# Advances in In-line Inspection Technology for Pipeline Integrity

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**V Annual International Pipeline Congress**

Oct 18-20th 2000
Morelia, Mexico

## Abstract

In Magnetic Flux Leakage (MFL) inspection technology, corrosion anomalies are detected and identified via their leakage field due to changes in wall thickness. With the increasing demand for higher accuracy and reliability in metal loss corrosion sizing, we present some of the distinctive advances made in the MFL pipeline in-line inspection industry. Designed and built with state of the art technology, a novel family of high-resolution MFL pipeline inspection tools is the first to successfully incorporate these advances into proven operational tools. We explain the technological advances of inertial mapping, circumferential sensor measurements, neural networks for metal loss sizing, and gas-bypass speed control. Experiences from recent projects is discussed including quality assurance practices within a pipeline integrity program.

## Introduction

Today pipeline operators have many options when choosing an internal inspection technology to investigate the structural integrity of a pipeline. Two ILI techniques are available for wall thickness measurement, namely magnetic flux leakage (MFL) and ultrasonic (UT). UT pigs require introduction of a liquid into the pipeline to couple the sensor signal to the pipe wall, require a very "clean" pipeline and product and are generally excluded from inspecting gas pipelines. The MFL method involves inducing a magnetic field into the pipe wall and sensing leakage of the field inside the pipe as the wall thickness changes. The magnetic flux leakage technique is the most commonly used technique to inspect large diameter gas transmission lines [1,2].

For gas transmission pipelines, the fact that the medium in which the inspection pig must travel is compressible presents added challenges in maintaining velocity control in order to collect good quality data. Additionally the product flow rate of a gas transmission pipeline must typically be reduced during an inspection run. For transmission lines operating at or near capacity the economic impact of reduced throughput can be greater than the cost of the inspection survey itself. Incorporating gas by pass and on-line speed control into an MFL pig improves data quality and reduces throughput reduction costs.

The term "high resolution" has become somewhat confused with "high accuracy". The two may imply the same thing but in fact are different. The term high resolution implies increasing the number of sensors and/or by increasing the sampling rate. Such changes involve acquiring more data. It says nothing about the quality or accuracy of the data collected. Accuracy includes the amount of uncertainty in a measurement and therefore reflects a system characteristic since it is determined by factors beyond acquisition resolution [3].

The goal of incorporating advances in technology into a new inspection pig should be to provide better more reliable information not just more information. Improvements in the miniaturisation and speed of electronic and computer components have facilitated the incorporation of many more sensors into the latest inspection tools.

The following technological advances have been incorporated into the design and operation of the advanced inspection tool shown in Figure 1. These advances have led to significant improvements in quality and accuracy of data and reliability of tool performance.

- New design, modelling and conceptualisation tools
- 3 Component magnetic flux vector sensor head with integrated Eddy Current ID/OD discriminator.
- Digital signal processing horsepower.
- Neural Network data analysis
- Gas Bypass with speed control
- Strapdown inertial navigation system (INS)
- Modern software and information technology systems

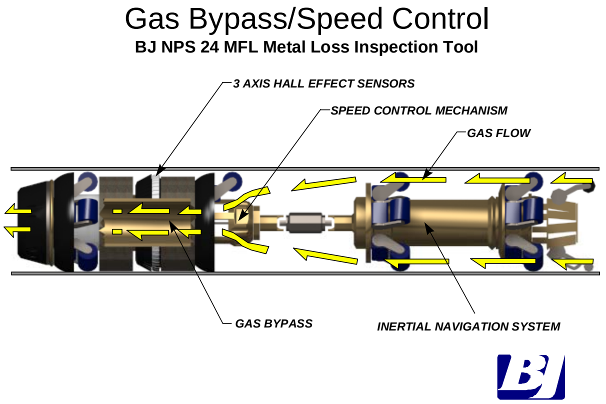


Figure 1. The Vectra MFL In-line Inspection Tool

## The Basics

Magnets produce magnetic fields that exert a force of attraction on ferromagnetic materials. Lines of flux can represent the strength and direction of the magnetic field. Magnetic flux tends to travel through steel rather than air or gas since it is a ferromagnetic material. Magnetic saturation occurs when the amount of flux through an area starts to limit itself or saturate Once the steel becomes saturated some of the flux actually starts to significantly leak out of the material. The magnetisation system is the foundation upon which magnetic flux leakage measurement is built. Accurate determination and interpretation of the length, width and depth of the defects relies upon a field that is not only strong but uniform and consistent.

For pipeline inspection tools, a magnetic circuit is constructed with magnets, pliable steel brushes to couple the magnetic flux into pipe wall and a "backing bar". This magnetic assembly is represented in Figure 2. Flux leakage is measured by placing sensors adjacent to the pipe wall within the magnetic circuit. These magnetic assemblies are repeated completely around an inspection vehicle to provide full circumferential coverage. Stronger magnets can help minimise the effects of changes in wall thicknesses, stress and velocity since they produce strong leakage fields [4]. The Eddy Current sensor was incorporated into the sensor head design of the tool in order to interpret and correlate its ID/OD signals with the magnetic measurements. Elimination of a secondary sensor ring also affords a more robust mechanical tool design.

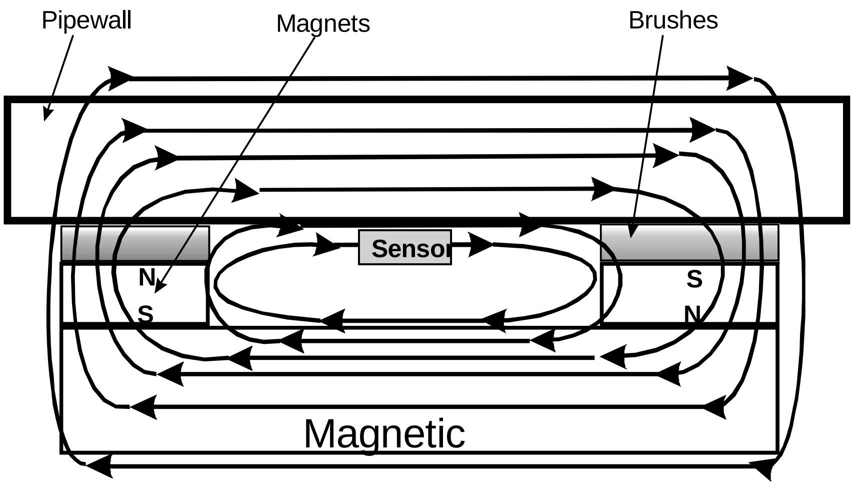


Figure 2. MFL Pipeline Inspection Magnetic Circuit

Advances in electronics, software, digital signal processing (DSP) and data storage technologies allow massive amounts of data to be collected and stored within a self contained pipeline inspection vehicle. As these technological advances improve metal loss detection and sizing accuracy, other inspection variables that could affect sizing accuracy should also be examined in order to make appreciable improvements [4].

## Circumferential Sensors

The magnetic field (H) and the flux density (B) indicated above exist as vector quantities (Figure 4). In order to precisely measure the flux leakage, not only the magnitude of leakage must be measured but the direction of leakage must be considered as well.

Hall Effect sensors collect flux data in each of the axial, radial and circumferential directions allowing for measurement of the absolute flux leakage field vector. BJ was the first to utilise the circumferential sensor technology and is the only inspection vendor using it in field operations.

Incorporating the circumferential sensor provides much needed information for improving defect length and width accuracy. More accurate length and width measurements improve defect depth estimation. Since MFL tools use an axially oriented magnetic field it is extremely difficult to detect axially oriented pipe wall defects such as long narrow axial corrosion (LNAC or NAEC) and cracks using just the axial and radial sensors. The circumferential sensor provides data

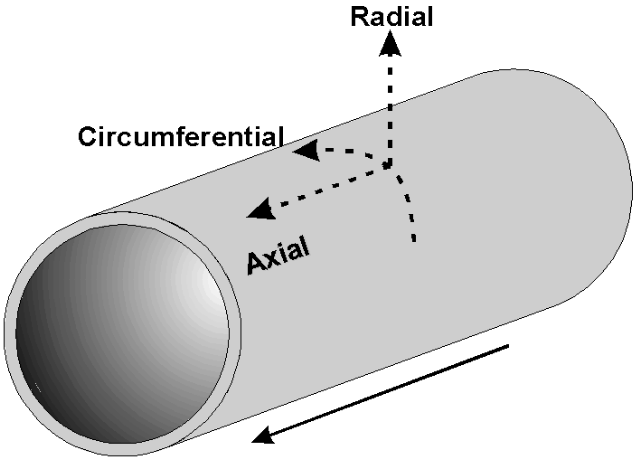
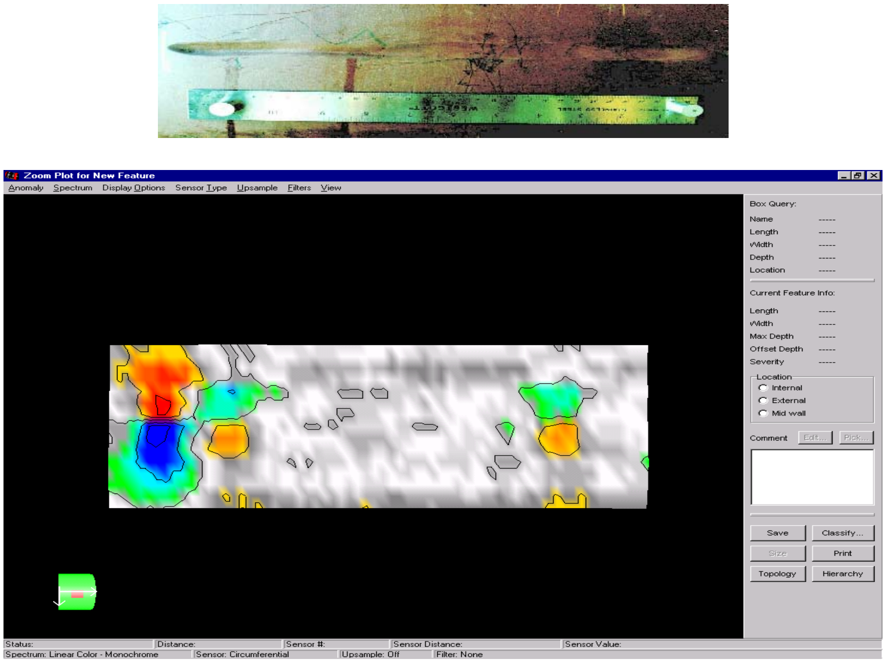


Figure 3. Magnetic Flux Components as referenced for a pipeline.



Box Query:
Name -----
Length -----
Width -----
Depth -----
Location -----

Current Feature Info:
Length -----
Width -----
Max Depth -----
Offset Depth -----
Severity -----

Location
○ Internal
○ External
○ Mid wall

Comment

Status: Distance: Sensor #: Sensor Distance: Sensor Value:

Spectrum: Linear Color - Monochrome Sensor: Circumferential Upsample: Off Filter: None

Figure 4 Use of the circumferential sensor to distinguish a long, narrow corrosion defect that greatly enhances the probability of detecting such defects. [5] Because of the critical length dependence in most defect assessment criteria (eg. B31G,NG-18,RSTRENG [9,10]), obtaining correct length and depth values is crucial.

### Data Analysis and Interpretation

Once defect signals have been collected they must finally be interpreted. It is at this analysis and interpretation stage where the most significant difficulties can arise. Resolution of the data collected is a factor in the final analysis but as stated previously high resolution should be considered in terms of better accuracy. And with the detailed information that a high-resolution tool provides, more detailed severity criteria can be used with greater confidence. Of course more sophisticated analysis and interpretation techniques must be used to process and manage the large amounts of data as well. A combination of many analysis methods is the most reliable and accurate choice of in which artificial intelligence is taking a significant role [6].

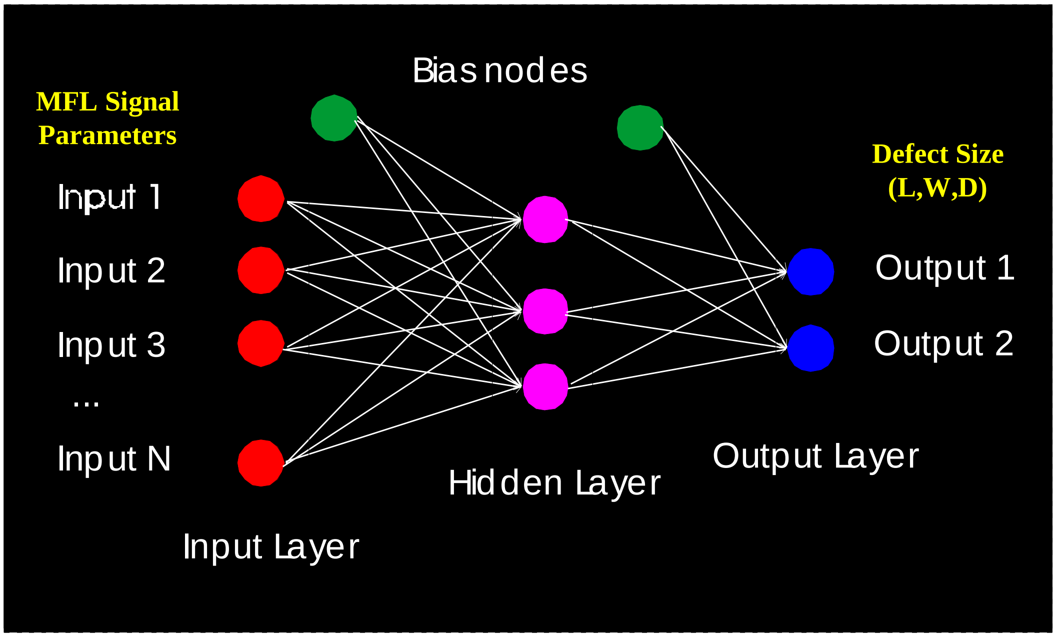


Figure 7. Schematic layout of a Neural Network

The most widespread use of artificial intelligence is neural network computational techniques. Neural networks attempt to mimic the human brain’s past experience decision making process. The interaction of nodes in a neural network is analogous to the interactions of neurons in the brain as shown in Figure 7. These neural networks can be useful in pattern qualification and quantification where there are too many variables for effective traditional analysis or if the pattern is vague and not clearly defined [7].

The accuracy of defect sizing obtained allow for confident calculations of failure pressures. Hence prioritisation of defects can be done based on their predicted threat to the integrity of the pipeline. Having accurate data leads to fewer digs and repairs and higher overall confidence in the integrity plan. However, field verification and assessment of any defect should be performed for any engineering or repair decision. Traditionally, the verification of defect assessment has become the determining task of the success of any project. It promotes that the quality and reliability of the inspection information and company. Results from verification digs from a recent gas pipeline inspection project in South America are shown in Figure 6.

Other recent results have been published from an extensive evaluation of a recent oil pipeline inspection where the Vectra depth sizing accuracy was found to be reliably better than 6% WT. [8] But to do a true comparison, defects should be assessed and considered for more than just peak depth. To do more advanced integrity and pressure based assessments like RSTRENG [9,10], detailed depth profile information along the entire length of the defect or group of defects in question should be compared (as illustrated in Figure 7). From such comparisons, the operator can then assess the accuracy of predicted failure pressures from the inspection as well [8]

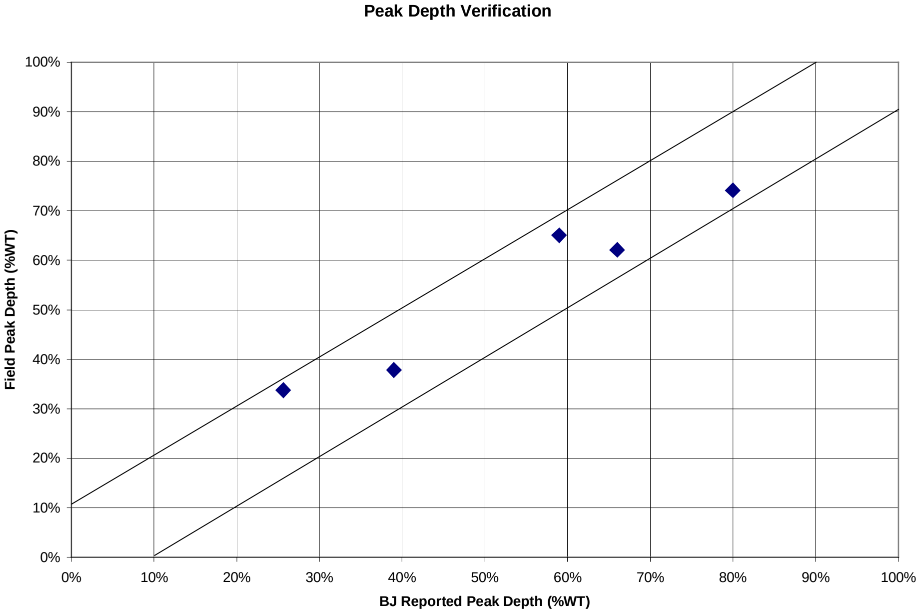
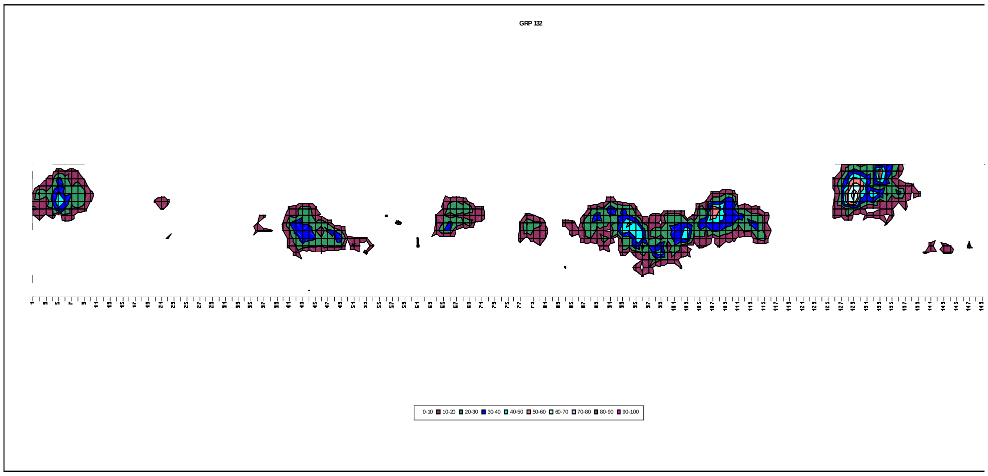


Figure 6. Field comparison/verification for peak depth prediction accuracy of clustered defects from a recent gas pipeline inspection . There are over 100 individual defects represented here so more than just depth accuracy can be assessed.

Status:
Distance = 776.218 m
Sensor # = 74
Sensor Value = -31.31 G

Spectrum: Linear Color - Monochrome
Sensor: Topology
Upsample: Off
Filter: None

Figure 7 . (a) Vectra prediction of defect layout and depth



(b) Field measurement results of defect layout and depth

## Gas Bypass & Speed Control

Velocity variations associated with pigging in gas pipelines affect the flux leakage signal because it is distorted under high speed conditions resulting in unusable MFL data and incomplete coverage of the pipeline. The Vectra magnetic flux leakage inspection tool incorporates a dynamic gas bypass and speed control system into its design. [19] (Figure 1). Gas bypass decouples the pig speed from the pipeline gas flow. The velocity of the pig is then controlled by a valve or throttle control mechanism. A hole through the centre of the tool's cupped front magnetiser module forces the gas flow away from the sensor heads and arms, resulting in better quality of data collected. The velocity plots from a recent 30" gas line inspection is shown in Figure 8, where the tool maintained itself well within its operating speed range while the line speed at 8.3 m/s did not need to be altered to accommodate the ILI tool. By maintaining a more constant speed during an inspection the flux leakage field has less variability which in turn improves defect characterisation.

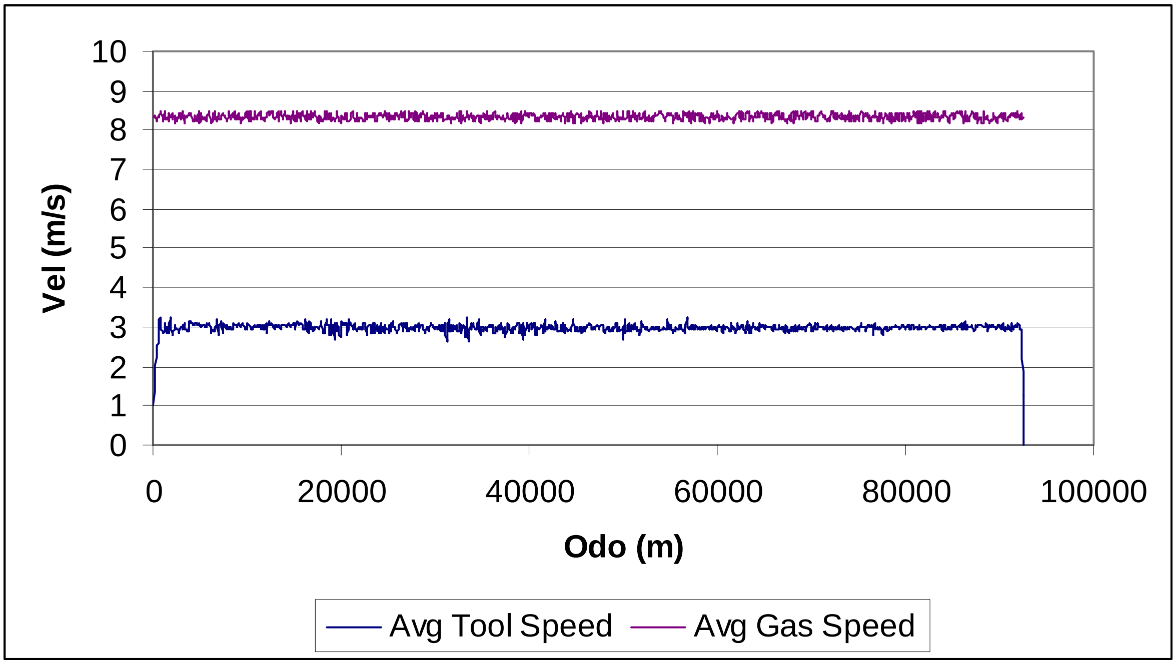


Figure 8. Velocity plot from recent 30" inspection.
The tool speed was 3 m/s and well under the average gas speed of 8.3 m/s

Another design consideration in speed control is that of incorporation of a backup fail safe or override mechanism should the throttle control fail open thereby preventing the tool from moving in the pipeline. The BJ gas bypass/speed control pig incorporates an autonomous bypass override system (B.O.S.). This system consists of a flapper valve operating via independent power source and control electronics. The valve actuates in a positive close manner and is time based. Today's new gas transmission pipelines are operating at higher and higher pressures while demands are also being placed on existing lines to maintain maximum allowable operating pressure (MAOP). During an MFL inspection the gas throughput of the line typically must be reduced substantially with conventional ILI tools in order to accommodate data acquisition speeds (1 - 4 m/s). If a transmission line is operating at maximum throughput there is an additional cost of "loss revenue" from the "lost product" associated with the reduced throughput during inspection.

As the demand for gas grows, more and more large gas transmission pipelines may be required to operate at capacity year round. Inspecting such pipelines may only be economically feasible with gas bypass capable inspection pigs. Another example is that of a NPS 36 pipeline at 1000 psi and running at 9.5 m/s. Using the bypass technology, the inspection tool ran at 3 m/s while allowing the full gas throughput at 9.5 m/s. The difference in gas delivered over that time compared to reducing the gas speed to 3 m/s and running a conventional tool was 28 million cubic meters which was worth $1,000,000 in revenue to the pipeline company [12] That product delivery revenue significantly overshadowed the cost of running the inspection tool, making it a "profitable" inspection project over a conventional tool inspection.

## Defect Location Using Inertial Navigation and GPS

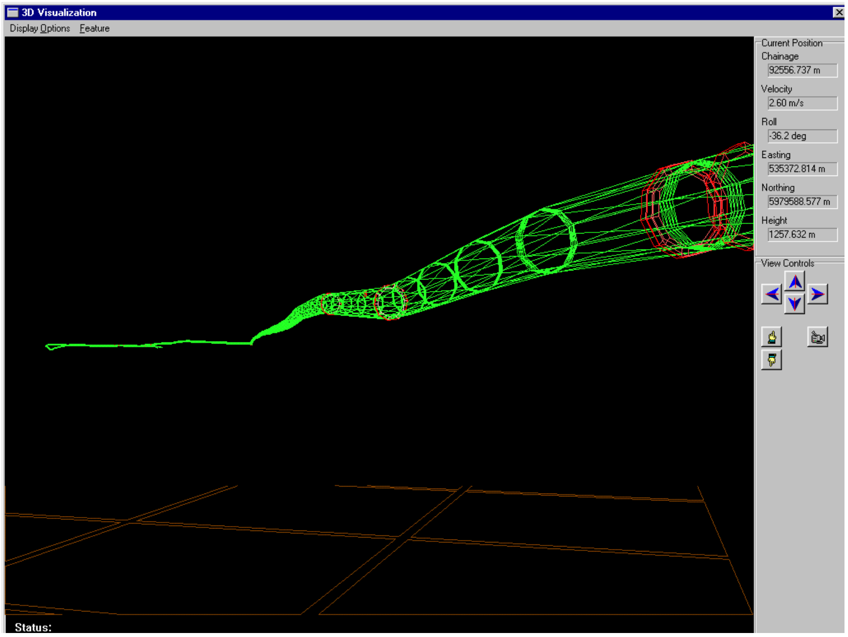
Once a severe or critical defect has been characterised it must be located in the field. The BJ MFL tool incorporates a strapdown inertial navigation system (INS) to determine position and attitude of the pig along its trajectory within the pipe. Three axis gyros and accelerometers combined with odometer information are used to determine three-dimensional changes in the pig's position on earth as it travels through the pipeline. Such a system has been well proven via the Geopig$^{TM}$ [13-17].

Actual geographic co-ordinates are calculated by establishing Global Positioning System (GPS) control points along the pipeline and then "tying" the inertial data to these points. By transforming the pig's trajectory into the tie points, accurate "real world" GPS co-ordinates are obtained for any point along the pipe [18].

From knowing all points along the pipeline, we can generate a "virtual pipeline", created from the processed inertial data directly. All pipeline features are given a co-ordinate and ancillary information such as bends and the welds in the pipeline are all identified and provided which aids in location in the field (Figure 9).

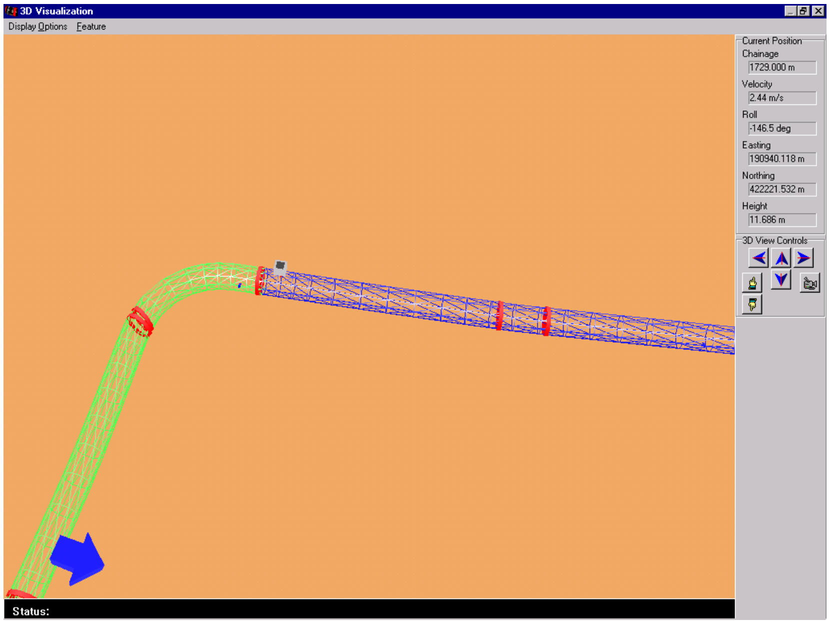
The sensitivity of the inertial devices provides information regarding dents and other physical anomalies that affect the tool's motion the pipeline. Inertial deflection information can then be used to correlate the location of dents with specific metal loss regions that are often the result of third party damage.

Since the final processed inertial data (plan and profile) is in geographic co-ordinate form all the data collected by the MFL tool can be readily be presented and incorporated into a Geographic Information System (GIS) or an automated mapping/facilities management (AM/FM) system.



Chainage: 92556.737 m
Velocity: 2.60 m/s
Roll: -36.2 deg
Easting: 535372.814 m
Northing: 5979588.577 m
Height: 1257.632 m

Figure 9. (a) The "Virtual Pipeline" generated from inertial data



Chainage: 1729.000 m
Velocity: 2.44 m/s
Roll: -146.5 deg
Easting: 190940.118 m
Northing: 422221.532 m
Height: 11.686 m

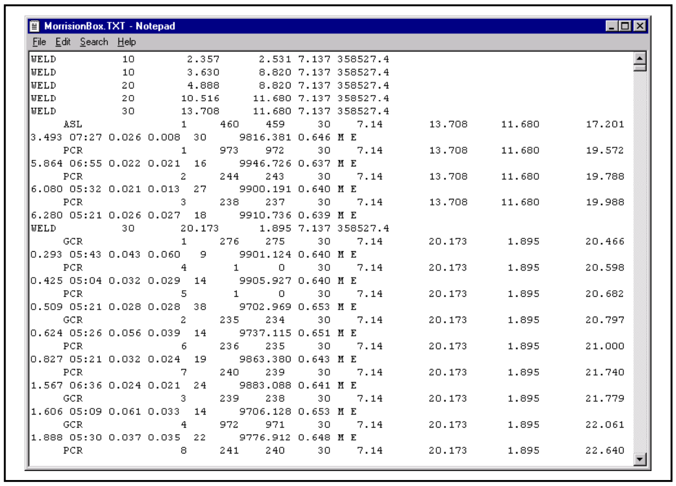
(b) "Virtual Pipeline" showing a 3D bend, a marker box location (grey box just before the bend) and a heavy wall section (purple). The blue arrow indicates North.

## Data Presentation

In today's digital world it's impractical to attempt to manage a pipeline integrity program without some formal information technology especially with the amounts of data that ILI tools can provide. This can be as simple as a desktop spreadsheet/database to a company wide integrated GIS system.

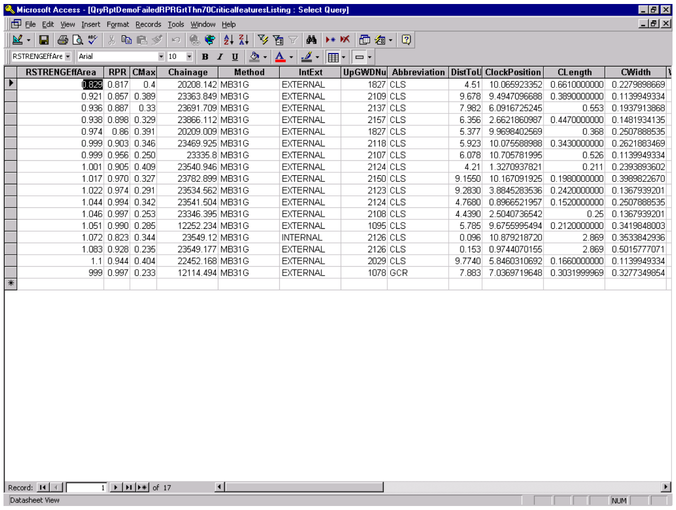
In either case, one of the time-consuming and critical issues is getting the new data into the system. Although provided with each inspection, paper copies of the report are usually only good as a reference. The useful data comes in a digital "softcopy" form such as in a spreadsheet or even a pre-determined formatted file agreed to by the pipeline company and the inspection company. Figure 10 demonstrates some options from recent examples of preferred reporting formats for pipeline operators. With the flexibility of commercially available databases, data can be reported in many different ways. The biggest benefit comes from the flexibility to sort and filter information on demand according to different criteria, eg.

all defects > 20%WT between 100 and 2000 meters (odometer) in order of decreasing predicted failure pressure. Hence prioritisation of the worst defects has already been done. Understanding the way that a pipeline company prefers the data format has resulted in less time taken in manipulating and reformatting data for input into an integrity database and less confusion and potential mistakes from what data means. This allows more time to be spent reviewing and prioritising for upcoming maintenance planning and scheduling.



```
WELD          10        2.357      2.531 7.137 358527.4
WELD          10        3.630      8.820 7.137 358527.4
WELD          20        4.888      8.820 7.137 358527.4
WELD          20       10.516     11.680 7.137 358527.4
WELD          30       13.708     11.680 7.137 358527.4
     ASL               1     460    459     30    7.14        13.708     11.680       17.201
3.493 07:27 0.026 0.008  30     9816.381 0.646 M E
     PCR               1     973    972     30    7.14        13.708     11.680       19.572
5.864 06:55 0.022 0.021  16     9946.726 0.637 M E
     PCR               2     244    243     30    7.14        13.708     11.680       19.788
6.080 05:32 0.021 0.013  27     9900.191 0.640 M E
     PCR               3     238    237     30    7.14        13.708     11.680       19.988
6.280 05:21 0.026 0.027  18     9910.736 0.639 M E
WELD          30       20.173      1.895 7.137 358527.4
     GCR               1     276    275     30    7.14        20.173      1.895       20.466
0.293 05:43 0.043 0.060   9     9901.124 0.640 M E
     PCR               4       1      0     30    7.14        20.173      1.895       20.598
0.425 05:04 0.032 0.029  14     9905.927 0.640 M E
     PCR               5       1      0     30    7.14        20.173      1.895       20.682
0.509 05:21 0.028 0.028  38     9702.969 0.653 M E
     GCR               2     235    234     30    7.14        20.173      1.895       20.797
0.624 05:26 0.056 0.039  14     9737.115 0.651 M E
     PCR               6     236    235     30    7.14        20.173      1.895       21.000
0.827 05:21 0.032 0.024  19     9863.380 0.643 M E
     PCR               7     240    239     30    7.14        20.173      1.895       21.740
1.567 06:36 0.024 0.021  24     9883.088 0.641 M E
     GCR               3     239    238     30    7.14        20.173      1.895       21.779
1.606 05:09 0.061 0.033  14     9706.128 0.653 M E
     GCR               4     972    971     30    7.14        20.173      1.895       22.061
1.888 05:30 0.037 0.035  22     9776.912 0.648 M E
     PCR               8     241    240     30    7.14        20.173      1.895       22.640
```

Figure 10. (a) Example of formatted file for input to pipeline operator's integrity database. [19]



| RSTRENGEffArea | RPR | CMax | Chainage | Method | IntExt | UpGWDNu | Abbreviation | DistToU | ClockPosition | CLength | CWidth |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.829 | 0.817 | 0.4 | 20208.142 | MB31G | EXTERNAL | 1827 | CLS | 4.51 | 10.065923352 | 0.6610000000 | 0.2279898669 |
| 0.921 | 0.857 | 0.389 | 23363.849 | MB31G | EXTERNAL | 2109 | CLS | 9.678 | 9.4947096688 | 0.3890000000 | 0.1139949334 |
| 0.936 | 0.887 | 0.33 | 23691.709 | MB31G | EXTERNAL | 2137 | CLS | 7.982 | 6.0916725245 | 0.553 | 0.1937913868 |
| 0.938 | 0.898 | 0.329 | 23866.112 | MB31G | EXTERNAL | 2157 | CLS | 6.356 | 2.6621860987 | 0.4470000000 | 0.1481934135 |
| 0.974 | 0.86 | 0.391 | 20209.009 | MB31G | EXTERNAL | 1827 | CLS | 5.377 | 9.9698402569 | 0.368 | 0.2507888535 |
| 0.999 | 0.903 | 0.346 | 23469.925 | MB31G | EXTERNAL | 2118 | CLS | 5.923 | 10.075588988 | 0.3430000000 | 0.2621883469 |
| 0.999 | 0.956 | 0.250 | 23335.8 | MB31G | EXTERNAL | 2107 | CLS | 6.078 | 10.705781995 | 0.526 | 0.1139949334 |
| 1.001 | 0.905 | 0.409 | 23540.946 | MB31G | EXTERNAL | 2124 | CLS | 4.21 | 1.3270937821 | 0.211 | 0.2393893602 |
| 1.017 | 0.970 | 0.327 | 23782.899 | MB31G | EXTERNAL | 2150 | CLS | 9.1550 | 10.167091925 | 0.1980000000 | 0.3989822670 |
| 1.022 | 0.974 | 0.291 | 23534.562 | MB31G | EXTERNAL | 2123 | CLS | 9.2830 | 3.8845283536 | 0.2420000000 | 0.1367939201 |
| 1.044 | 0.994 | 0.342 | 23541.504 | MB31G | EXTERNAL | 2124 | CLS | 4.7680 | 0.8966521957 | 0.1520000000 | 0.2507888535 |
| 1.046 | 0.997 | 0.253 | 23346.395 | MB31G | EXTERNAL | 2108 | CLS | 4.4390 | 2.5040736542 | 0.25 | 0.1367939201 |
| 1.051 | 0.990 | 0.285 | 12252.234 | MB31G | EXTERNAL | 1095 | CLS | 5.785 | 9.6755995494 | 0.2120000000 | 0.3419848003 |
| 1.072 | 0.823 | 0.344 | 23549.12 | MB31G | INTERNAL | 2126 | CLS | 0.096 | 10.879218720 | 2.869 | 0.3533842936 |
| 1.083 | 0.928 | 0.235 | 23549.177 | MB31G | EXTERNAL | 2126 | CLS | 0.153 | 0.9744070155 | 2.869 | 0.5015777071 |
| 1.1 | 0.944 | 0.404 | 22452.168 | MB31G | EXTERNAL | 2029 | CLS | 9.7740 | 5.8460310692 | 0.1660000000 | 0.1139949334 |
| 999 | 0.997 | 0.233 | 12114.494 | MB31G | EXTERNAL | 1078 | GCR | 7.883 | 7.0369719648 | 0.3031999969 | 0.3277349854 |

(b) Example of prioritisation report based on predicted failure pressure and depth.

## Conclusions

The goal of the inspection vendor should be to provide as accurate information as possible regarding the metal loss condition of a pipeline so that the pipeline operator can make the best decisions with respect to integrity assessment. The accuracy of magnetic flux leakage as a technique to detect and size metal loss defects in gas pipelines will continue to improve as the latest technological advancements are incorporated into both the ILI tools and the interpretation of the data collected. Ongoing improvements in electronics, computing power, software and data analysis techniques should readily facilitate this.

Gas transmission pipelines previously not inspected due to reduced gas throughput considerations now have the option of running gas bypass MFL inspection pigs. Many pipeline operators can now benefit from flexibility in scheduling of ILI runs while greatly reducing or eliminating gas throughput costs. Onboard pig speed control will also provide more reliable MFL data and reduce the chances of reruns caused by speed excursions.

MFL data provided with inertial navigation data will allow ease of incorporation into a pipeline GIS. The MFL data can then be accurately cross referenced to other pipeline information at that location, thereby, providing more complete pipeline integrity information. Information technology has advanced and can be readily utilised for easier pipeline data reporting and management.

Other novel solutions to ongoing gas transmission inspection and integrity problems should be sought via the application of the latest technologies as they emerge.

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