Integrity Management of Difficult to "Smart-Pig" Pipelines Using Minimally Intrusive Sensors

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Abstract

While many upstream pipelines and flowlines are piggable, their operating characteristics may render them not smart piggable because they cannot be practically cleaned or configured to enable successful conventional high resolution in-line inspections. Minimally intrusive sensor platforms known as Multi Sensor Inspection Ball (MSIB) are now available to pipeline operators that manage in-line navigation risks while recording full length data used to understand the condition of the pipe wall equivalent to a hydrostatic integrity assessment. This paper presents the results from a pilot deployment of a multi sensor device comprised of large standoff passive magnetometer sensors coupled with acoustic, pressure and temperature sensing capability all integrated into the form factor of a minimally intrusive maintenance pig. An understanding of fundamental magnetic theory is applied to the sensor data to characterize the interaction of a ferro magnetic body, i.e., steel line pipe, within a native magnetic field to conclude relative changes in the mass or changes in pipe wall thickness along the full length of the pipeline. Comparison of fundamental magnetic quantities, measured by the sensors with physical pipe wall truth data illustrates the basis for models developed to conclude pipe wall condition and integrity management actions consistent with equivalent understanding derived from a hydrostatic integrity assessment and effective loss of containment risk management using cloud-based software applications.

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Background

Since their inception, pipeline Integrity Management Programs have steadily expanded their scope from liquid and gas transmission pipelines to include downstream distribution and upstream gathering pipelines. Integrity assessment methods are an important element of any Integrity Management Programs. The Industry Codes and Standards as well as jurisdictional regulations that govern Integrity Management, prescribe in-line inspection, hydrostatic proof test or "Other technology" as integrity assessment methods. Upstream pipeline operating characteristics can present increased difficulties for successful, intrusive, in-line inspection compared with transmission or distribution pipelines. Examples of such difficulties can include the presence of internal deposits such as wax, sand or scale that adversely affects non-destructive examination sensor performance and impede flow conveyed navigation. Some upstream pipelines cannot be rendered "smart-piggable" for in-service inspection due to design and operating conditions. Those pipelines can benefit from internal in-line inspection technologies that are less intrusive than conventional ILI tools with sensors that are more tolerant to internal bore deposits. In-line flow conveyed sensor platforms are, by their nature, intrusive. Recent innovations by technology providers integrate multiple non-destructive sensors with less intrusive flow conveyed platforms and have been deployed by Chevron in operating pipelines to evaluate and qualify navigation and pipe condition measurement capability with one such pilot described in this paper.

Compared with conventional in-line inspection (ILI) tools, pipeline maintenance and cleaning pigs generally have form factors that are less intrusive and have lower navigation risks. Deployment of NDE sensors integrated with cleaning pig form factors offer the potential for managing the integrity of pipelines that are not practically "smart-piggable" and maintenance pigs are generally deployed more frequently than ILI. Technology providers have developed ILI tools that reflect the materials of construction and form factors like maintenance and cleaning pigs and incorporate NDE sensors that trade off inspection resolution to achieve objectives such as pipe-to-wall standoff and pipeline flowing speed ranges and leverage more frequent opportunities to obtain supplemental condition data associated with maintenance pigging schedules. The value in obtaining more frequent integrity related data to enhance pipeline safety has been recognized in a recent United States Pipeline and Hazardous Materials Safety Administration (PHMSA) Research and Development Program, established with the goal of adapting video sensors to maintenance pigs that can supplement conventional inspection and monitoring data to improve decision making and enhance pipeline safety.[1]

Technology development by Industry has also continued to pursue less intrusive, or "minimally intrusive" sensor platforms that do not necessarily contact with the pipe wall or can be easily attached to existing maintenance pigs. Free swimming or buoyant sensor balls are examples of such minimally intrusive sensor platforms. Micro-electromechanical systems (MEMS) are a class of semiconductor devices that can fit inside the minimally intrusive platforms that can measure multiple pipeline environment characteristics such as: elapsed time, pressure, temperature, platform movement and

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magnetic field density giving rise to a class of inspection technologies known as Multi-Sensor Inspection Balls (MSIB).

Figure 1 shows the condition of cleaning pigs received after multiple operational intervals and illustrates a case where successful inspection by conventional smart pig is difficult. We conducted a pilot deployment of a MSIB technology in a similar service pipeline where reliable pipe wall condition truth data from prior conventional ILI was available after extensive cleaning and offer the sensor data obtained and possible insights into pipeline integrity gained from that deployment.

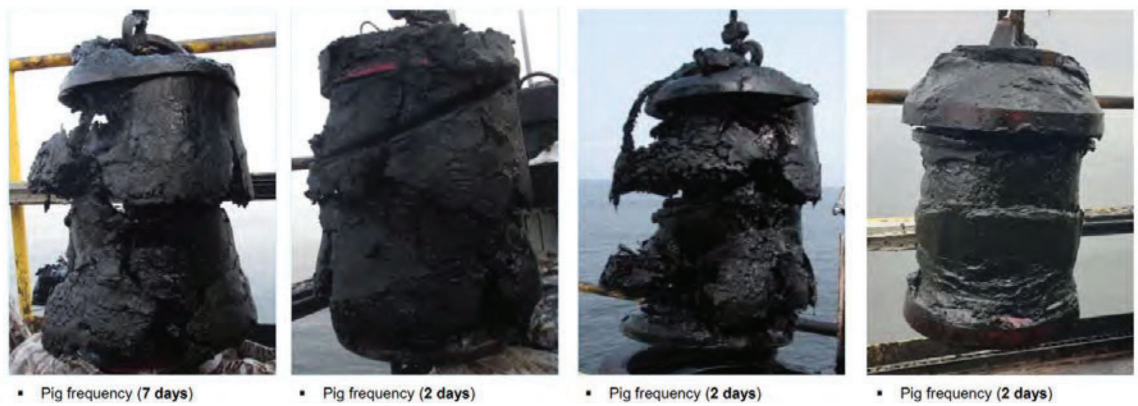

Figure 1: Example of cleaning pigs after deployment in a Chevron upstream pipeline that is difficult to inspect because it is difficult to clean during operation.

Pilot Opportunity for a Minimally Intrusive In-Line Sensor Platform

Free floating MSIB's are commercially available as sphere or slug shapes with diameters that range from 1.5 inch to 3-inch diameter and represent the least intrusive form factor for an internal inspection platform.[2,3,4] Pipelines that operate in gas or multi-phase service make it difficult to deploy free floating sensor platforms. The integration of sensors with a maintenance pig form factor is more intrusive than a free-floating sensor but is significantly less intrusive compared with conventional ILI smart-pigs.

A pilot deployment was conducted of the MSIB technology in a subsea pipeline in gathering service. The physical attributes of the pipeline are listed in Table 1. The MSIB sensors used in the pilot deployments are typically attached to the rear of pipeline maintenance cleaning pigs using a fixture supplied by the technology provider as shown in Figure 2.

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Table 1. Pipeline Attributes

Outside Diameter	16	inch	406	mm
Nominal Wall Thickness	0.5	inch	18	mm
Operating Pressure	140	psi	9.7	bar
Overall Length	6767	feet	2063	meter
Operating Temperature	122	feet	50	C

The pipeline was previously cleaned multiple times and successfully inspected by an ILI smart pig. While this pipeline is not as difficult to clean as the example shown in Figure 1, it is a relatively simple pipeline in terms of having no bore changes, no changes in direction and it has reliable truth data for the condition of the pipe wall. This pipeline provided a good opportunity to evaluate both sensor platform navigation and understand what the sensors can tell us to justify future deployment in difficult to inspect pipelines.

Figure 2: Maintenance pig integrated with a Multi Sensor Inspection Ball (Chevron South Africa Strategic Business Unit)

The integration of a MSIB sensor at the rear of a maintenance pig has proven to not adversely affect piggability compared with attaching sensors to the central mandrel of a pig. While the pilot pipeline was equipped with a typical pig launcher and receiver it should be noted that if the MSIB is inserted inside the central mandrel of a maintenance pig the overall pig length can be short and compatible with three-way pigging valves. The piggability form factor of maintenance pigs compatible with pig

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valves offers a path for deployment into pipelines that are not piggable due to lack of conventional launchers and receivers.

The pipeline was previously cleaned multiple times and successfully inspected by an ILI smart pig offering the opportunity to compare sensor measurements from a MSIB sensor.

Sensors- What Can They Tell Us?

As mentioned earlier, the MSIB sensors can record pressure, temperature, platform movement and magnetic field density all integrated with an internal elapsed timer. Time based sensor measurements are correlated to linear reference distance based on measured flow rate at the time of the tool run and calibrated by the passage of the tools registered by the response of the magnetic flux density sensors to the positions of known in-line features such as valves and flanges. The pressure sensor response also can be used to align the time-based data to distance.

After successful deployment of the cleaning pig integrated MSIB, in the 16-inch pipeline, the sensor was returned to the MSIB provider where the recorded raw data was downloaded and converted to distance-based sensor values (events) related to the environment surrounding the MSIB for use in post run assessment summarized in Table 2.

Table 2. Multiple sensors deployed in the MSIB platform.

Sensor	Primary Application	Secondary Application
Acoustic (sound amplitude and frequency)	Leak Detection	Third Party Damage
Pipe pressure	Bore Restrictions	Leak Detection
Temperature	Leak Detection	Bore Restriction
Accelerometers	Sensor Movement	Pipe Route Mapping
Magnetometer	Relative In-line Metal Mass	

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The MSIB providers also perform, to varying degrees, post run evaluation of the sensor data listed in Table 2. Pipeline operators have the option to develop and deploy their own post run data evaluation to serve the applications noted in Table 2. The focus of this paper is the post run evaluation of passive magnetometer data for the purpose of understanding the condition of a pipe wall.

Magnetometer Magnetic Field Measurement

The MSIB technology deployed in the pilot pipeline utilized magnetoresistive magnetometer sensors that measure the strength of the magnetic field, commonly measured in units of Gauss or Tesla, surrounding the MSIB.

Most ferrous line pipe is magnetic to varying degrees where magnetism can be induced by manufacturing, construction or pipeline operation practices and can change over time. While it is possible to demagnetize steel pipe it can be re-magnetized by long term alignment with the earth's North-South magnetic field or parallel alignment and proximity to high voltage AC power lines. It is common to encounter line pipe that exhibits magnetic field strength that ranges from 10 μTesla to 500 μTesla. Non-Destructive Testing of pipe using the Magnetic Flux Leakage in-line inspection technique depends on locally saturating a pipe wall by an energizing H field of 10 kA/meter that results in a B-field magnetic field strength of 1.8 Tesla. Magnetic saturation allows for high resolution detection and sizing of pipe wall loss by measuring increases in local magnetic field strength due to leakage of magnetic flux and avoids complications arising from the effects of pipe wall strain from operating pressure variations on material properties such as magnetic permeability. Magnetic saturation cannot be maintained when the energizing field is removed from the pipe wall and the residual magnetic field strength level immediately drops below the knee of the line pipe B-H curve or less than 1.4 Tesla and can continue to decrease at a decreasing rate over time. The flux leakage effects associated with changes in the volume or mass of ferro-magnetic line pipe diminish and eventually disappear with decreasing residual strength of the magnetic field. However, there is a fundamental relationship between low level residual magnetic field strength and the mass or volume of line pipe that can be leveraged to provide some indication of the condition of line pipe.

The presence of a ferromagnetic mass disturbs the Earth's magnetic field that causes a local magnetic field perturbation that can be measured by a magnetoresistive magnetometer.[5] The extent of perturbation of the background field should be proportional to the volume of the ferromagnet considering other variables such as magnetic permeability, magnetic strength, orientation within the background field and distance of the sensor to the ferromagnet are constant. The proposed relationship is derived from Maxwell's equations:

$$B \sim V/r^3 \qquad \text{Equation 1}$$

Where B is the magnetic field density, V is the metal volume, and r is the distance from the pipe to where the magnetic flux density is being measured. When the MSIB is fixed to the back of a cleaning pig the stand-off distance, r, is fixed constant. When a pipe exhibits wall loss by corrosion, the volume of metal in the pipe has decreased and so according to this relationship the magnetic flux density measured at a fixed distance from the pipe wall should be smaller.

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The pilot pipeline (Table 1) is a single bore diameter, nominal bore and pipe grade throughout the length of the pipeline. The on-bottom segment centerline is oriented in a South to North direction without any changes in direction. Therefore, of the variables noted above, that affect the magnitude of perturbation of the background magnetic field, all are constant along the segment except for the volume or mass of the pipe wall affected by wall loss due to corrosion.

The MSIB magnetometer measures increased magnetic field density at locations of girth welds and in-line features such as valves and flanges that allows for alignment of the data with the MFL inspection log. The MSIB records time-based magnetometer measurements that are later converted to linear reference distance based on the nominal flow rates recorded during the inspection run. A software application was developed that segments MSIB magnetometer data into sub-segments with common magnetic heading orientation of the pipe centerline. A screenshot from the software application is shown in Figure 3.

The application aligns the distance-based magnetometer measurements with the locations of pipe joint girth welds and flanges and identifies a minimum root of the sum of the three magnetic vector measurements for each pipe joint excluding the magnetic measurements associated with girth welds and flanges. The minimum magnetic field measurements for each pipe joint are plotted against sum of MFL metal loss volume for each pipe joint in Figure 4.

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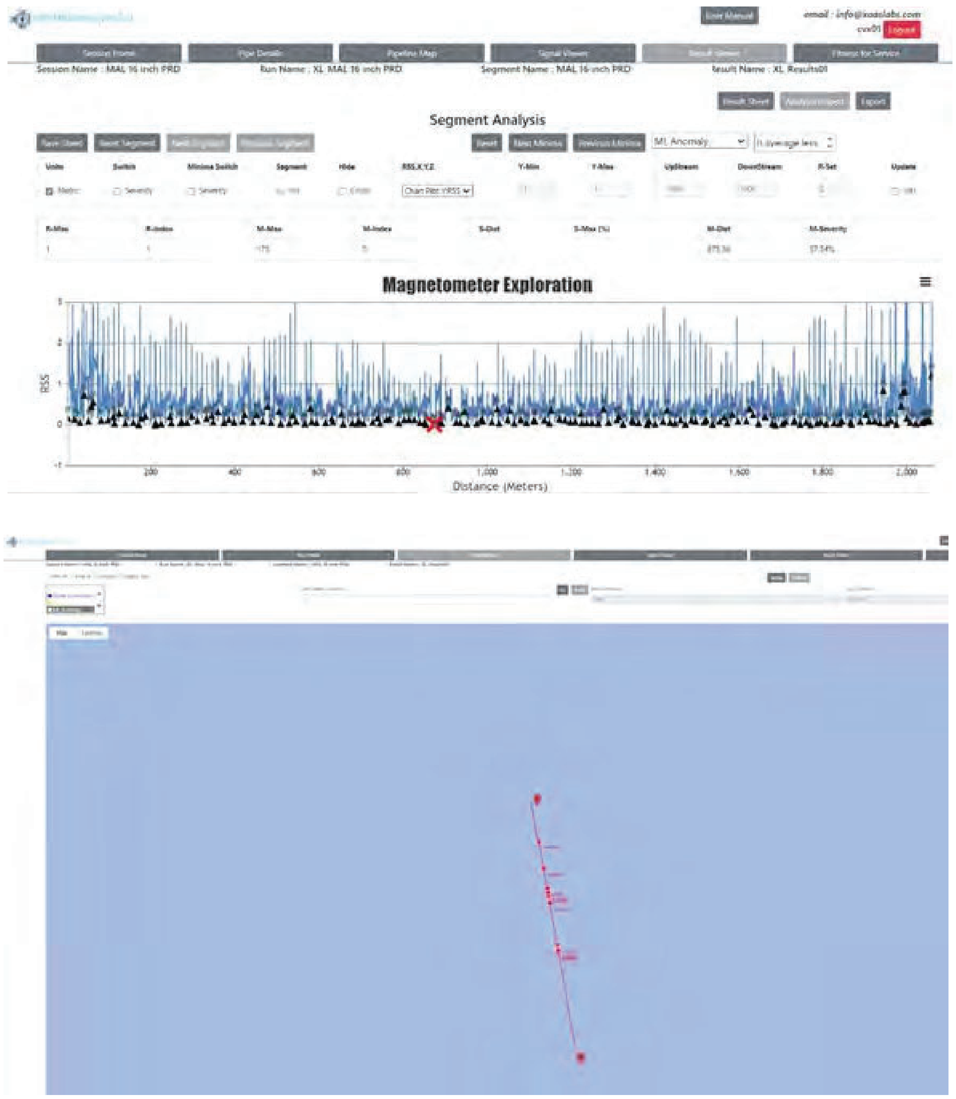

Figure 3: Screenshot from the software application used for post run analysis of MSIB magnetometer data depicting both linear reference magnetic and GIS representation. (Chevron Technical Center)

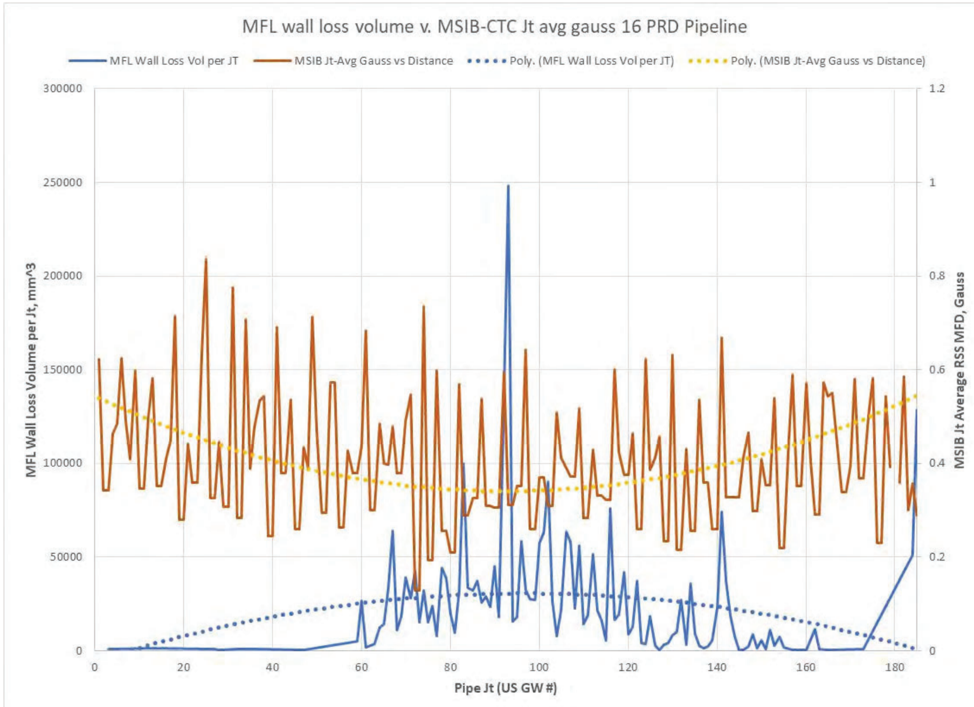

Figure 4: Internal wall loss anomaly feature volume from 2016 MFL plotted against 2023 MSIB magnetic field density measurements for each pipe joint. (Chevron Technical Center)

The MSIB pilot deployment in the 16-inch production pipeline was conducted in 2023. This pipeline was inspected by high resolution MFL technology in 2016. The MFL inspection reported internal wall loss anomalies segregated within the middle half of the segment length. Most of the wall loss anomalies exhibited a length and width shape factor classified as pitting according to the Pipeline Operator Forum standard.[6] The maximum wall loss depth was 30 % nominal wall thickness deep. The volume of wall loss represented by the depth, length, and width of the MFL anomaly box dimensions was calculated and are plotted in Figure 4 for linear reference segment distance represented by the upstream girth weld number from the inspection log.

A second order polynomial trendline was fitted to both the MFL ILI wall loss volume data and the aligned MSIB magnetometer data. The linear reference distance (pipe joint number) trendline minimum for the MSIB magnetometer data coincides with the distance location for the maximum of the MFL ILI volumetric wall loss trendline. This behaviour is demonstrating the proposed correlation model from Equation 1.

Empirical observations obtained from MSIB magnetometer sensors deployed in other pilot pipelines and small-scale laboratory tests were used to develop a wall loss severity model based on the fundamental physical relationship between magnetic field strength and pipe mass and establish a performance specification for limits of wall loss detection and measurement as well as guidelines

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regarding pipeline sizes and low risk operating conditions. The performance specifications for MSIB have been found to be low resolution compared with conventional high resolution in-line technologies such as MFL and Ultrasonic technologies. Our experience is that the use of MSIB technology for the purpose of screening the length of a pipeline, that might be otherwise be "un-smart piggable", for the purpose of later verification and validation as described in API Standard 1163 provides for understanding of the condition of the pipe wall, due to corrosion threat, that is at least equivalent to hydrostatic test for low pressure pipelines.[7]

Conclusions

Some upstream pipelines cannot be rendered "smart-piggable" for in-service inspection due to design and operating conditions. Those pipelines can benefit from internal in-line inspection technologies that are less intrusive than conventional ILI tools with sensors that are more tolerant to internal bore deposits.

The Multi Sensor Inspection Ball platform, when integrated with a conventional cleaning pig is less intrusive compared with conventional in-line "smart" pigs with lower navigation risks. Large stand-off magnetometer sensors as deployed in the pilot described in this paper have the potential for measuring low levels of changes in magnetic fields that under certain conditions can be correlated to the mass or wall thickness of pipe.

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