TECHNOLOGY ASSESSMENT FOR DELIVERY RELIABILITY FOR NATURAL GAS - INSPECTION TECHNOLOGIES: RFEC

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INTRODUCTION

Pipeline Threats

Preventative measures would increase the safety of our pipelines by reducing the chances of incidents. The need for technologies to monitor pipelines is driven by threats to pipeline integrity. To improve clarity in the analysis of DOT reportable incidents, Kiefner et al. [1] divided reported incidents into 22 incident causes. These incidents consisted of three types of pipeline threats: static, time dependent, and random. Static sources do not grow with time. Examples of static sources are manufacturing related defects and welding/fabrication related causes. This type of threat is normally eliminated during hydrostatic testing, and any remaining static defects are not a threat because they will not become worse with time. Time dependent defects grow with time. Pipelines need to be monitored for these threats in order to prevent incidents and maintain integrity. Examples of this type of threat include corrosion and environmental cracking, such as stress corrosion cracking (SCC). Random threats can occur at any time and in random locations. These include third party damage, weather related threats, incorrect operation, and outside force. Tools to manage the more common threats of this type are under development.

Technologies already exist to mitigate pipeline threats. More are needed to improve delivery reliability. Available technologies and technologies under development are discussed in this assessment.

AVAILABLE PIPELINE INSPECTION TECHNOLOGIES

Magnetic Flux Leakage (MFL)

Magnetic flux leakage [2] continues to be the most common method for inspection pipelines. Figure 1 is a schematic showing how MFL works. Powerful magnets magnetize the pipe wall to saturation. At any location where the wall is thinner, it cannot retain all of the magnetic flux, and the flux leaks out on both the outside and the inside of the pipe. Pigs with magnetic sensors measure the leakage flux and analysis programs convert the measurements to metal loss.

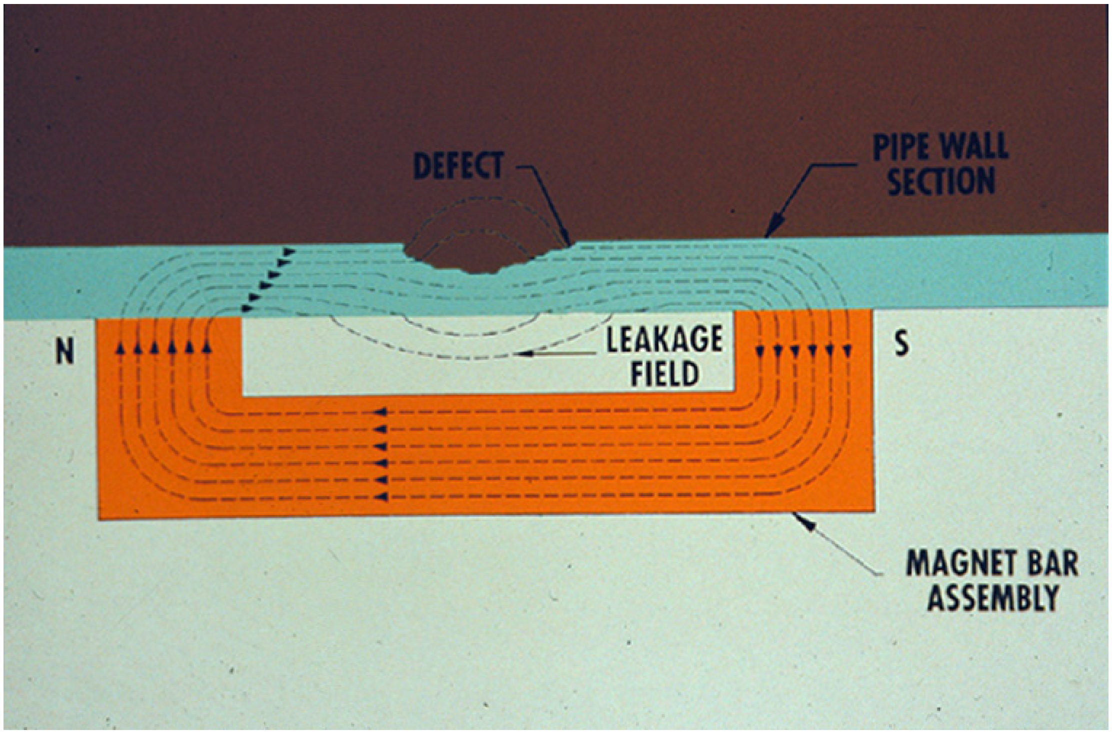

Figure 1. MFL: In areas of metal loss, the pipe can no longer contain the magnetic field, and it leaks out of the pipe wall and is measured by magnetic filed sensors.

The technique is popular for pipeline inspection because it is relatively inexpensive and is well understood, and it has been used for 40 years. Its main disadvantage is that it lacks accuracy. Because MFL measures the metal lost, the remaining wall thickness is found by assuming nominal wall thickness. The measurements have an accuracy of +/- 10% at the 80% confidence level. Greater accuracy is achieved by inspection methods that make direct measurements of the remaining wall thickness, as is the case with ultrasonic inspection.

Ultrasonic Inspection

Ultrasonic inspection [3] pigs were developed because MFL inspection results are not accurate enough to calculate the remaining strength well enough. Although ultrasonic inspection is more expensive and requires a liquid filled pipeline, its precision is few percent. Ultrasonic inspection measures the remaining wall thickness, and the results can be used directly in formulations such as B31G, RSTRENG, or finite element calculations to determine remaining strength.

Ultrasonic crack detection pigs are currently the only pigs available that have proven ability for detecting and measuring cracks. Alternatives for gas pipelines are available or under development.

Elastic Wave Vehicle

The Elastic Wave Vehicle [4] was developed in 1993 to detect and measure SCC in gas pipelines. It uses a liquid filled wheel to inject ultrasound into the pipe wall in the circumferential direction. It detects cracks deeper than 25% of the wall thickness and greater than 2” long. It has also proven useful for detecting coating disbondment. Although the Elastic Wave Vehicle finds SCC, there are too many false positives. This results in too many verification digs. A recently developed support vector machine analysis should greatly reduce the number of false positives.

EMAT (Electromagnetic Acoustic Transducer) Pigs

EMAT [5] pigs were also developed to detect and measure cracks and SCC in pipelines. EMATs generate ultrasonic waves but do not need to contact the pipe wall to do so. EMAT pigs send the ultrasonic waves around the circumference of the pipe. The first generation EMAT pigs could detect cracks but not measure them, but the market for just detection was too small. The current generation can measure crack size as well as detect cracks. False calls may also be a problem with EMAT inspections.

Inspection for Mechanical Damage

Technologies for characterizing mechanical damage became available at the end of 2003 [6], and two of them are ready for pipeline inspection. One of these is high-low magnetization. High magnetization is sensitive only to geometry effects. Low magnetization is sensitive to stress as well as geometry. Subtraction of scaled high-field results from the low-field results leaves only the stress effects. An example is shown in Figure 3. The reround halo gives the depth of the original dent, and the gouge signal gives an indication of the extent of gouging and work hardening. Analysis then qualitatively characterizes mechanical damage severity.

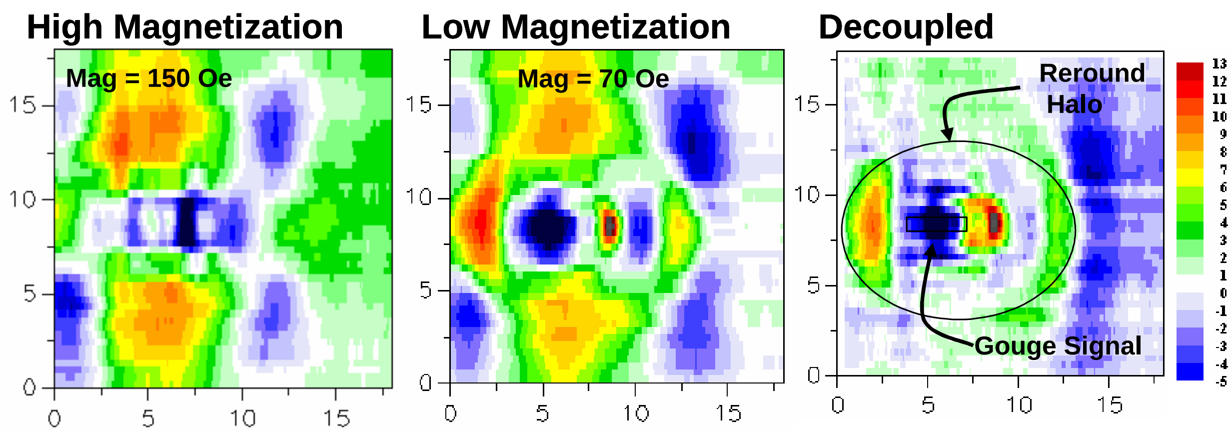

Figure 3. Subtraction of high-field results from low-field results leaves stress effects sensitive to the extent of mechanical damage.

A second technique for characterizing mechanical damage is to use circumferential magnetization (a.k.a. transverse magnetization). When used in conjunction with axial magnetization, the technique becomes sensitive to axial defects as well as circumferential defects and greatly improves the circumferential resolution. Figure 4 shows the advantage of using both axial and circumferential fields. Axial field results show strong signals from circumferential defects, while axial defects show very week signals. The converse is true for circumferential magnetization.

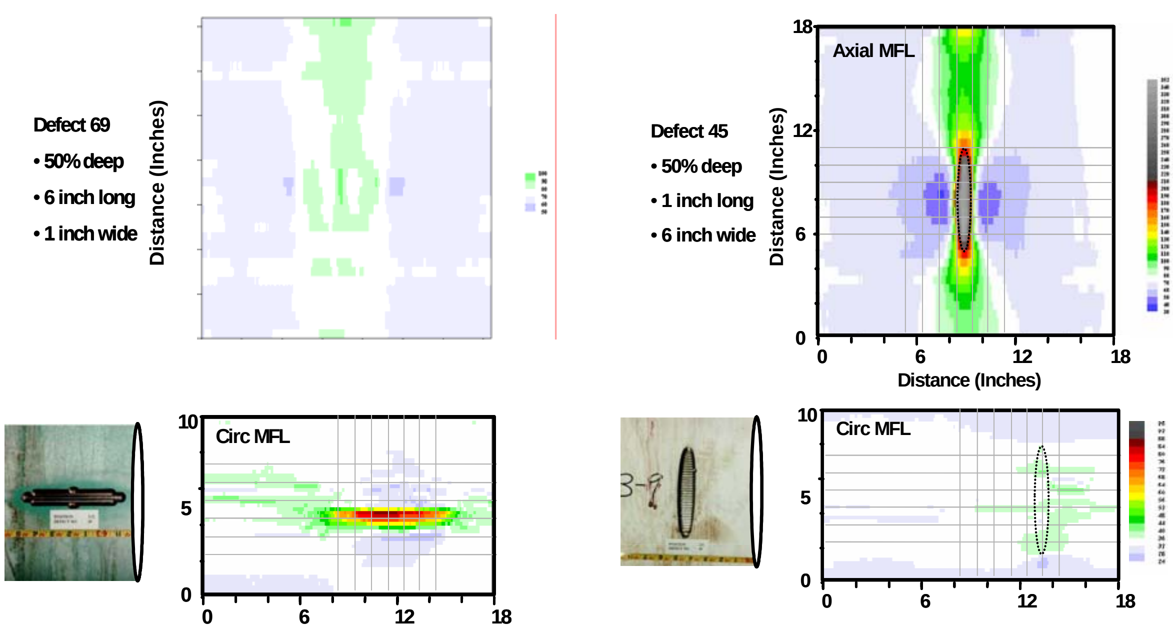

Figure 4. The response of axial and circumferential defects to axial and circumferential magnetic fields.

Difficulties with the method are non-uniformity of the circumferential field and the pipe wall is not magnetically saturated in some places. These difficulties will need to be handled in the analysis.

The third method for characterizing mechanical damage uses non-linear harmonics to measure stress levels at mechanical damage sites. This method is still under development.

TECHNOLOGIES UNDER DEVELOPMENT

MFL Fundamentals

The Applied Magnetics Group at Queen's University in Kingston, ON, has been investigating the fundamentals of MFL technology [7] for 25 years. Among the group's many achievements is the investigation of stress on MFL signals, including the first measurements of components of the magnetic anisotropy tensor. Stress can alter MFL signals by as much as 70%. Magnetic Barkhausen Noise stress measurement techniques were developed and used to analyze stress at defects. Barkhausen noise was found to be sensitive to stress in the elastic region but not the plastic region. More recently Queen's began investigating MFL signals generated by mechanical damage to determine what MFL signals are generated by it and which mechanisms contribute to the signal. Figure 5 shows MFL signals generated by defects under circumferential stress.

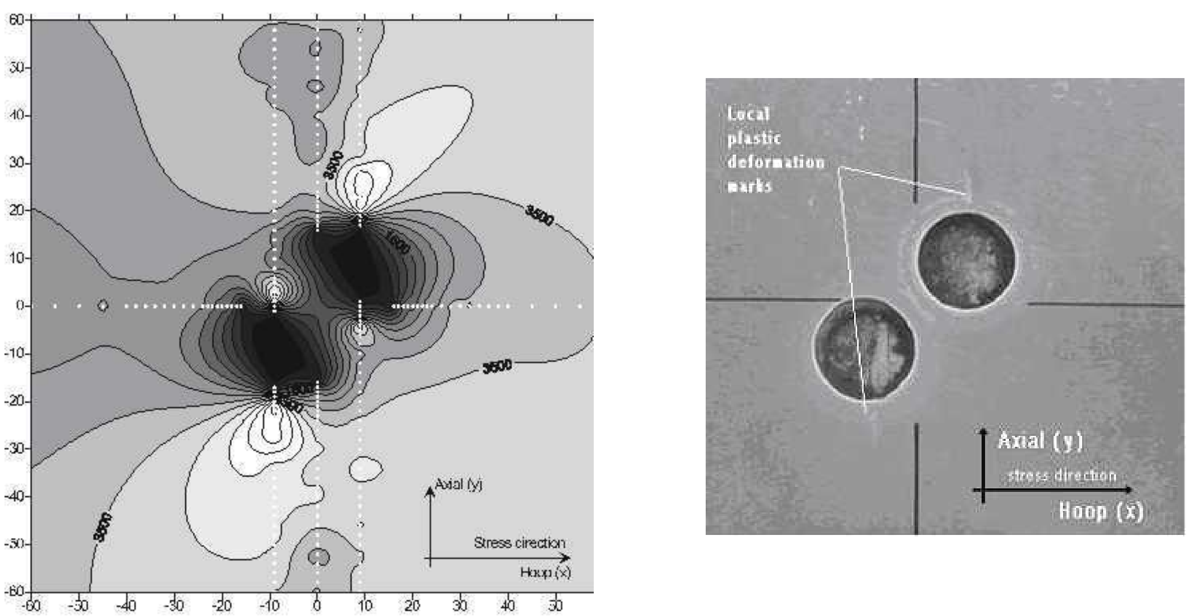

Figure 5. MFL signals at defects under stress.

Gas Coupled Ultrasonics

MFL, although popular, does not provide inspection results with adequate precision and will not detect and measure cracks such as SCC. However, conventional ultrasonic pigs cannot inspect natural gas pipelines unless they are put in a liquid slug. They need a liquid couplant to get signals in and out of the pipe wall. To overcome this limitation, ultrasonic transducers are under development for in-line inspection that can be used in high-pressure gas [8]. GTI expects to use these sensors early in 2005 to calibrate MFL pig results. Los Alamos National Laboratories is developing a techniques that work at much lower pressure. However this technique is not suitable for high-speed in-line inspection. Both methods could be used to inspect unpiggable pipelines. Figure 6 shows some laboratory results. The time between two consecutive pulses is proportional to the wall thickness.

Gas Coupled Ultrasonics should detect and measure cracks as well and is also under investigation for measuring the severity of mechanical damage.

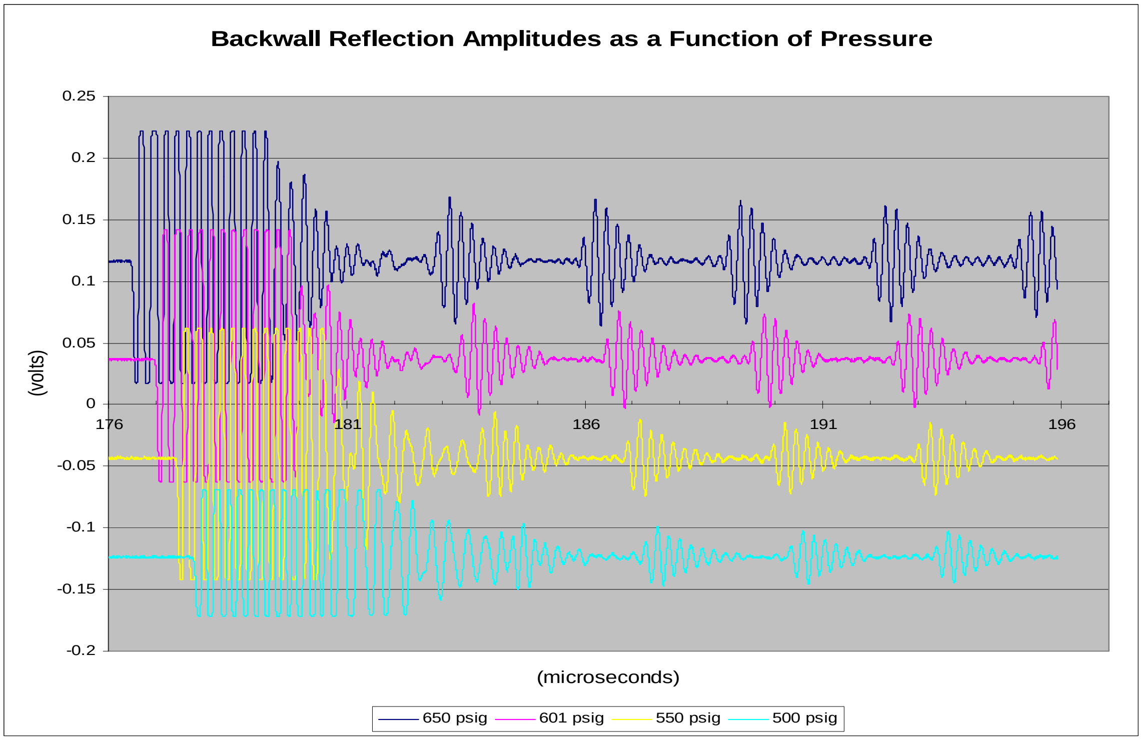

Figure 6. Back wall reflection amplitude as a function of pressure. Pulses can typically still be detected at 200 psig.

Remote Field Eddy Current Inspection of Unpiggable Lines

Regulations put in place in late 2003 have encouraged the development of technologies for inspecting unpiggable pipelines. In addition to the development of sensing technologies, robots for moving sensors through unpiggable pipelines are also under development. Among possible sensor technologies for unpiggable pipelines, the Remote Field Eddy Current technique [9] stands out as a very good candidate. Its chief advantage is that its components can be much smaller than the diameter of the pipeline. GTI for example has used a 2” exciter coil for 6” pipe and a 4” exciter coil for 12” pipe. Figure 7 shows the basic technique.

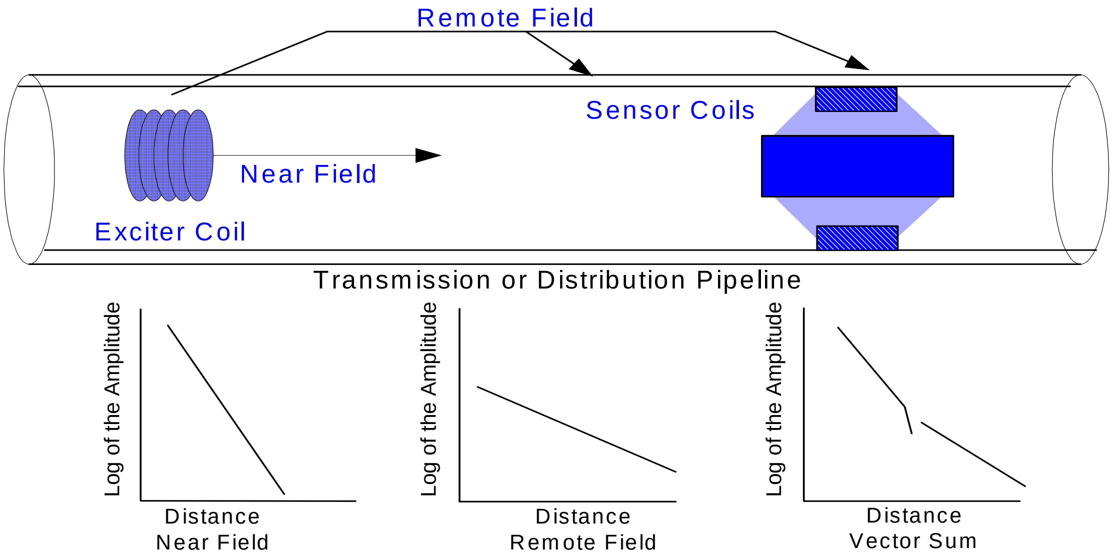

Figure 7. The Remote Field Eddy Current technique: low frequencies cannot travel down the bore of the pipe. The only field seen by sensor coils two or more pipe diameters from the exciter coil are those that have traveled back into the pipe from outside. Defects change field propagation thus generating signals that determine defect severity.

At frequencies from tens to hundreds of Hertz, electromagnetic waves will not propagate down the bore of the pipe because these frequencies are well below the cutoff for propagation, which is at several gigahertz. About two pipe diameters down the pipe, this direct field has all but disappeared. However low frequency electromagnetic fields can travel out of the pipe and then reenter the pipe at this point. Because the attenuation for this path is much less, at two pipe diameters these indirect or remote fields swamp the direct field. But, this is exactly what is needed. Any defect near the sensing coils will alter the propagation of the waves back into the pipe and hence generate a signal that differs from the defect free signal by a calculable amount related to the defect severity. It is anticipated that the method will have accuracy comparable to MFL. Its disadvantages are power consumption and inspection speeds of ½ mph or less.

SwRI is also developing the technique, but uses a collapsible exciter coil. Battelle, in an interesting innovation, uses a rotating magnet instead of an excitation coil.

NoPig

NoPig (now FINO AG) developed an above ground method for detecting and measuring corrosion in unpiggable pipelines [10]. It uses an applied signal of various frequencies at two points along the pipeline up to 1 km apart. The magnetic field at these frequencies is measured above ground at inspection points along the pipeline. Calculations use the measurements to determine the cross-sectional position of an equivalent current line. Due to the skin effect, a variation of this position with frequency indicates a local wall thickness reduction of the pipeline. This dependence is evaluated quantitatively to give the percentage of the wall's metal loss.

Remote Detection

Remote detection [11] involves generating ultrasonic waves at one location and sending them down the pipe using any one of several transducer types. Discontinuities in the pipe wall, such as corrosion, cause reflections back towards the transducer which then measures the reflections and determines the size of the reflector and hence its severity. So far standard piezoelectric transducers, EMATs, and magnetostriction have been used to generate the ultrasound. Maximum range currently is about 100 feet from the transducer location, but for coatings such as coal tar, the range can be less than 10 feet. Remote detection is useful for inspecting critical piping, such as at road crossing or in compressor station yards. The method is used extensively in refineries and chemical plants

Two methods are being used to increase the range. A brute force method lowers the frequency and increases the power. A subtler method involves selecting wave modes that have most of their energy at the center of the pipe wall, thus reducing the attenuation due to the coating.

RIGHT OF WAY MONITORING AND MANAGEMENT

Real-Time Acoustic Monitoring

Something hitting a pipeline will generate sound [12] that travels in the gas stream of the pipeline. The sound remains higher than the noise level for several miles and can therefore be detected up to several miles away. Placing sensitive microphones on the pipe every few miles can, for example, detect a backhoe hitting a pipeline. Figure 8 shows a schematic of the system.

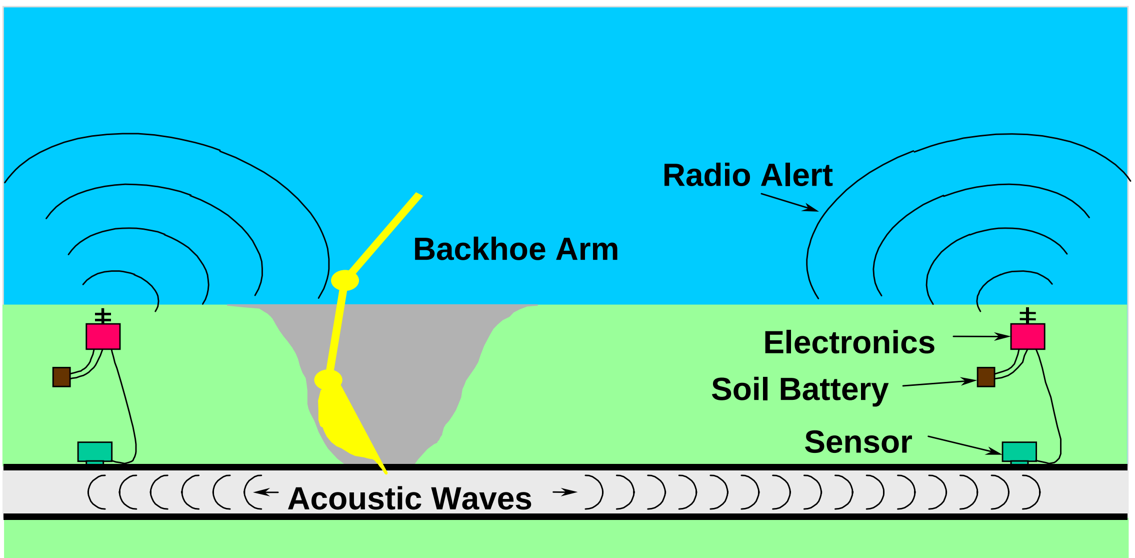

Figure 8. Sound from a backhoe hitting the pipe travels to microphones where it is heard. An operator or security firm is alerted when this happens to stop the activity and investigate the damage.

Electronics at the microphone filters and analyzes the sound and, if it is of concern, radios the information to a security firm or the pipeline operator who can then investigate the activity and assess any damage. The system is being field tested.

Right of Way Monitoring

Prevention would be better than waiting for something to hit a pipeline. A vehicle moving on the right of way generates sound [13] in the ground that can be detected using an optical fiber and optical time domain reflectometry. The sound can be monitored and analyzed to determine what kind of vehicle might be on the right of way and where it is going. If for example it is heavy enough to be a backhoe, and it stops near the pipeline; it might be worth sending some one out to determine what it is and what it is doing. This system is has been deployed in the field, but is still testing artificial situations.

Other Monitoring Methods

A simple trip wire buried above the pipe can alert an operator of potential problems when it breaks. Infrared systems are available that can detect and identify (using computer software) equipment on the right of way and alert an operator. Microwaves and ultrasonics can detect movement on the right of way. Transmission line impedance spectroscopy can detect damage to coating when it is scraped off. Backhoe sensors that tell the backhoe operator when he is too close to a pipeline are also under development.

Satellite monitoring is also becoming more convenient. In particular, visual images can be used for pipeline planning, for monitoring urban encroachment, and for detecting equipment on the right of way. Radar satellites can monitor ground movement by using interferometry to compare satellite images taken days, weeks, or months apart.

CONCLUSIONS

Past research and development has resulted in pipeline inspection techniques such as caliper pigs, inertial pipe mapping, magnetic flux leakage, ultrasonic inspection, and ultrasonic crack detection that are now in common use. Many technologies new to pipeline inspection and monitoring are at various stages of development. Not all of these technologies will make it to market. Some will not work well enough, some will be too expensive, and some will simply lose sponsorship. We have reviewed many of these new technologies, all of which still look promising for improving the delivery reliability of natural gas.

Method	Principle	Comments
	AVALABLE TECHNOLOGIES	
Caliper	Measures pipeline ovality and dents using mechanical fingers or non-contact acoustic or eddy current methods	Widely available. Simplest of useful pigs
Inertial Mapping	Uses accelerometers to locate and map the pipeline in 3 dimensions relative to survey marks	
Magnetic Flux Leakage	Uses massive magnetizers to magnetize the pipe and Hall effect sensor to measure flux leakage at defects.	Most common corrosion inspection method. Inexpensive, simple and vendors have lots of experience with it. *Good accuracy but not enough to avoid investigative digs*.
Ultrasonic	Uses ultrasonic transducers to accurately measure pipe wall thickness.	Very accurate Only good method for measuring and detecting cracks *Very expensive, especially the crack detection.*
Elastic Wave Vehicle	Uses liquid filled wheels to send ultrasonic waves around the circumference of the pipe. Developed for crack detection in gas pipes	Finds and measures cracks Finds disbanded coating *Too many false calls, but recent analysis improvements may greatly reduce them*
EMAT	Uses electromagnetic acoustic transducers to send ultrasonic waves around the circumference of the pipe. Developed for crack detection in gas pipes.	Finds and measures cracks Commercially available *Too many false calls?*
High-Low Field MFL	Determines stress levels and patterns by subtracting high field results from low field results. Used to find mechanical damage.	Characterizes mechanical damage *Qualitative results only* *Has not yet been used commercially*
Circumferential MFL	Uses circumferential magnetization to better measure long defects, and improve circumferential resolution. Used to find mechanical damage	Finds mechanical damage *Qualitative results only* *Has not yet been used commercially*

	UNDER DEVELOPMENT	
Nonlinear Harmonics	Uses changes in amplitude of the 3rd harmonic of the detected caused by changes in the magnetic hysteresis curve to determines stress levels and patterns	To be used in conjunction with High-Low field MFL or circumferential MFL to better characterize mechanical damage
Standard MFL	Analyze standard MFL signals to detect and characterize mechanical damage.	*Strictly experimental for now.*
Gas Coupled Ultrasonics	Uses specialized transducers to couple enough ultrasound into high pressure gas to enable ultrasonic inspection of gas pipelines.	Planned deployment for calibrating MFL pigs next year *Progress has been slow*
Remote Field Eddy Currents	Uses eddy currents at a defect to measure its severity. The primary use is for unpiggable pipelines. The drive coil is at least two pipe diameters from the inspection point	Commercially available for non pipeline use Precision comparable to MFL *Slow inspection speed* *Power consumption*
NoPig	Uses analysis of multiple frequency current impressed on a pipeline to detect and measure corrosion	Above ground method Only needs access to a pipeline at 1km intervals *Inspection is slow*
Remote Detection	Ultrasonic waves that reflect off defects are sent down the length of a pipeline. Reflection timing gives location. Reflection amplitude is a measure of severity.	Commercially available and in use at refineries and chemical plants R&D to increase the range and accuracy *Maximum range 100 feet and can be less than 10 feet.*
Acoustic Monitoring	Sound generated by a backhoe is detected up to several miles away	Undergoing field trials
Time Domain Reflectometry	Optical fiber detects the sound generated by machinery on the right of way	Being tested under field conditions with artificial simulations.
Other Right of Way Monitoring	Trip wires Infrared cameras Microwaves Ultrasonic motion detection Impedance spectroscopy Multi spectral satellite monitoring Radar satellite monitoring Backhoe mounted sensors	

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