects typical of microbial corrosion. Therefore, it is possible that through wall, leaking defects can be missed. A typical in-line inspection tool is shown in Figure 8.



Figure 8. Traditional In-Line Inspection Tool

3.3 External Leak Detection Systems

3.3.1 Optical Remote Sensor Methods (Gas Detection Only)

Several optical remote sensor systems exist for the remote measurement of trace gases in the atmosphere. These include Differential Absorption LIDAR (DIAL), differential optical absorption spectroscopy (DOAS) and Fourier transform IR (FTIR) and are available as a truck mounted mobile laboratory or installed in aircraft. DIAL technology vendors claim that the existing technology is able to detect leakage rates in the 100ppmm range, which is roughly equivalent to 4SCFM. Remote sensing technology deployed by helicopter is illustrated in Figure 9.



Figure 9. Helicopter Deployment of Remote Sensing Technology

3.3.2 Acoustic Emissions

A pressurized fluid leaking from a pipe generates a characteristic acoustic event that can be detected using suitable technology. AE systems are typically based on permanently mounted discrete sensors, or portable sensors used as part of an above-ground survey (Figure 10). For arrays of discrete sensors, relative signal magnitude or correlation techniques may be used to determine the leak location.

These systems are limited by the rapid attenuation of the AE signal as the distance from the leak increases. To cover a sizeable length of pipe, large numbers of sensors are required.

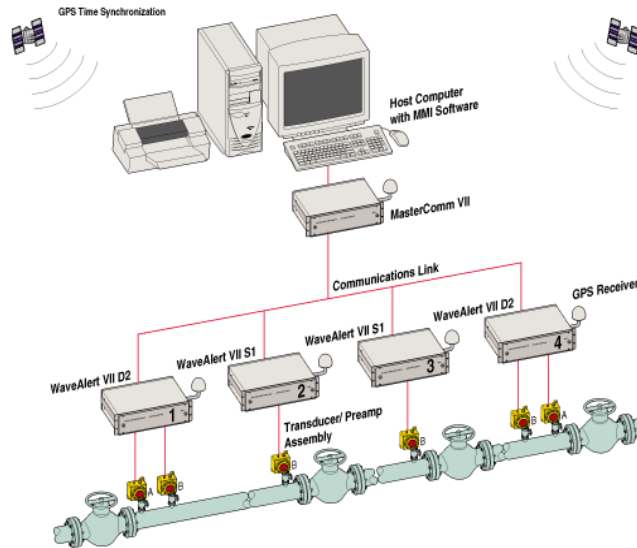


Figure 10. Acoustic Emission Array

3.3.3 Fiber Optic Sensing

Fiber optic systems have been used to detect leaks in a number of ways. The cable can be used as an extended acoustic detection instrument and used to detect leaks in a similar manner to the AE systems described above. Alternatively, they can be used as distributed temperature sensors using the Raman backscattering principal with the objective of detecting the local temperature change associated with a leak. There are also systems that use a buried fiber with a hydrocarbon sensitive coating that changes its refractive index in the presence of leaking product.

The effectiveness of these systems depends on the placement of the fiber in a suitable position relative to the pipeline. Installation and ongoing monitoring costs can be significant.

3.3.4 Liquid Sensing

Liquid sensing cables utilize the principal of a change in electrical impedance in the presence of hydrocarbons. They are buried in the proximity of the pipe in a similar fashion to the fiber-optic systems described above and exhibit the same limitations of costly installation and monitoring.

3.3.5 Vapor Sensing

Probes are placed in the soil close to the pipeline and configured so that a vacuum can be applied to them. Periodic samples are taken from the probes and the contents analyzed in a laboratory for traces of hydrocarbon or chemical markers that have been added for the purpose. These systems are of limited

practicality for pipelines because of the problems associated with sample collection. A conduit linking the probes can be used, but required a significant infrastructure investment.

An overview of internal and external detection systems is presented in Table 1.

Table 1. Overview of Currently Available Leak Detection Systems

System	Observations	Cost
INTERNAL SYSTEMS		
Basic mass-balance analysis system	High detection threshold. No locational ability	\$200,000 + monitoring costs.
Ultrasonic mass-balance analysis system.	Improved sensitivity. No locational ability	\$500,000 + monitoring costs.
Real-time transient modeling system.	Improved sensitivity. Coarse locational ability	\$200,000 to \$1,000,000 + monitoring costs.
In-Line Inspection	100% coverage. Insensitive to certain defect geometries. Not able to directly identify leaking features.	\$300 - \$1000 per km
EXTERNAL SYSTEMS		
Fiber-optic/liquid sensing cable:	Effective with adequate installation. Installation costs significant. Best suited for new construction.	\$4,000 - \$64,000 per mile + monitoring hardware @ \$50,000 - \$150,000
Soil gas tracer.	Requires complex infrastructure installation for pipelines.	Probe at 20ft intervals (\$4,000 per mile), + field stations at 2 mile intervals (\$25,000 per mile)
Acoustic Emissions system. 300ft per AE sensor.	Limited range for individual sensors	\$50,000 per mile
Aerial Visual Survey	Low cost and rapid coverage. Limited sensitivity.	\$10 – 50/mile/survey
ROW Survey by Remote Sensing	Inexpensive. Labor intensive.	\$100 – 1000/mile/survey

3.4 Patent Search

The patent search for other leak detection methodologies and for prior art was performed in four areas.

1. Search of the USPTO and European database for keywords and citations in known patents;
2. Presentation of relevant art by and to Pure Technologies’ attorneys for comment and consideration before drafting our own applications;
3. Preparation of Applications in U.S. and other countries; and
4. Constant industry searching and awareness of potential prior art

To date, no prior art has been identified such that it might affect the use of SmartBall. Recently, a second application incorporating the latest developments was filed in the United States as follows:

Application 61/075,497 titled, "Locating Apparatus and Method for Pipeline Anomaly Detectors"

4.0 TASK #2 – PRODUCTION OF OIL AND GAS BALLS

Initially, two each of 6” and 10” Generation #1 SmartBalls for oil product applications were manufactured as per the deliverable milestone. Enhancements were performed and incorporated into Generation #2 SmartBalls, which included the manufacture of two each of 4”, 6”, and 10” OilBalls. Additionally, two each of 4”, 6”, and 10” Generation #1 GasBalls for natural gas applications have been manufactured. Dimensional information can be found in Appendix B.

4.1 Electronic and Mechanical Design

The preliminary electronic and mechanical design involved the design, manufacture, and testing of a free-swimming leak detection device capable of detecting small leaks (< 1 GPM) in oil product pipelines 4” in diameter and larger. The Electronic design was expected to incorporate: 1) Internal power supply; and 2) On-board electronics and data storage. The Mechanical design was expected to incorporate a sensor package.

To accommodate for transmission lines of long lengths the battery life needed to be upgraded from the original SmartBall design for water leak detection. Surveys requiring multiple days of battery life would be not possible using the original lithium primary battery set up. Subsequently, to allow for maximum battery life, the switch to rechargeable lithium ion batteries was made to enable up to 110 hours of battery life.

Final electronic design (Figure 11) involved altering the design of the Piezo attachment to the shell to minimize leak detection threshold and increase acoustic sensitivity. The adhesive which couples the Piezo to the SmartBall shell was identified through extensive lab testing as being the limiting factor in increasing the sensitivity of the tool. An adhesive supplying a better acoustic coupling to the Smartball shell was identified and tested. The new adhesive “G-flex” allows the SmartBall to provide an acoustic signal of increased sensitivity while still maintaining a high strength bond required for durability of the tool. Figure x. illustrates the circuitry for the electronics design of the SmartBall.

Five sensors comprise the sensor package and include: 1) acoustic sensor; 2) accelerometers; 3) magnetometers; 4) pressure sensor; and 5) temperature sensor. Acoustic sensors act as transmitters to facilitate ball tracking, accelerometers are used to record ball rotation, while magnetometers are used to identify pipe weld joints, block valves and in-line valves. Data storage includes 16GB (4” ball) and 32GB (>4” balls) with a direct data link (Figure 12) for downloading captured data and an enhanced electromagnetic tracking system. Figure 13 illustrates the internal components and the protective polyurethane shell for oil applications. The polyurethane shell and foam outer shell as illustrated in Figure 14.

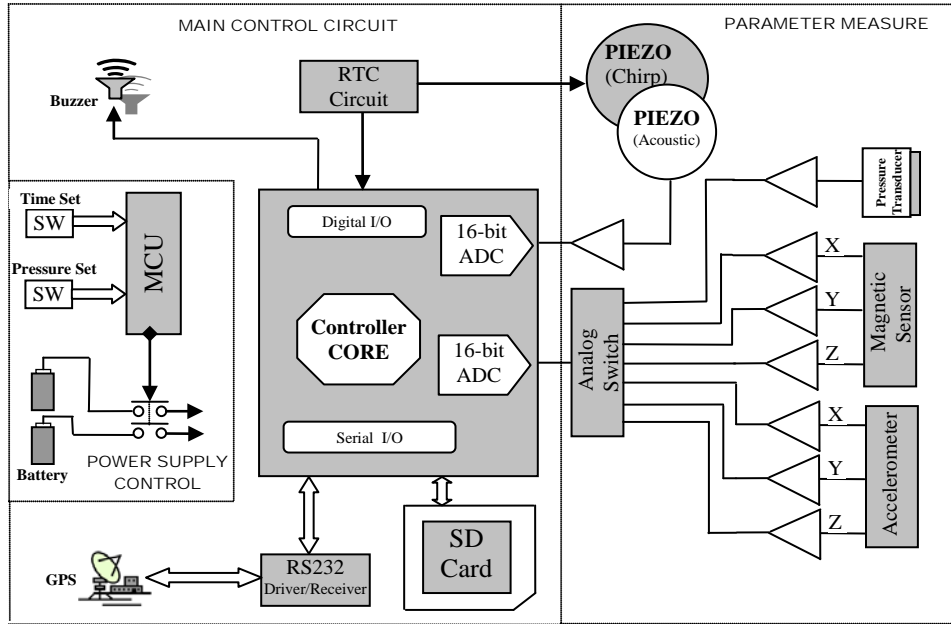


Figure 11. Electronic Design Package



Figure 12. SmartBall Docking Station for Direct Uploading of Captured Data

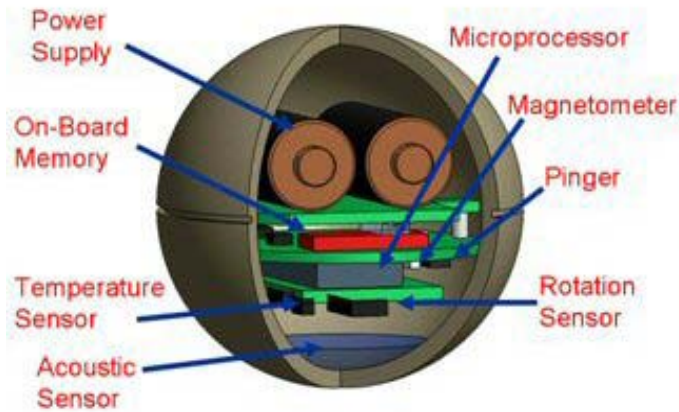


Figure 13. Internal Components (L) and Outer Polyurethane Shell (R)



Figure 14. OilBall with Polyurethane Shell (L); GasBall with Foam Shell (R)

5.0 TASK #3 – LABORATORY TESTING

As part of the research and development, each manufactured SmartBall underwent a rigorous laboratory testing program to ensure operability in a hazardous and damaging environment inherent in operating oil and natural gas pipelines. Subsequently, a series of tests were performed to ensure that the device would perform as intended, in a safe manner and be sufficiently robust to resist damage during operation. The tests performed included the following:

- External Pressure Test
- Rolling Noise Test
- Inclined Line Propulsion Test
- Impact (Drop) Test
- Thermal Test
- Sensor Attachment Integrity Test

All six tests were successfully completed prior to field application. Details of the Inclined Line Propulsion, External Pressure, and Temperatures Tests are presented in the following sections.

5.1 Inclined Line Propulsion Test

The SmartBall must be able to traverse varying inclinations involved with pipelines dependant on the topography associated within geographical regions. Ensuring that the tool keeps moving along the line is less certain than for conventional full-bore pipeline “pigs” because the SmartBall does not seal across the pipeline, rather it is pushed by the product flow with a certain degree of product bypass. Critically, it is necessary to ensure that the ball can be propelled up the steepest incline in the pipeline under the available product pressure and flow speed. The purpose of the incline test was to determine minimum flow rates required to negotiate different slopes.

The data accumulated from the inclined line test were then used to validate the developed computational fluid dynamics (CFD) flow modeling software (Figure 15) used to determine the minimum flow velocities required to move the tool up varying slopes. Prior to running the SmartBall in an operational line, the validated CFD model can be used to ensure that the line conditions are suitable for propulsion of the ball.

A short section of inclined pipe was used to represent an uphill section in an operational pipeline as illustrated in Figure 16. The test pipe was made from a clear polymer to allow the movement of the ball to be observed. The test rig allowed the angle of incline to be varied. A portable compressor was used to create a variable rate of flow in the line. The flow speed was measured by means of a velometer. Test results from 4” and 10” SmartBall inclined pipe tests are presented in Table 2.

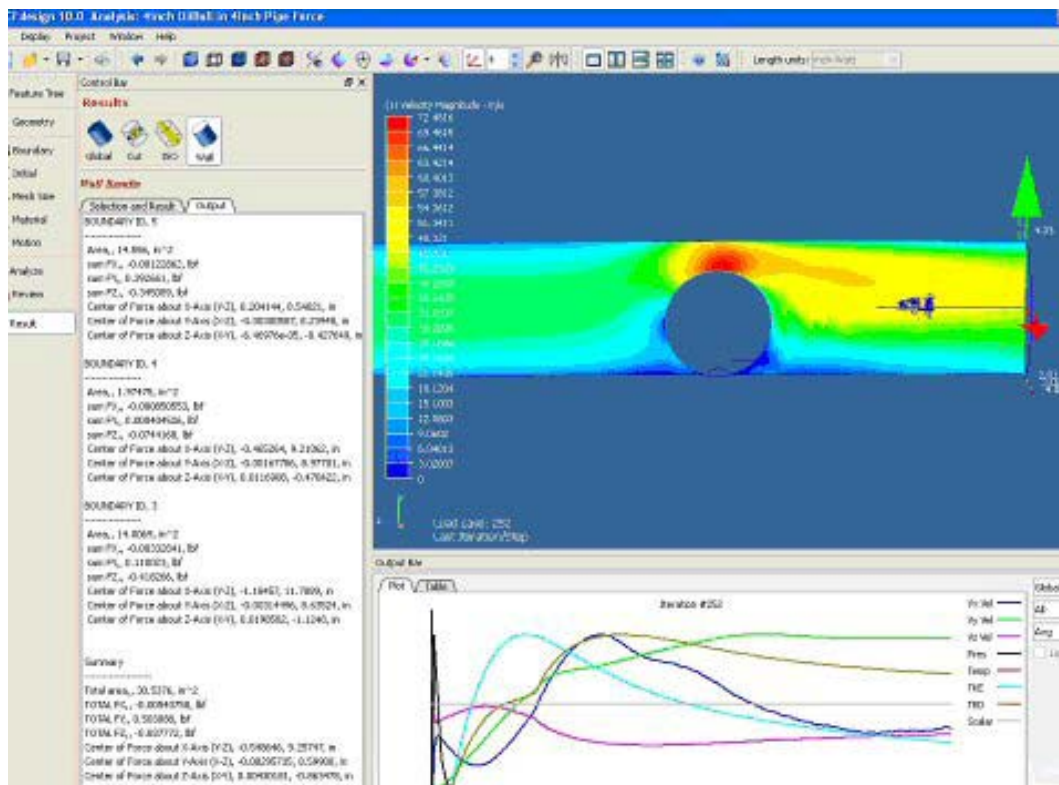


Figure 15. CFD Software Model Results

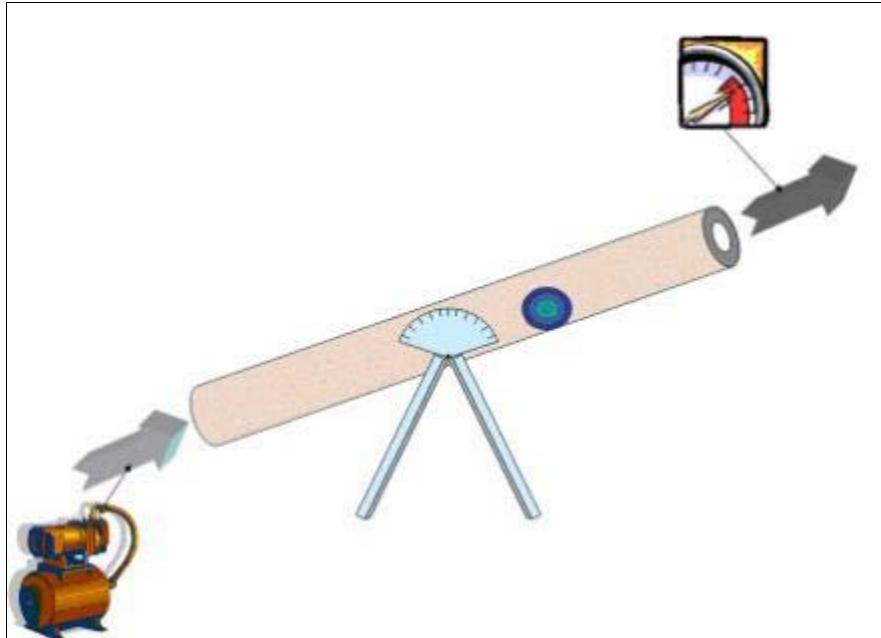


Figure 16. Inclined Line Propulsion Test Apparatus

Table 2. Velocity Required by Degree of Incline (4" and 10" Balls)

Degree of Incline	Velocity Required (in/sec)
0	1
10	7
20	9
30	12
40	14
50	15
60	15
70	16
80	16
90	17

The incline test was not performed using liquid because gas is the primary concern with regard to propulsion. Validation of the CFD model in gas provides confidence of the model pertaining to use in liquid lines. Additionally, there are numerous live runs that have previously been conducted in liquid (water) to use for validation.

5.2 External Pressure Test

The SmartBall must be able to withstand pressures realized in a normally operating pipeline. Any breach of the ball in service would result in damage to the internal electronics and a potential safety risk in the case of an inflammable product.

The external pressure test was designed to confirm the SmartBall's capability to withstand pressures of 2000 psi (138 bar). Though the tool is designed for pressures higher than 2000 psi, due to factor of safety requirements, the quoted maximum operating pressure for SmartBall is 2000 psi. The tool is not anticipated to be used in line pressures greater than 2000 psi.

A test vessel was designed and built for the purpose of pressure testing all SmartBall's that are produced. It comprised of a sealed container sized to fit the largest SmartBall under production. Pressurization was achieved by means of a standard air compressor. The internal pressure is monitored continuously throughout the test. The pressure vessel is illustrated in Figure 17.



Figure 17. Pressure Vessel Closed (L) and Open (R)

SmartBall sizes of 4", 6", 8", and 10" diameters were pressure tested at 2,000 psi for a duration of 12 hours. All sizes were able to successfully withstand the 2,000 psi pressures with no damage.

5.3 Temperature Test

The SmartBall needs to withstand normal operating temperatures within oil and natural gas lines. Temperatures can vary widely from far below freezing for cryogenic applications to in excess of 100°C in some production systems. Due to the sensitivity of electronic components and batteries to temperature extremes, it is not practical to design the SmartBall to withstand all possible environments. A decision was made to design the ball for the 0°C to 85°C range. This will allow the ball to operate in the majority of operational pipelines.

The temperature test was performed to verify that the tool in actuality will continue to operate and collect data at 85° Celsius. An electrically heated thermal chamber sized to accommodate all sizes of production SmartBalls was used. The internal temperature was logged throughout the 28 hour duration

of the test. Table 3 presents results of temperature tests performed on 4" and 10" SmartBalls. The testing procedure is listed as follows:

- 1) Operating SmartBall placed into thermal chamber
- 2) Thermal Chamber set to 85 degrees
- 3) Tool left in Chamber for 28 hours
- 4) Electronic capability re-tested.

Table 3. Temperature Test Results

SmartBall	Temperature (Degrees Celsius)	Time in Thermal Chamber	Result
4"	85	28 hours	Operational
4"	90	28 hours	Failed
10"	85	28 hours	Operational

6.0 TASK #4 – SOFTWARE DEVELOPMENT

6.1 SmartBall Analyst Software

Proprietary software, SmartBall Analyst, was developed by Pure Technologies Limited as the main application used to process data collected by the SmartBall hardware and above ground locators. The goal was to develop and test a comprehensive program that imports collected data from the SmartBall and above ground locators to detect leaks and present a report of their magnitude and location expressed in pipeline stationing units and GIS coordinates. The application runs on a Windows platform and was developed using the Microsoft .Net framework.

The application is document based, with one document representing a run of a pipeline from insertion location to extraction location. A document enables multiple inspections, or traverses of the pipe and their associated data. Each inspection is analyzed independently of the others with the option of a comparison step to use trend information to detect, confirm, and verify the location of leaks.

The software program flow is as follows.

1. **Run Setup.** This view indicates units, medium, time zone, distance from insertion to extraction and location of above ground locator installation positions and other features in terms of linear distance from start and GIS coordinates. This step will ideally only be performed once and the data used across multiple inspections.
2. **Ball Data Import.** This starts a new inspection and load acoustic, pressure, temperature, accelerometer and magnetic data as well as the time of the inspection from the data file generated by the ball after an inspection.
3. **Above Ground Locator Data.** These positions, associated with locations as indicated in the run setup, are used to assert known ball locations and increase the accuracy of the detected leak locations.
4. **Time/Position Model.** This step creates an internal model of how far the ball has traveled at any given time. This model is crucial in later steps to locate detected leaks. (see Figure 18)

5. **Leak Detection/Calibration.** This step locates and determines the size of any leaks recorded by the ball and may include comparison with leaks from previous inspections to use trending information. Detected leaks that were manually created to calibrate the system will be marked to determine the size of spontaneous leaks detected by the system.
6. **Reporting.** The end result of the process will be a report listing the locations and sizes of all leaks, along with images of the GIS location plotted on a map and graphs of the data where appropriate.

The final, fully automated software application takes the form of a wizard, prompting the user for information and decisions to walk them through the analysis of the data. The following are major enhancements that were made in developing the current SmartBall PC Analysis Software:

- 1) Wizard-based above ground locator (SBR) calibration
- 2) Wizard-based accelerometer calibration
- 3) Enhanced ball roll detection
- 4) Acoustic data summarization and browsing

The speed of data analysis is critical in supplying clients with a high level of desirable service and is directly correlated with the ability of the software to aid the processor in detecting and locating leaks accurately. Enhancements in the current software version have decreased analysis time by up to 20%.

A 12 hour SmartBall inspection generates 4 gigabytes of data split into 3.95 GB of acoustic data and .05 GB of "low frequency data"; being accelerometer, magnetometer and pressure data. Low frequency data is sparse enough to load into memory and provide the user with the ability to zoom in and out of the data freely with the mouse and scroll wheel. The high volume of acoustic data, coming from its relatively much higher sample frequency did not allow this capability. In order to make the system responsive when viewing acoustic data, the viewable range had to be limited to very small time windows.

Figure 19 shows a typical time range to zoom into the data. The limitation was the number of data points that could easily be plot at one time. The added ability to zoom out further to obtain a more meaningful view of the data was acquired by adding an acoustic data summarization step to the ball data import that creates a visualization pyramid of the data at different resolutions. By trading off space (twice as much on-disk storage to process the data is now required) it is now possible to zoom in and out of the data freely to any resolution with no delays.

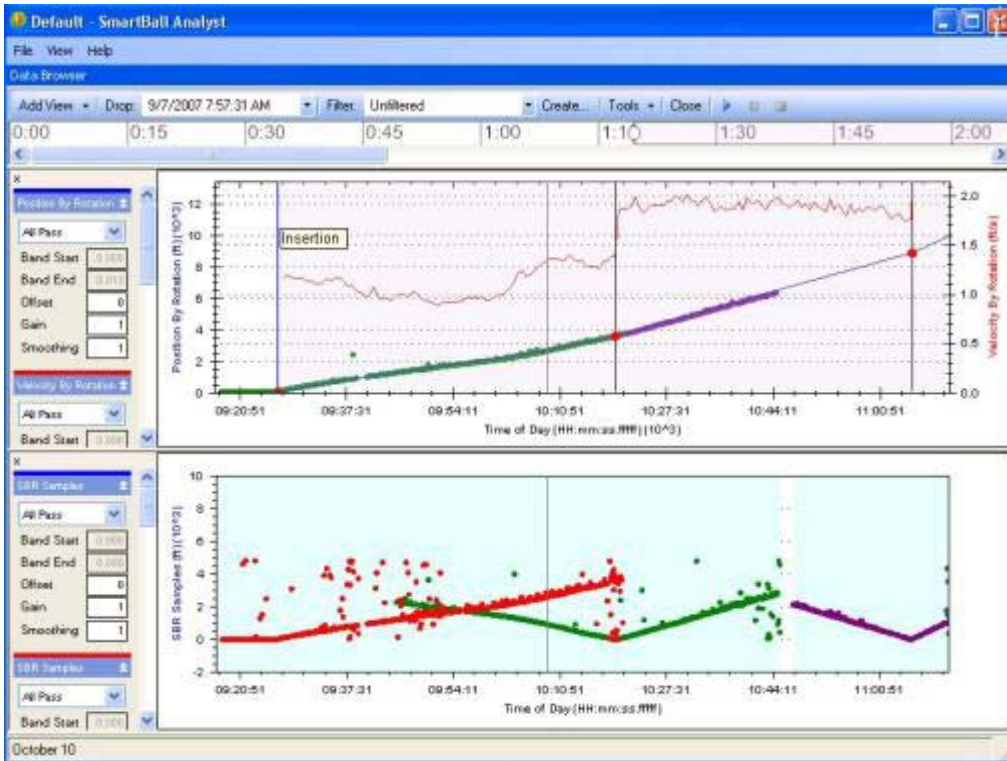


Figure 18. Sonic Tracking of SmartBall

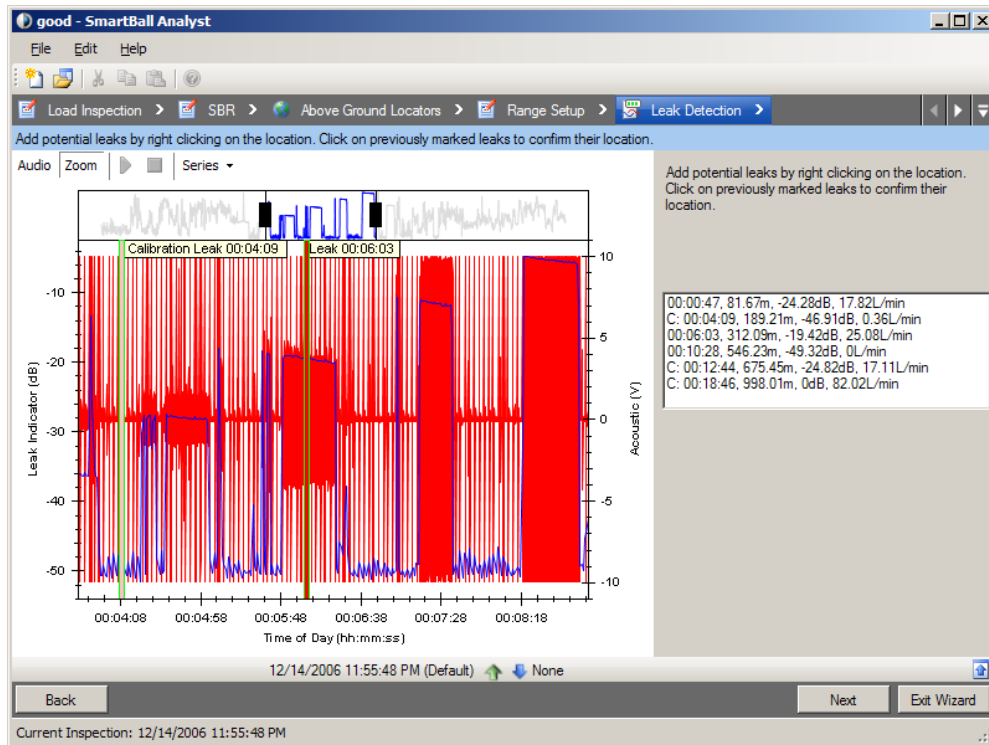


Figure 19. Acoustic Summarization

7.0 TASK #5 – FIELD TESTING IN OPERATIONAL LINES

The project involved deploying the SmartBalls in live operational lines to examine their performance. One run of the 10" OilBall was performed on October 15, 2008 in the CLH Loeches-Villaverde gasoline line in Madrid, Spain. Two runs of the 10" OilBall were performed on April 23-24, 2009 on the MOL Szajol-Tiszaujvaros gasoline line in Siofok, Hungary. Two runs of the 6" OilBall were performed on February 19, 2009 in the Plains Midstream Senlac to Unity Line in Unity, Saskatchewan. Two runs of the 4" OilBall were performed on June 3, 2010 in the Plains Midstream Manitou condensate line outside Calgary, Alberta.

To evaluate the GasBall, four runs of the 4" ball were performed on June 10, 2010 in the EnCana Pipeline Severn to Crowfoot Gas Line in Calgary, Alberta.

7.1 CLM Loeches-Villaverde Line – Madrid, Spain

The SmartBall was deployed to inspect the Loeches to Villaverde portion of CLH's gasoline pipeline on Wednesday October 15th 2008 (Figure 20). The tool was inserted and extracted through CLH's existing pig traps. Total run length was approximately 28 km of pipeline. Three simulated leaks were generated along the pipeline as both a test of the SmartBall's ability to locate leaks and as reference points for calibrating unknown leaks. Two of the simulated leaks were made known to Pure Technologies staff while the third leak was not. Calibration leaks of varying sizes were also generated while the SmartBall was still inside the insertion trap prior to launch.



Figure 20. Loeches to Villaverde Pipeline

The OilBall operated extremely well in the CLH field trial. The acoustic data was of a high quality and the analysis of one simulated leak and one blind test leak were easily identified and located to within ± 6 ft (± 2 m), see Table 5 (Page 34). The second simulated leak created in the field trial was not identified by the ball as the CLH operations group produced the leak improperly. The leak had a 30 m plastic hose attached to the needle valve, which was routed to a barrel a fair distance away. This leak is an inaccurate representation of an actual leak that would occur on a pipeline. The pressure drop that is created when an actual leak on a line exists is what creates the acoustic signature associated with a leak. In the leak simulation that CLH created, the tube being 30 m meant that the pressure drop was occurring 30 m from the pipe at the end of the tube where it was extricating the product into the waste barrel. This means that pressure drop was occurring at 30 m from the actual pipeline.

The leak quantification was off by about approximately 10%. This early test revealed that further leak calibration testing needed to be completed on 10" pipelines at different pressures to be able to accurately quantify leak sizes.

The pressure sensor and temperature sensors both operated accurately. Pressure and temperature data from the CLH pipeline SCADA system was matched to the data from the OilBall. All data points were also in agreement. Unlike the SCADA data, which relies on discrete metering points, the SmartBall data produced a pressure and temperature profile of the entire section of pipeline surveyed. Overall, the 10" operated to the designed specification.

7.2 MOL Szajol to Tiszaujvaros Line – Siofok, Hungary

The SmartBall was deployed to inspect the Szajol to Tiszaújváros portion of MOL's 12" gasoline pipeline on Thursday and Friday, April 23rd and 24th of 2009. The tool was inserted and extracted through MOL's existing pig traps. Figure 21 shows the OilBall after extraction from the pipeline. Total run length was approximately 126 km. One simulated leak known to Pure staff was generated along the pipeline as both a test of the OilBall's ability to locate leaks and as reference points for calibrating unknown leaks. A second unknown leak was discovered upon running the analysis on the data retrieved from the tool. The ball identified leak readings for the simulated leak of 1.321 GPM (0.792 GPM actual) and for the unknown (blind leak test) 1.268 GPM.

Pure staff were present at the first simulated leak location due to this valve station also being used as a tracking point for the Smartball tool during the inspection. The second leak was unknown to Pure staff, both in location and in flow rate. Analysis of the data allowed for an estimation on the location and size of the leak. Leak location was estimated at 76+458 (actual location: 76+460), and the leak rate was estimated at 1.3 GPM. The nearest tracking point was 12,700 meters downstream.

The first run on the MOL Szajol – Tiszaújváros Line was unsuccessful as the SmartBall turned itself off 60 km into the run. A setting was incorrectly input into the ball's start up wizard.

The second run was successful on all fronts. Acoustic data was of a high quality, temperature and pressure data matched up exactly with MOL's operations center and their segregated sample points along the line.

The blind test leak was identified and accurately located. Location was ± 6 ft (± 2 m); however, similar to the CLH runs, leak quantification were slightly was off for both the known and blind leaks. Additional calibration data on 10" crude pipelines at varying pressures is required.



Figure 21. The 10" OilBall Removed from Pipeline

7.3 Plains Midstream Senlac to Unity Line - Unity, Saskatchewan

The SmartBall was deployed in the 26.5km Senlac to Unity portion of Plains Midstream 6" steel pipeline on February 19th 2009 (Figure 22). There were no simulated leaks in the line as the main objective of the run was to test durability of the OilBall in a Heavy crude environment and evaluate its ability to collect and record acoustic, temperature, and pressure data. The tool was inserted and extracted through Plains Midstream's existing pig traps.



Figure 22. Senlac to Unity Pipeline

The Plains Midstream survey had two separate 6" tools launched thirty minutes apart from each other. Both tools successfully recorded acoustic, temperature, and pressure data. Additionally, both runs

showed consistency in acoustic, temperature, and pressure profiles. Overall, these two runs provided evidence in the OilBall's ability to physically handle Heavy crude environments.

7.4 Plains Midstream Manitou Line – Calgary, Alberta

A survey of a 1.7 km portion of the Plains Midstream Manitou pipeline using a 4" OilBall was performed on June 3, 2010. The Manitou pipeline is a 4" steel line that transports condensate. The purpose of the SmartBall survey was to identify any locations where the main may be leaking in the area of the North Saskatchewan River crossing illustrated in Figure 23. A total of two runs of the 4" OilBall were performed along the section of pipeline and did not indicate any leaks in the system.



Figure 23. Section of Manitou Pipeline

During the survey, the tool was inserted into the pipeline through a standard pig launcher and released into the flow of the pipeline. It traversed the pipeline with the flow and in so doing acquired acoustic and positional data. This data was evaluated to identify the acoustic activity associated with potential leakage.

Figure 24 shows the value of the leak indication power as detected by the tool with respect to the position of the SmartBall along the pipeline. The magnitude of leaks is estimated by correlating the value of the leak signal with calibrations performed on the SmartBall as detailed in Section 2.5 if available, or with previously discovered leaks.

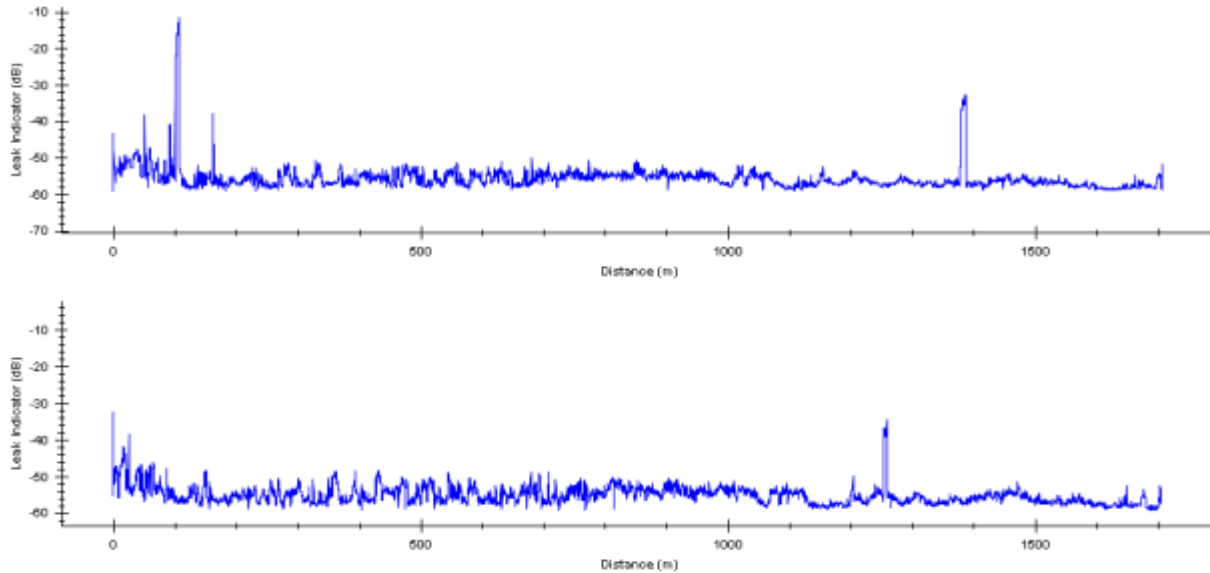


Figure 24. Acoustic Profile of the OilBall vs. Distance Traveled (Top – Run 1; Bottom – Run 2)

7.5 EnCana Pipeline Severn to Crowfoot Natural Gas Line – Calgary, Alberta

Part of the project objectives was to evaluate the applicability of the SmartBall for natural gas applications. Development of the tool from water applications to petroleum products involved movement along the pipeline via fluidic flow. Flow parameters of the tool in natural gas applications are different in its propelling mechanism. Subsequently, the GasBall tool with a foam overshell was developed and trialed on a live line in Calgary, Alberta.

The GasBall tool was used in partnership with EnCana Pipelines to conduct a series of trial inspections of a 6-inch natural gas transmission pipeline that transports natural gas 27 km from the Severn Compressor Station to the Crowfoot Gas Plant for dehydration prior to returning to the Severn plant and on to sales. Figure 25 illustrates the pipeline test section. Trial inspections, conducted on June 8, 2010, were intended to further test the natural gas leak detection performance of the GasBall. The selected pipeline section had previously been successfully inspected twice in the past. Prior to the runs, maintenance to a booster pump required a temporary drop in pressure rate. Subsequently, pressure on the line averaged 797 psi (55 Bar). The new inspections were intended to quantify the leak detection resolution of the tool, specifically determining the smallest detectable leak under normal pipeline operating conditions. Four separate inspections were conducted with a simulated leak created at a midpoint riser location. The simulated leaks were created at progressively smaller leak rates. The intention was to determine the relationship between leak rate and the acoustic energy of the leak as recorded by the GasBall tool as it passed by the leak location. The resulting logarithmic curve can be used to extrapolate a theoretical lower leak detection threshold for specific flow/pressure parameters, thereby making the EnCana inspections an invaluable asset in the continuing development of the Smartball tool for natural gas applications.

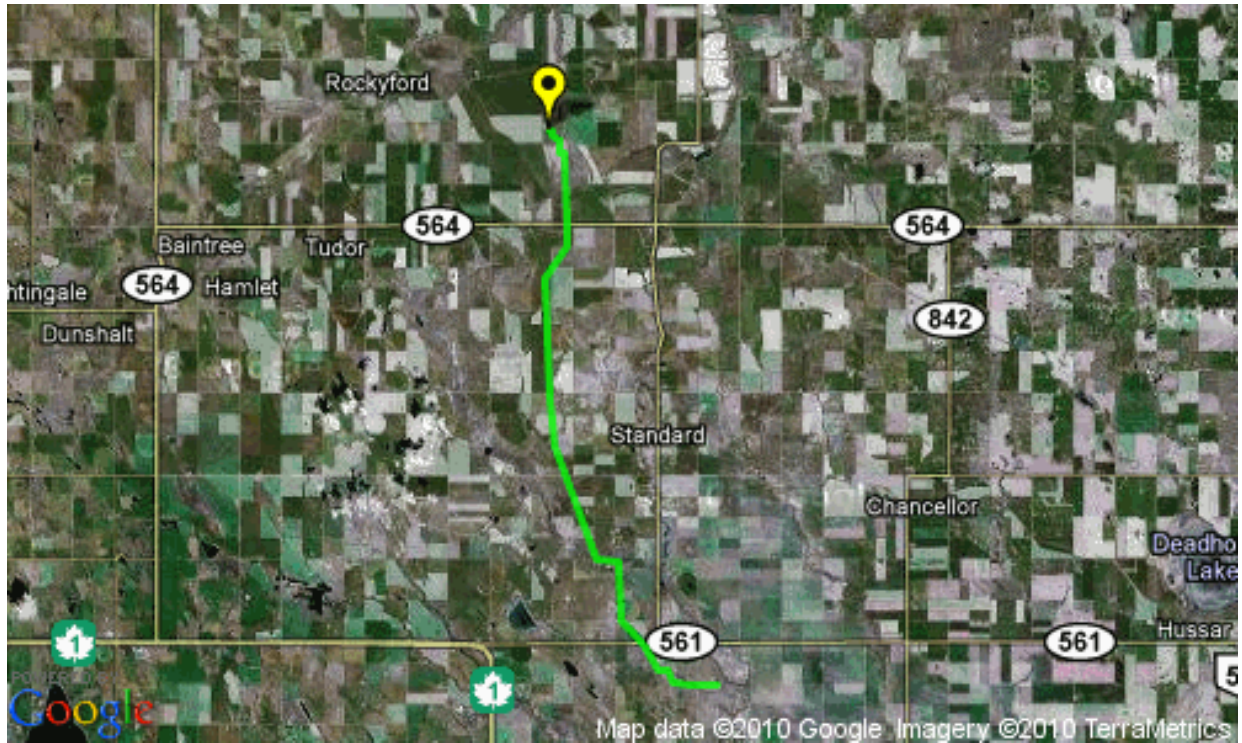


Figure 25. Severn to Crowfoot Natural Gas Pipeline

During the four surveys conducted, the GasBall was inserted into the pipeline through a standard pig launcher and released into the flow of the pipeline. It traversed the pipeline with the gas flow and in so doing acquired acoustic and positional data. The tool was subsequently extracted through a standard pig receiver fitted with a strainer to prevent passage of the tool through the kicker line. This data was evaluated to identify the acoustic activity associated with leakage. The GasBall tools were all launched on the same day; however, due to the client's reluctance to have all four tools inside the pipeline at one time, the launches were staggered so that there were never more than 2 tools inside the pipeline at a given time.

Each simulated leak was created at the above ground section of the pipeline prior to the GasBall arrival by means of an existing 1" tap on the pipeline. The existing tap is capped with a 1" gate valve and plug. For the purposes of the inspection, the plug was removed and replaced with a 1" pipe nipple. Above the nipple a 1" needle valve was installed in order to have precise control over the quantity of escaping gas. The collection manifold of the flow metering equipment was then placed above the needle valve to quantify the leak rates. Figure 26 shows the collection of measured leak flow rate data. The intent was to create a progressively smaller leak for each pass of the tool in order to gain a better understanding of the lower leak detection threshold of the GasBall in natural gas pipelines.



Figure 26. Measuring Gas Leak Flow Rate

The position of the SmartBall within the pipeline is critical for locating leaks. Individual SBR's and AGM's were able to track the ball's progress through the pipeline for up to 1,000 ft (300 m). The distance between and location of these SBR's and AGM's was based on information provided by EnCana. The result of the rotation profile and SBR/AGM tracking was a position versus time relationship for the entire run of the tool. The methodology used to locate leaks as the tool traverses the pipeline involves obtaining a velocity profile using data obtained from the accelerometers and magnetometers on board the GasBall. Absolute position reference points obtained from the SmartBall Receivers (SBR) and AGM's are then applied to time stamped data. Since the quality of the gas leak detection ability of the SmartBall was the primary focus of these tests, there was also an SBR tracking point at the location as the simulated leak points. Thus leak location accuracy wasn't applicable.

The results revealed the smallest leak detected to be 0.138 CFM (1.03 GPM). This is extremely small and would likely have gone undetected without prior knowledge of the simulated leak location. Leaks this small will typically be obscured by other noise sources within the pipeline. Other leaks recorded were 2.91, 1.59, and 0.78 CFM (21.268, 11.888, and 5.812 GPM) as presented in Table 4. Based on initial field trials, the GasBall should conservatively be able to detect leaks as low as 0.706 CFM (5.28 GPM) with accuracy of within ± 3 ft (± 1 m). Continued testing is necessary to confirm minimum detection standards for natural gas applications. All of the leaks were detected accurately at the simulated points along the pipeline.

Table 4. Leak Rate Results for GasBall Run

Run No.	Leak Rate (SCF/M)	Comments
1	2.91	
2	1.59	
3	0.78	
4	0.138	Extremely small and not typical of GasBall capability. Was only detected because at a known leak point.

Overall, a total of 19 runs of the Oil and Gas SmartBalls were completed during the project duration using tools ranging from 4” to 10”. This included 15 runs of the OilBall (Table 5) and 4 runs of the GasBall (Table 6). A total of 15 leaks were detected during these runs. All of the detected leaks were located within ± 6 ft (± 2 m) or better of the leak location. These are promising results and show the applicability of the OilBall and GasBall tool for commercial application in oil and natural gas leak detection.

Table 5. List of Field Test Results of OilBall in Live Lines

Operator	Location	Date	Nom. Diam. (in.)	Sensor Device	Leak Type	Peak Leak Signal	Leak Rate (GPM)	Nearest Sensor Location (ft)	Leak Accuracy (ft)
CLH	Spain	10/15/08	10	10” OilBall	Simulated	-34 dB	0.499	5,399	< 6
CLH	Spain	10/15/08	10	10” OilBall	Simulated	-42 dB	0.291	3,779	< 6
YPF	Buenos Aires	10/22/08	12	10” OilBall	Densitometer	-39 dB	0.05	13,120	< 6
Plains Midstream	Saskatchewan	02/19/09	6”	6” OilBall	None	N/A	N/A	N/A	N/A
MOL	Hungary	4/24/09	12	10” OilBall	Simulated	-19 dB	1.321	n/a	< 6
MOL	Hungary	4/24/09	12	10” OilBall	Simulated	-24 dB	1.268	41,656	< 6
Magellan	Kansas City	8/8/09	6	6” OilBall	Simulated	-27 dB	0.04	590	< 3
Magellan	Kansas City	8/17/09	8	6” OilBall	Simulated	-44 dB	0.039	590	< 3
Magellan	Kansas City	8/18/09	8	6” OilBall	Simulated	-19 dB	0.132	590	< 3
PetroChina	China	9/17/09	14	10” OilBall	Simulated	-39 dB	0.132	9840	< 3
CLH	Spain	01/13/10	12	10” OilBall	Actual	-3 dB	1.136	19,680	< 6
Plains American	Oklahoma City	5/6/10	10	10” OilBall	Simulated	-35 dB	0.029	59,040	< 6
Tampa Pipelines	Puerto Rico	5/18/10	6	6” OilBall	None	N/A	N/A	N/A	N/A
Plains Midstream	Alberta	6/3/10	4	4” OilBall	None	N/A	N/A	N/A	N/A
Plains Midstream	Alberta	6/3/10	4	4” OilBall	None	N/A	N/A	N/A	N/A

Table 6. List of Field Test Results of GasBalls in Live Lines

Operator	Location	Date	Nom. Diam. (in.)	Sensor Device	Leak Type	Peak Leak Signal	Leak Rate (CFM)	Nearest Sensor Location (ft) *	Leak Accuracy (ft)
EnCana	Alberta	6/8/10	6	4" GasBall	Simulated	-42.9 dB	0.138	34,440	< 3
EnCana	Alberta	6/8/10	6	4" GasBall	Simulated	-32.5 dB	2.91	34,440	< 3
EnCana	Alberta	6/8/10	6	4" GasBall	Simulated	-44.3 dB	1.59	34,440	< 3
EnCana	Alberta	6/8/10	6	4" GasBall	Simulated	-44 dB	0.78	34,440	< 3

* For the purposes of leak location accuracy testing, the SBR point directly at the leak location was removed

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 SmartBall Benefits

This report presents the development of an innovative free-swimming leak detection technology for application to oil and natural gas. SmartBall was initially developed in 2005 for inspecting leaks in water pipelines. Since its introduction, it has been successfully run in over 50 water inspections totaling over 300km. Within those, more than 120 leaks have been detected. Research and development efforts between Arizona State University and Pure Technologies Limited resulted in the development of a fully commercial version of the SmartBall technology for both oil (OilBall) and natural gas (GasBall) leak detection. Funding from the U.S. Department of Transportation’s Pipeline and Hazardous Materials Safety Administration (PHMSA) was instrumental in the technological advancements discussed in this report. SmartBall for oil applications provides pipeline operators with a cost effective and proactive solution for evaluating the presence of possible leaks as small as 0.028 GPM in oil pipelines as part of their integrity management program. Proactive system evaluation serves as a preventive measure when considering public safety and environmental consequences of line leaks.

A total of 19 runs of the Oil and Gas SmartBalls were completed during the project duration using tools ranging from 4” to 10”. This included 15 runs of the OilBall and 4 runs of the GasBall. A total of 15 leaks were detected during these runs. All of the detected leaks were located within ±6 ft (±2 m) of the leak location. For the purposes of location accuracy concerns, during those inspections were a tracking point was at the same location as the leak it was removed from the analyst software prior to calculating the leak locations. These are promising results and show the applicability of the OilBall and GasBall tool for commercial application in oil and natural gas leak detection.

Development also included the addition of increased internal memory and battery capacity to extend the range of SmartBalls in larger sizes. Additionally, the upper temperature limit was increased to allow the tool to operate in an even wider range of pipelines. For example, typical high temperature applications include the production from the Alberta Oil Sands.

A simplified arrangement for data download that avoids the need to open the ball was introduced. This has an additional advantage of reducing the risk of damage to internal components and helps to ensure that the seals around the ball remain intact.

A new and user-friendly SmartBall Analyst Software was developed and modified to increase the level of automation and reduce the need for technical expertise from the user. The current version of the software provides excellent graphical representation of the SmartBall operation and enhanced reporting capability.

8.2 SmartBall Limitations

All non-destructive testing technologies have unique capabilities and limitations that affect the accuracy and efficacy of the technology. The SmartBall device has the following limitations that are worthy of noting:

- **Minimum Pressure:** The acoustic activity associated with a leak is derived from the pressure differential across the pipe wall. With little to no pressure differential, the device will not detect leakage as there will be no associated acoustic activity.
- **Minimum Sensitivity:** The sensitivity of all leak detection technologies is a function of several variables and as a result, no resolute thresholds can be established. In general, with SmartBall, the acoustic sensor inside the ball always passes within one pipe diameter of a leak and therefore it can be used to identify very small leaks. For example, on a 150 psi pipeline, during a blind simulation, it was confirmed that a leak of 0.028 GPM minute could be detected. Other experiences have confirmed this ability; however, variables associated with a specific leak should be understood. For pipes with significant pressure of 50 psi or more, under ideal conditions, SmartBall may detect leaks as small as 0.028 GPM. For pipelines that operate at pressures less than 10 psi, small leaks in this range may not be identified. Based on initial field trials, the GasBall should conservatively be able to detect leaks as low as 0.706 CFM (5.28 GPM). Continued testing is necessary to confirm minimum detection standards.
- **Ambient Noise:** SmartBall detects and reports anomalies that have acoustic characteristics similar to leaks on pressurized pipelines. However, other forms of ambient noise may be identified during the data analysis. For medium and large leaks there is very little that can match these acoustic characteristics and therefore, these events are almost certainly leaks. However, for small leaks, there may be other forms of ambient noise that are difficult to evaluate. Pure has invested significant resources into characterizing acoustic anomalies and consequently believes the leaks described in this report are leaks. Cars, pumps, boat traffic and other forms of common ambient noise should not be reported as leaks as they contain different acoustic signatures. However, unknown pressure reducing valves, cracked valves in close proximity, interconnected pipelines that have not been completely isolated and leaks in pipelines immediately adjacent to the subject pipe do contain a similar acoustic signature and could be reported as leaks in this report.
- **Reported Locations:** The reported locations contained in this report are accurate to within ± 6 ft (± 2 m). This is based on project experience and the limitations of the technologies used to calculate location. However, if SBR or AGM devices are more than 4,000 ft apart, or if the actual pipeline length between tracking points is unknown, this error may increase. In order to ensure leak location accuracy of less than 2m, it has been determined based on field inspection experience in oil, gas and water environments that the spacing between SBR, AGM, or other reference points must fall within 4,000 ft. In addition, if the length of pipeline between SBR's and AGM's is incorrectly provided, this will increase the error as well.

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APPENDIX A – Operating Protocol

SmartBall[®] Operating Protocol

SmartBall[®] Leak Detection Services



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Executive Summary

The SmartBall[®] leak detection tool is intended for use in live oil and gas pipelines. This manual is intended to give an overview of the overall protocol undertaken to perform a SmartBall[®] leak detection survey.

Though every inspection conducted will be different in many ways, this manual will attempt a general overview of a typical Oilball inspection, specifically with respect to configuration, launch/receive, and tracking of the Oilball throughout an inspection.

1.0 Oilball Configuration and Setup

The Pure Technologies Ltd. OilBall is a sensitive instrument that requires careful handling during configuration, charging, and data extraction. All of these functions are performed through the OB Docking Station and SmartBall Configuration Wizard.

1.1 Overview





The OB Docking station connects the SmartBall to a laptop computer for configuration and data extraction and acts as a charging station. The OilBall cannot be charged, started, configured or have its data extracted without using this station.





Connecting the OilBall to the docking station and the docking station to the computer requires a very precise procedure. This procedure is guided, step by step, through the SmartBall Configuration Wizard, run on the laptop.


1.2 Components

Consult the following table to see which components need to be used to configure, charge, or extract data from the SmartBall.

Image	Name	Config	Extract	Charge
	OilBall	YES	YES	YES

	OBDS	YES	YES	YES
	GPS Antenna	YES	NO	NO
	Chirp Sensor	YES	NO	NO
	Pulser Antenna	YES	NO	NO

	Charger	YES	YES	YES
	Data Extraction Cable	YES	YES	NO
	USB Cable	YES	YES	NO
	SB Charging Cable	YES	YES	YES

	SB Control Cable	YES	YES	NO
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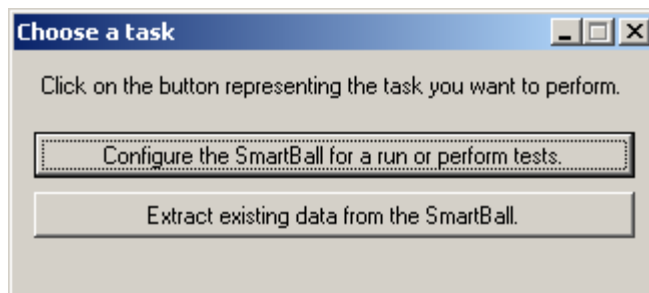
1.3 SmartBall Configuration Wizard

The SmartBall Configuration Wizard is a program that runs on the laptop to provide step by step instructions on connecting the OilBall to the OB Docking Station and laptop for configuration and data extraction. When it is run, no cables should be connected to the OB Docking Station or laptop.

It is run on the laptop from the desktop icon or “Start Menu\Program Files\Pure Technologies.”



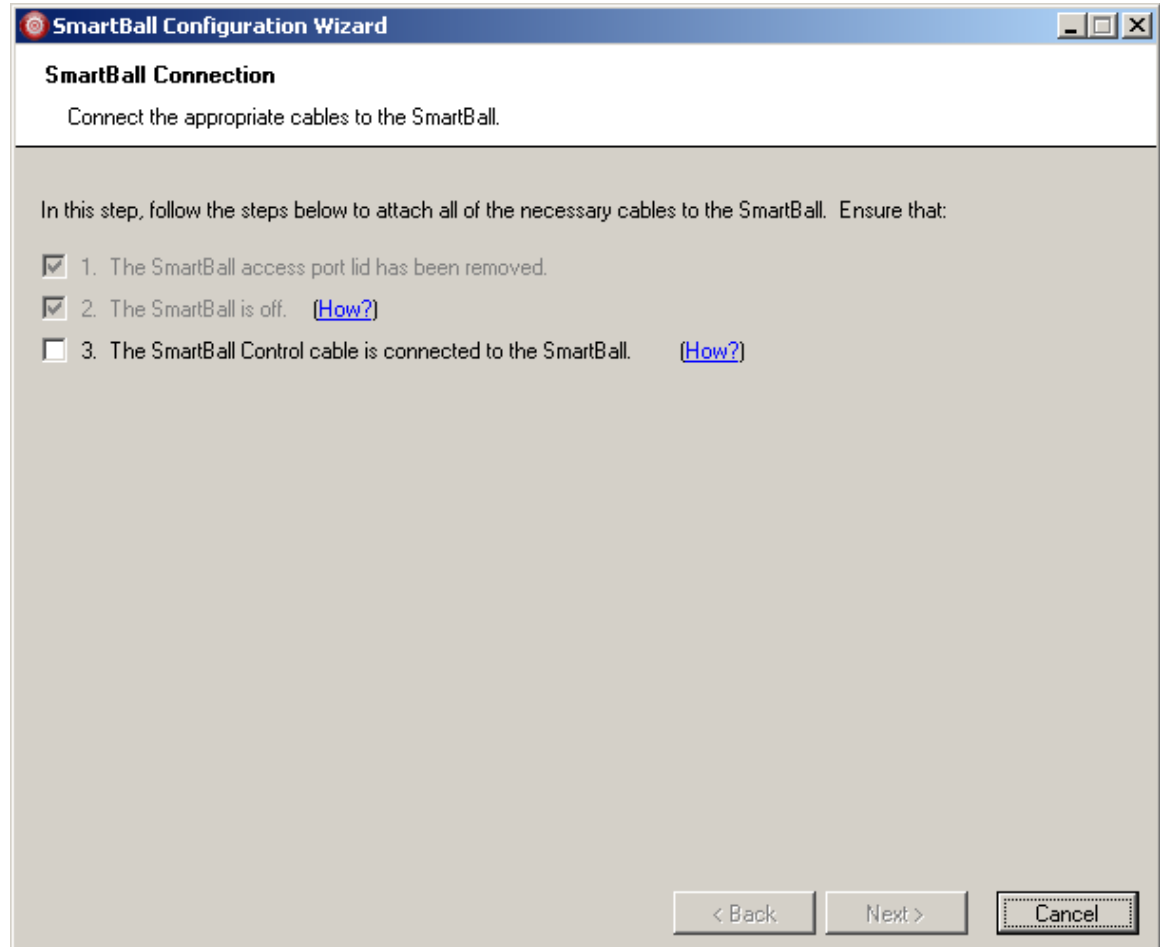
When you first run the program, the “Choose a task” window will appear presenting you with the option of configuring the OilBall for inspection or extracting data after an inspection.



Press the button of the task that you would like to perform and another window will appear guiding you through the necessary steps.

Individual steps are broken into sub-steps which are listed as items with checkboxes to select once the step has been performed.

Note: Only select a checkbox after the corresponding sub-step has been completed.



Each time a sub-step is checked, it is grayed out and the next sub-step is presented. When all of the sub-steps for a step have been completed the “Next>” button is enabled allowing you to go on the next step.

Some sub-steps may require further information for people unfamiliar with the OB Docking Station. In these cases a “[How?](#)” hyperlink can be clicked to display extra details.

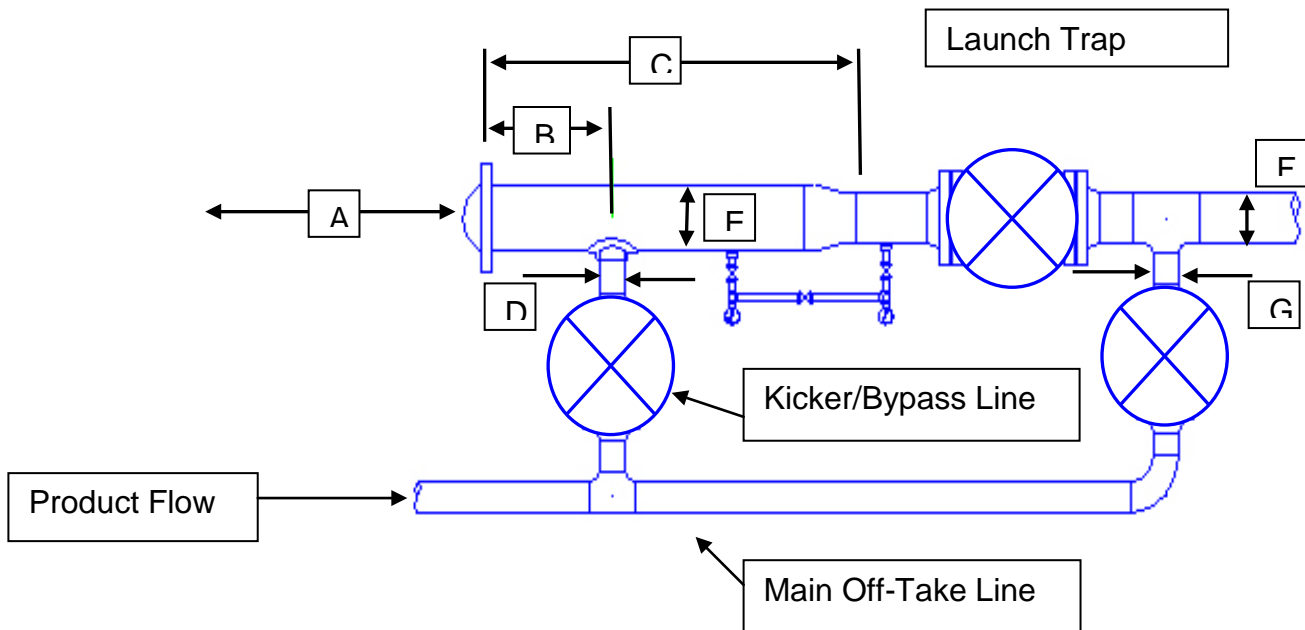
Follow all of the steps until the “Next>” button changes to “Finish”, indicating that you can press the finish button to complete the wizard.

At this point you will need to replace the O-ring on the top cap, lubricate it, and install the top cap assembly on the Oilball to seal it in preparation for inspection.

Oilball Operations Manual

2.0 Launch:

Typically all Oilball inspections will make use of an existing pig trap facility to launch the Oilball down the pipeline. A typical layout of a pig trap can be seen in the figure below. Details may vary but every trap will have the main features seen below.



2.1 Key Features of the Pig Trap:

- A- Working area: This will be how much room you have to work in when extracting the Oilball from the trap
- B- Distance from the Trap door and the Kicker/Bypass line.
- C- Distance from trap door to beginning of nominal pipe size.
- D- Kicker/Bypass line inside diameter.
- E- Oversize barrel inside diameter. Typically 2" to 4" larger than the pipeline.
- F- Main line pipe inside diameter
- G- Main Off-Take inside diameter

2.2 Launching the Oilball

- 2.2.1** The client's pipeline operations group will handle all the valve work required in launching the Oilball. Pure's duty throughout launch is simply to provide the fully configured and recording Oilball, ensuring that all O-rings are new and lubricated and that the Oilball has already been fully pressure tested and duration tested under heavier conditions than expected during the actual inspection on site.
- 2.2.2** Client will first ensure the trap is isolated from product flow and then drain the trap and open the door. Pure representative will then hand over the Oilball for insertion.



Oilball ready for insertion

- 2.2.3** Client will load the Oilball inside the oversize barrel of the pig trap. Care must be taken to ensure the Oilball remains ahead of the kicker/bypass line and does not roll back to the trap door. The product flow that will launch the Oilball comes from the Kicker/Bypass line, so the Oilball must be in front of it so that the product flow can push it out of the trap and down the pipeline.
-



Oilball Ready Loaded inside Trap

- 2.2.4** While the client is sealing the trap and preparing for launch is often a good time to attach your sensor to the pipe and set up your SBR for tracking the launch. The best place to glue your sensor is outside the pig trap proper, typically downstream of the last mainline valve just before where the pipeline will typically move underground. This way you can be a little more isolated from the noise associated with launching the Oilball and can continue to track once the operations crew has started to isolate and drain the trap after the Oilball launch. *Note: Once you have installed your sensor you may find that you can not hear the chirp of the Oilball yet. This will be because the launch trap has not yet been filled and pressurized with product. Your distances on the SBR will also be higher than normal due to a closed mainline valve separating the Oilball from the SBR.*
-



- 2.2.5** The client will now commence the pressurization of the trap. To do this they will crack open the valve on the kicker/bypass line a small amount to release product into the trap. This will take some time, depending how large the pig barrel is. This will create a lot of noise and will likely prevent you from hearing the Oilball's chirp on the SBR while this process is being carried out. Now the pressure inside the pig trap will be equal to the pressure in the main pipeline.
- 2.2.6** The client will now close the valve on the kicker/bypass line that was cracked open to equalize the pressure in the trap.
- 2.2.7** Next the client will open the main valve in the launch trap, connecting the pig trap and the main pipeline. At this point you should be getting good readings on your SBR and clearly hearing the chirp of the Oilball. The Oilball will still be in the trap at this point and should not be moving down the pipeline.
- 2.2.8** The client will now fully open the valve on the kicker/bypass line. At this point enough product might flow through the kicker/bypass line to launch the Oilball out into the pipeline. Should the Oilball still not launch, as evidenced on the SBR, the client will now start to slowly close the valve on the main off-take line. This will have the effect of redirecting more flow through
-

kicker/bypass line and push out the ball. At times it may be required to fully close the main off-take valve in order to direct all flow through the kicker/bypass line to launch the ball. Note: Make sure you get several good readings on the SBR showing the ball moving away from the pig trap before you confirm to the client that the ball has indeed been launched successfully.

2.2.9 At this point you will continue tracking the Oilball with the SBR for as long as possible. Depending on differing pipeline conditions, i.e. pump noise nearby, bends or elevation changes in the pipeline, etc... you may lose track of the Oilball quite quickly.

2.2.10 The client will now start the process of isolating the pig trap from the pipeline once again, so that all flow goes through the main off-take line.

3.0 Tracking the Oilball:

Tracking the Oilball is a different process from methods used on the water side. Typically there will be very few locations along the pipeline where you might be able to mount an SBR. They may be dozens of kilometers apart in fact, or there may even be none at all.

3.1 SBR Tracking

The best and most reliable method of tracking the Oilball is using the SBR. When planning an inspection ensure you get as much information regarding the pipeline from the client as possible. Specifically you will want to know if there are any main line valves along the inspection, and whether they are above ground or not, or if the pipeline travels above ground at any locations, etc...Even riser pipes coming off the pipeline to service equipment like densitometers will work for mounting a sensor, as long as there is acoustic coupling between the product in the riser pipe and the main pipeline itself.



SBR Ready for Tracking

The more SBR locations you have the closer you will be able to locate any anomalies should you find them. So take advantage of any that are available.

3.2 Above Ground Markers

To supplement the SBR locations it is possible to use the Above Ground Marker boxes purchased from CDI. These marker boxes are used to track the Oilball from above ground. They track the ball using two separate systems, magnetics and acoustics. The pulser inside the Oilball generates a small magnetic field as well as a 20 Hz pulse. The magnetic field will typically be too small to detect with the above ground marker boxes while the pipeline remains under the ground. So the acoustic sensor in the marker boxes is usually the sensor that successfully picks up the Oilball passing by.

The reliability of the marker boxes depends a lot on the environment in which they are deployed. Nearby active train tracks, road traffic, high voltage power lines, etc... can cause false positive readings with the marker boxes. If you are experiencing many false positive triggers with the marker boxes it is a good idea to disable the magnetic sensor inside the marker box menu and rely entirely on the acoustic sensor. This procedure can be found in the marker box manual supplied by CDI.

The amount of marker boxes you can deploy during an inspection will depend largely on staffing. Many pipeline operators will have large support teams to work with during inspections. Often some of these

people can be recruited to help with deploying and relocating marker boxes during the inspection. This is a good thing to talk about with the client rep prior to the inspection.

Location is another variable that will affect marker box deployment. If the pipeline right of way is running through isolated country then it is often possible to deploy a marker box and leave it there for later collection once the Oilball has passed by. In more urban areas where theft may be a concern it may not be advisable to leave a marker box unattended.

The more marker boxes that can be deployed, the better the locational accuracy will be for the inspection.

3.3 Alternate Methods

Alternatively, some clients will have the capacity to rerun an inspection multiple times. In such cases if there is insufficient staff to deploy the above ground markers you can get away with using fewer or no marker boxes. Then, in the case of finding a leak or anomaly, the line can be re-run deploying markers concentrated near the area of the anomaly. This would obviously be less of an acceptable solution as the inspection lengths increase.

3.4 Confirming Oilball Arrival at Receive Trap

The final tracking point of an inspection will be an SBR sensor placed at the receive trap. At this point the client should already have the pig receive trap valved so that all flow is moving through the pig trap barrel and the kicker/bypass line. Again, it is preferable to mount the sensor outside the pig trap proper to reduce your proximity to the noise generated by the flow moving through the kicker/bypass line in the trap. As the Oilball comes within range of the SBR you will be able to track its progress right until it enters the pig trap. Though the Oilball is smaller than the inside diameter of the pipeline you will often be able to hear the sound of the Oilball rolling into the pig trap. Further confirmation of the tool's arrival can be had with the SBR.



SBR Setup at Receive Trap

3.4 Tracking Data Download

At the conclusion of an inspection all tracking information should be downloaded from the Vaio's inside the SBR's as well as from the marker boxes for importation into the analyst software.

4.0 Receive Trap:

Modifications to the client's pig traps are often necessary prior to being able to run an Oilball inspection. The issue that needs to be resolved is the possibility of the Oilball plugging the kicker/bypass line when it arrives into the pig trap and causing a high pressure shutdown of the pipeline and possible damage to the pipeline.

4.1 Trap Modifications

There are several ways to prevent such a situation that are relatively simple for the client to implement.

4.1.1 Basket Strainer

Some clients will have basket strainers available for use with the pig trap. These strainers can be placed inside the oversize barrel portion of the pig trap. They are essentially a section of pipe that is perforated with small holes throughout its entire length and diameter to allow flow passage. These outside diameter of the strainers will be need to be of a smaller diameter than the inside diameter of the oversize barrel of the pig trap. In addition, the inside diameter of the basket strainer will need to be sufficiently large for the Oilball to roll inside. The basket strainer prevents the Oilball from being sucked up against the kicker/bypass line by the flow and plugging the line.



4.1.2 Blocker Bar

A blocker bar can be deployed inside the pig trap to simply prevent the Oilball from rolling up to the kicker/bypass line. Typical arrangements will be a perforated plate sized with a diameter close to the inside diameter of the oversize barrel of the trap. The perforations or holes must be large enough for flow to pass through but small enough to prevent passage of the Oilball. A length of pipe will connect this rod to the back of the trap. This rod must be long enough to keep the perforated plate situated upstream of the kicker/bypass line. These blocker bars can be tack welded in the trap if the client has the capability, or simply placed inside. However there is a potential for noise pollution if the blocker bar is not secured inside the pig trap.



Blocker Bar used in Receive Trap

4.1.3 Dual Kicker/Bypass lines

Some pig traps have two or more kicker/bypass lines connected to the oversize barrel of the trap. In such cases there is no need for modification to the trap since the product will have two or more points for flow exit from the pig trap, preventing the Oilball from stopping flow.

Note: Bypass lines must either be barred or of a smaller diameter than the Oilball to prevent the Oilball from being sucked it in.



Receive Trap with 2 Bypass Lines

4.2 Isolation of Pig Trap

The client will now commence isolation of the pig trap, starting with opening the valve on the mainline off-take. This will have the effect of redirecting the majority of product flow through the mainline off-take instead of through the kicker/bypass line. Once this valve is completely open the client will start to close down the main valve connecting the pig trap to the pipeline proper. Lastly, the valve on the kicker/bypass line will be closed and the pig trap is now completely isolated from the pipeline.



Typical Pig Trap Layout

Pressure inside the pig trap will now be released and the trap drained of product. This can again take a significant amount of time given larger lengths and diameters of pig traps.

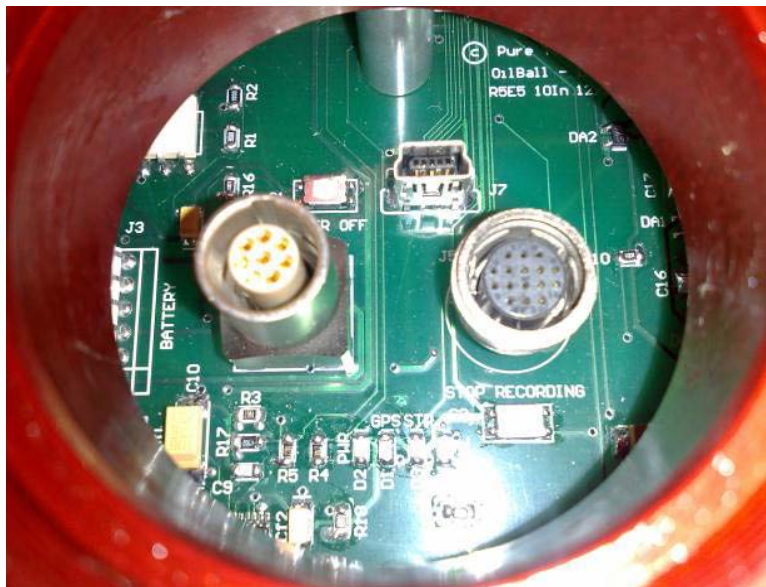
Once the trap is drained the clients will open the trap door and remove the ball. Depending on the length of trap and where the Oilball ends up, a long rod or tool might be required to reach inside the trap far enough to pull the Oilball out. Typically the clients will have something suitable on site.

Depending on the product in the pipeline it might take a good amount of time and effort to clean up the Oilball before opening it. Ensure the Oilball is as clean and dry as possible prior to opening the top cap, lest any product inadvertently enter and damage the internals.



Oilball after Crude Oil Pipeline Inspection

Now that the top cap is removed, press the “stop record” button once to end the recording. The Oilball will then automatically shut itself down. Now is the time to refer to the Oilball Docking Station in section 1 of the manual to walk through the steps of data extraction. *Note: Be sure to make a redundant copy of the .bal file to guard against accidental loss of data.*



Stop Recording Button

APPENDIX A:
Alternate Insertion Methods

Appendix A: Alternate Insertion Methods

In some cases clients may want to perform a Smartball inspection yet do not have the requisite pigging facilities for normal launch/receive. Some clients will be willing to install new pig traps on their lines to accommodate inspection requirements, but in most cases they would prefer a more cost effective method of inserting the Smartball into the pipeline.

Above ground main line valve locations are good candidates for alternate insertion methods, though it does require taking the pipeline out of service temporarily.

The pipe section immediately downstream of the valve can be unbolted from the valve flange, then the valve and upstream pipe can be raised with a crane in order to allow access to the open pipe for Smartball insertion.



Valve Assembly Unbolted for Access

APPENDIX B:
Leak Simulation

Appendix B: Leak Simulation

Creating a proper simulated leak is a very important aspect of every Smartball Inspection.

Firstly, it gives the client confidence in the Smartball's leak detection capability should no real leaks be evident on the line. Being able to demonstrate the leak indicator and frequency spectrum of the leak in Soundprint Analyst to the client provides just that sort of confidence.

Secondly, simulated leaks are invaluable information to Pure as the Oilball development process continues to unfold. It gives us concrete data regarding leak detection thresholds, how pressure affects the leak indicator value, and how the methodology of the leak simulation affects the quality of the leak signature in the Smartball data.

Proper simulation of a leak is essentially in getting relevant data to predict leak rate detection thresholds on pipelines. The acoustic signature of any leak is generated at the point of pressure drop. Therefore, the closer that pressure drop is to the pipeline proper, the closer it is to the Smartball's hydrophone. In addition it would more closely approximate a real leak condition where the pressure drop occurs immediately outside the pipe.



Ideal Location for Simulated Leak

In addition to ensuring the pressure drop associated with a simulated leak is as close to the pipeline as possible, it is also necessary to be able to accurately measure the leak rate of any simulation. This leak rate value will be correlated to the sound pressure level recorded by the Smartball at this exact point in the inspection. These data points will be used to generate the leak rate calibration curve which is used to estimate lower leak detection thresholds as well as approximate leak rates of any real leaks discovered during the inspection.

A two valve assembly works best for leak simulation. The bottom valve closest to the pipeline should be a quick and easy valve to open/close. A 90° ball valve works best in this case. The top valve will be used to control the leak rate of the simulation and should be easy to calibrate. Needle valves tend to work best. Finally a hose sized large enough so that it does not provide any back pressure on the escaping product should be used to contain the flow and direct into some sort of containment vessel.



Things to avoid when simulating a leak:

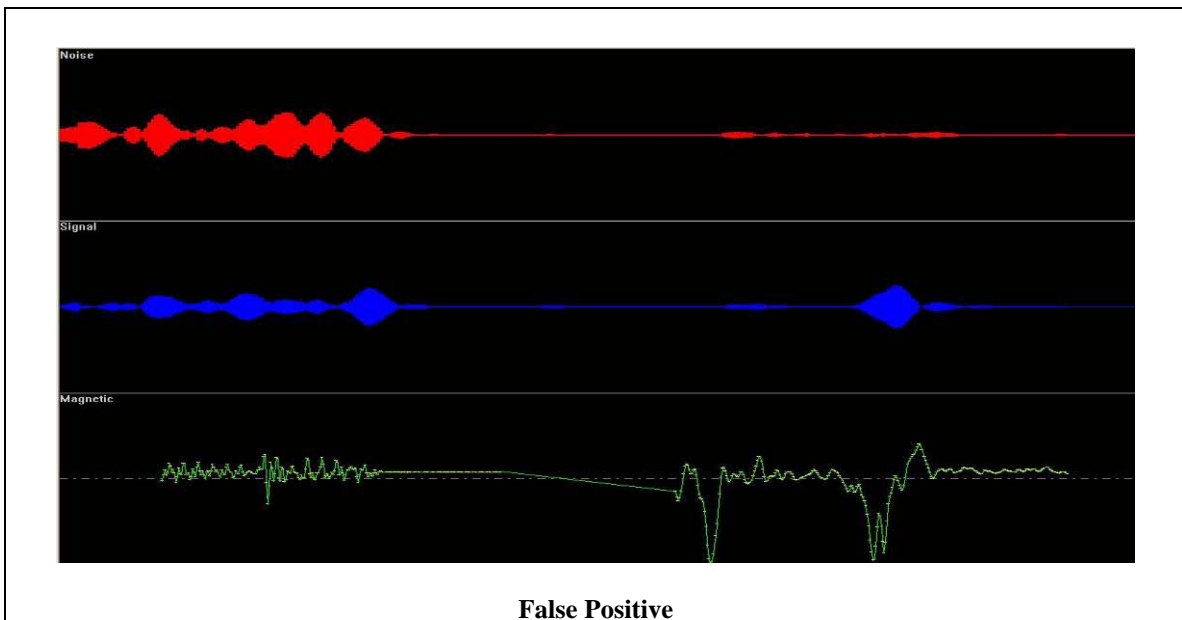
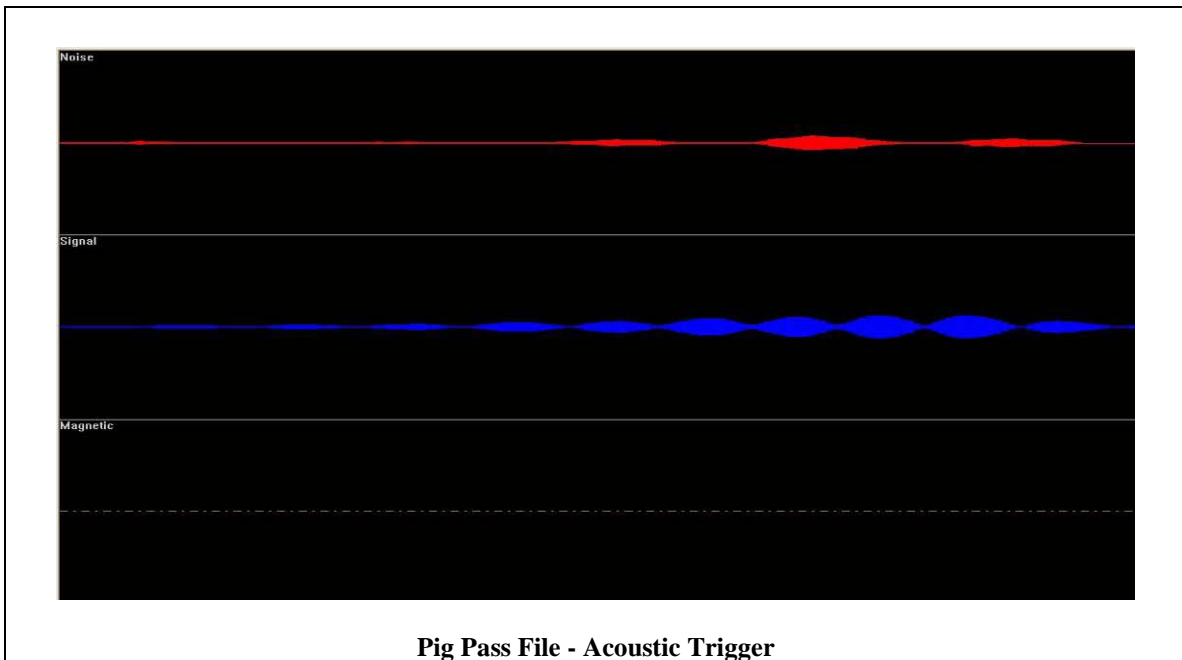
- Using large lengths of hose to direct the flow.
 - Using small diameter hose that restricts flow.
 - Simulating a leak off a pipeline riser pipe that is either long, or has bends in the piping.
-

APPENDIX C:
Marker Box Analysis

Appendix C: Marker Box Analysis

Using the software provided by CDI, the maker of the above ground markers used with Smartball, one can visually see the signals recorded by the marker when it detects a pig pass. Depending on the environment, in some cases you may encounter many false pass files being recorded by the marker due to excessive ambient noise or magnetism and not due to actual pig passage.

In such cases it is essential to be able to differentiate between actual pig pass files and false positive events. Typical pig pass signals as well as false positive signals are shown in the figures below.



APPENDIX B – SmartBall Dimensions







SmartBall Specifications										
Smartball Type	Core Diameter (in)	Outer Diameter (in)	Pressure Transducer	Temperature Sensor	Tri-Axial Accelerometer	Tri-Axial Magnetometer	Urethane Coating	Foam Overshell	Pipeline Size	Picture
4" Oilball	2.65	3.15	N	Y	Y	Y	Y	N	4"	
6" Oilball	4.8	5.3	Y	Y	Y	Y	Y	N	6"	
10" Oilball	7.75	8.75	Y	Y	Y	Y	Y	N	10" and greater	
4" Gasball	2.65	3.15	N	Y	Y	Y	N	Y	4"	
10" Gasball	7.75	8.75 and larger (depend. on foam overshell)	Y	Y	Y	Y	N	Y	10" and greater	
Foam Overshell	Sized to Suit		---	---	---	---	---	---	6" and greater	

Figure A - SmartBall Dimensions for Oil and Natural Gas Applications