**BI-MONTHLY REPORT –II**

**[JANUARY 1 –FEBRUARY 28, 2005]**

**PROGRESS-REPORT**

# Electromagnetic Analysis of Hydrogen Through Coated Linepipe Steel

## 1. Summary

With the rapid introduction of high strength linepipe steels (in excess of 70 ksi yield strength) for operation and use at higher pressures and thinner wall thicknesses, the need for new approaches for hydrogen management needs to be addressed. With increasing steel strength there is a reduction in the allowable diffusible hydrogen content to avoid hydrogen assisted cracking. Hydrogen-assisted cracking and hydrogen embrittlement are common terms used to describe sub-critical cracking due to hydrogen in metals. Hydrogen damage refers to the action of hydrogen reducing the physical and mechanical properties of a material to a degree that renders it unattractive, fallacious, or dangerous (Beachem, 1977).

Hydrogen can be introduced into the linepipe steel in numerous ways; for example, through welding procedures, cathodic protection, corrosion reactions with the environment, and interactions with the contained media in the pipes. Research efforts in hydrogen damage are seriously hampered because the equipment available only measures the total effects of very large numbers of hydrogen molecules, ions, or protons, as they act on a specimen or service component [Beachem, 1977]. Advanced research has lead to the improvement and development of hydrogen determination tools, which has lead to numerous non-destructive methods capable of measuring hydrogen content in steel and weldments. These techniques are, however, all contact techniques and, since pipelines are coated, it is necessary to develop a non-contact technique that can perform measurements through the pipeline coating.

This project offers research opportunities that will advance the available technology to measure and monitor the diffusible hydrogen content and increase our understanding of hydrogen management. Through the use of complimenting electromagnetic techniques, a new non-destructive, non-contact tool will be developed for in-situ determination of diffusible hydrogen content in coated linepipe steel. The electromagnetic techniques will allow for a means of measurement of hydrogen accumulation without damaging the linepipe coating. These tests will establish a threshold electromagnetic property value that will indicate when sufficient hydrogen has been absorbed, leading to a reduction in the integrity of the pipeline.

## 2. Background and Justification for Conducting the Research

The ever increasing demand for energy worldwide requires the construction of high pressure gas transmissions lines with the greatest possible transport efficiency, while reducing the cost of pipeline construction and transportion. In North America alone, the total length of high-pressure gas transmission pipelines is greater than 300,000 miles. In large diameter pipelines (OD: 48 to 56 inches (1212 - 1422 mm)), outage costs could be as high as one million dollars per day. In 2004, there were over 36 corrosion caused pipeline explosions with an average cost of over 13 million dollars.

New pipeline steels have been under development for over 40 years to provide better transport efficiency through larger diameter pipelines with a reduction in wall thickness such as X80 linepipe steel. X80 linepipe steel is currently available in the market. X80 is chosen and designed for linepipe steel because it has high strength with good weldabililty and toughness. X80 is not dependent upon the chemical composition, but depends on the strength of 80 ksi. X80 was first used in 1985 on a 3.5 km line on a trial basis. Germany then reproduced the X80 steel for use in longer pipelines across Germany. Hydrogen cracking is major problem associated with in-service pipelines, especially high strength steel pipelines.

In pipelines, there are numerous sources responsible for the production of hydrogen, some of which include welding procedures, cathodic protection, and corrosion reactions with the environment and with the contained media in the pipes. The most common source of hydrogen is from cathodic reduction of hydrogen and water during cathodic protection. The presence of hydrogen can lead to detrimental results in these high-pressure steel pipelines. Hydrogen damage reduces the physical and mechanical properties of a material to a degree that renders it unattractive, fallacious, or dangerous (Beachem, 1977). Because it is impossible to remove hydrogen from the system (pipeline), the hydrogen must be monitored in the system.

"The future of pipeline integrity is in the management and interaction of collected survey data." [Author unknown]. This statement should be taken very seriously because the only way to monitor a pipeline that cannot physically be inspected is through surveying data. There are many intelligent non-destructive tools offered on the market, which are used industrially for crack, surface, and corrosion inspections. Some of these non-destructive tools include eddy currents, magnetic flux leakage, ultrasonic, magnetic barkhausen noise, etc. [Griffith et al, 1997], [Mandal et al, 1999], [Crouch and Beuker, 2004]. These non-destructive tools are necessary to guarantee pipe integrity, however these tools do not assess diffusible hydrogen until significant cracking occurs. New tools need to be developed to monitor the diffusible hydrogen content before significant defects arise.

There are many methods and sensors available for diffusible hydrogen measurements, however a non-destructive technique is necessary for in-service hydrogen content measurements. Thermoelectric power (Seebeck effect) has been experimentally and thermodynamically proven to non-destructively measure diffusible hydrogen content in steel. The downfall to thermoelectric power for assessment of hydrogen in pipelines is that it is a surface contact measurement, which means measurements cannot be made through a coating. With this in mind, the focus of this research is to develop a new non-destructive, non-contact probe that can measure diffusible hydrogen content in coated linepipe steel.

The oil and gas industry currently utilizes a pipeline cleaning technique driven by product flow called pigging. A pig is a cleaning device that is pushed through the pipeline to remove deposits and water that could cause corrosion, but as the pig removes the residue, it is sequentially eliminating any films or deposits that may also be protecting the surface from corrosion. With this limitation in mind, "smart pigs" were designed, which includes cleaning and deposition removal as well as magnetic flux leakage (MFL) unit that can monitor the pipeline for cracks and defects. In MFL, a magnetic flux is generated in the pipeline and if there is a defect or a crack, the magnetic flux will leak in that area. The MFL unit is a precautionary tool to find potential problems.

The "smart pig" is an important factor in this research because recent studies at the Colorado School of Mines has found that magnetic flux in a pipeline steel increases the solubility of hydrogen by a factor of three. These experimental findings play an important role in the integrity of pipelines, thus increasing the need for a tool to monitor the diffusible hydrogen content in pipelines.

The following sections will discuss the importance of measuring hydrogen in linepipe steel and the consequences of hydrogen in linepipe. Then a discussion on a new non-contact, non-destructive method for assessment of diffusible hydrogen in coated linepipe steel will be described.

## 2.1. Role of Hydrogen in Line Pipe Steel

Hydrogen is the smallest element in the periodic table, so that when hydrogen enters the iron lattice it occupies interstitial sites. Hydrogen interacts with dislocations, second phase particles, voids, etc. in the material, thus influencing the distribution and mobility of hydrogen. Hydrogen is transient, the concentration and distribution is continually changing with time.

Due to the abundance of hydrogen sources in pipelines, it is important to quantify the amount and form of hydrogen present in the steel because there is a distinction between total, residual, and diffusible hydrogen. Diffusible hydrogen is considered to be mobile at lower temperatures (<100°C), whereas the remaining residual hydrogen is trapped in the metal at microstructural discontinuities or by the formation of hydrides with alloying elements. Total hydrogen is the combination of the two fractions. Each form of hydrogen exhibits different properties. For example, diffusible hydrogen increases dislocation motion, whereas dislocation motion would be temporarily hindered by a formed hydride because the dislocation will have to cut or bow around it (dependent upon the shear stress). It is also well established that the formation and fracture of brittle hydrides promote hydrogen-assisted cracking.

The formation of second phase particles is related to the atomic nature of hydrogen. Elements on the periodic table to the left of manganese are electron acceptors, having a negative heat of mixing, resulting in the formation of hydrides. The elements on the periodic table to the right of manganese are electron donors with a positive heat of mixing meaning that hydrogen stays in solution.

The solubility and diffusivity of hydrogen differ greatly between iron phases. The solubility of hydrogen in austenite is very large, while very small in ferrite. The diffusivity of hydrogen in austenite is very slow, but much quicker in ferrite. So in conclusion, austenite is a diffusion barrier for hydrogen transport, while ferrite facilitates hydrogen transport.

Thomas Graham coined the term "occlusive capacity" defined as the concentration of hydrogen within a compact metal when it has established a steady state of exchange with hydrogen gas of certain temperature and pressure [Thomas Graham], [Smith, D.P., 1948]. The occlusive capacity is the solubility dependent on the degree of strain or plastic deformation [Beck et al, 1965]. The occlusive capacity is important because hydrogen tends to accumulate in regions of high stress (stress-assisted hydrogen diffusion).

There are many regions of high stress in pipelines. Some examples include: (1) weldments (2) grain boundaries, (3) voids, (4) crack tips, and (5) the hoop stress is the most. The most common types of cracks occurring in pipelines are hydrogen induced cracks, fatigue cracks, stress corrosion cracks, and cracks in the weld HAZ. The occlusive capacity describes the true solubility of hydrogen in the pipeline due to stress.

### 2.1.1. Hydrogen Cracking Models

Beachem [1977] has divided hydrogen damage into different forms. One form of damage results in internal pores, cracks or other flaws arising from either the entrapment of hydrogen bubbles during solidification of the melt or diffusion of hydrogen through the metal lattice to cause flaws. At higher temperatures, hydrogen reacts predictably to alter chemical compositions to form collecting pockets of gaseous molecules that cannot escape by diffusion and remains trapped. The second form of damage results when formed hydrides assume specific lattice positions within the metal, thus lowering the mechanical properties and the toughness of the metal. The third form of hydrogen damage results despite the absence of a known chemical reaction or hydride formation; nevertheless the hydrogen causes crack formation and growth, particularly in the presence of sustained stress. This form of damage is called hydrogen-assisted cracking (otherwise known as hydrogen embrittlement) [Beachem, 1977]. This third type of damage has been related to localized microplasticity in the region of the triaxial stress at the crack tip.

The following conditions must be met for the occurrence of hydrogen assisted cracking: (1) sufficient atomic hydrogen in the material, (2) tensile stress, (3) susceptible material, (4) temperature range that supports very localized hydrogen transport (-50 to 150˚C in steel). When these conditions are met, in non-hydride forming elements, there are three mechanisms of hydrogen embrittlement worthy of consideration [Lynch, 1991]. These mechanisms include: (1) hydrogen-enhanced localised plasticity, (2) hydrogen-enhanced de-cohesion, and (3) adsorption-induced dislocation emission. These mechanisms have been proposed for embrittlement in external ($H_2$, $H_2S$, $H_2O$) and internal (introduced into steel during welding, plating, etc) hydrogen environments [Lynch, 2001]. It should be recognized that the cracking mechanisms could be similar, however the rate controlling processes are very different.

**<u>Hydrogen-Enhanced Localised Plasticity (HELP)</u>**

Hydrogen-enhanced localised plasticity is based on the presence of solute hydrogen ahead of cracks, specifically in hydrogen atmospheres around both mobile dislocations and obstacles to dislocations [Lynch, 1999], [Beachem, 1972]. It has been suggested that the hydrogen atmospheres distort when mobile dislocations approach obstacles, meaning that the repulsion by obstacles is decreased. Since hydrogen accumulation is localized near crack-tips, deformation is localized and facilitated near crack-tips, resulting in an overall lower strain for fracture [Lynch, 1999, 2001].

**Hydrogen-Enhanced Decohesion (HEDE)**

Hydrogen-enhanced decohesion is the weakening of iron-iron intermetallic bonds at or near crack tips due to high localized hydrogen concentrations in the lattice resulting in tensile separation of the atoms. The weakening of bonds may be the result of a decrease in the electronic charge density between metal-metal atoms due to the existence of hydrogen in the crystal lattice in interstitial sites [Lynch, 2001]. For hydrogen-enhanced decohesion, fracture surfaces should appear basically featureless with a few cleavage steps and tear ridges separating de-cohered regions [Lynch, 1999].

**Adsorption Induced Localised Slip (AIDE)**

Adsoprtion induced localised slip is based on hydrogen-induced weakening of interatomic bonds, but with crack growth occurring by localised slip [Lynch, 1999]. It has been proposed that adsorbed hydrogen weakens substrate interatomic bonds and thereby facilitates the emission of dislocations from the crack tips. There is also substantial dislocation emission ahead of the crack tip, resulting in the formation of voids around particles or at slip band intersections. This behavior means that crack propagation occurs due to dislocation emission from crack tips also with a contribution from the void formation ahead of the crack tip [Lynch, 1999, 2001].

A combination of these three mechanisms occur in most cases. Figure 1 schematically illustrates the HELP, HEDE, and AIDE. The most dominant mechanism will be dependent upon variables such as strength, microstructure, slip-mode, stress intensity factor, and temperature, thus affecting the fracture path and appearance [Lynch, 2001].

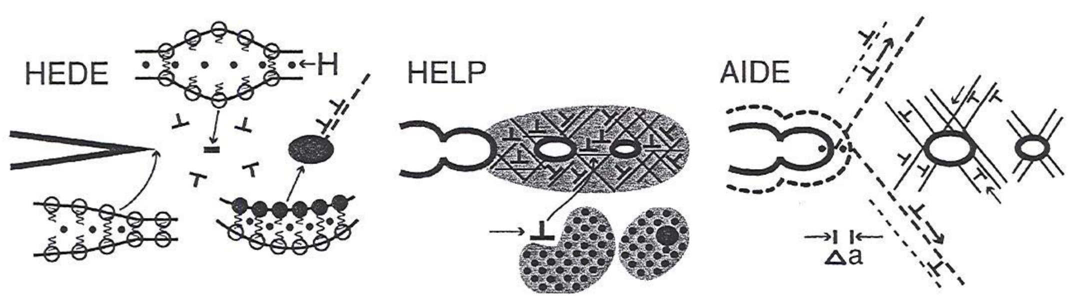


Figure 1: Schematic diagrams illustrating HEDE, HELP, AIDE mechanisms of hydrogen-assisted cracking [Lynch, 2001].

## 2.2. Electromagnetic Tools for Determination of Hydrogen Content in Line Pipe

Most non-destructive tools utilized in industry (ultrasonics, magnetic flux leakage, etc.) are used for determination of existing cracks, flaws, defects, etc, in other words, characterization after the fact. The development of a non-destructive diffusible hydrogen meter will allow for property prediction before significant defects or cracks occur. The non-destructive diffusible hydrogen meter can beneficially be used during production and in-service.

There are many variables associated with pipelines, such as temperature, pressure, coatings, etc. This research will employ the use of a combination of three different complimenting, non-contact electromagnetic methods to determine the diffusible hydrogen content in coated linepipe steel. The three methods utilized in this research will include eddy current analysis, magnetic barkhausen noise analysis (MBN), and electromagnetic acoustic transducer analysis (EMAT). The MBN and EMAT are necesary if the temperature, microstructure, and composition to be characterized to allow proper standardization to be used for the eddy current assessment of the hydrogen cotnent. All three of these non-destructive techniques are currently utilized for pipeline inspection, however they are used individually for only crack, defect, and corrosion monitoring. These three methods will be used together to eliminate extra variables to rapidly generate a quantitative hydrogen content associated with the coated linepipe.

### 2.2.1. Electromagnetic Theory

Eddy currents, magnetic barkhausen noise, and electromagnetic acoustic transducers are based on Faraday's law. Faraday's law states that, "a changing magnetic field induces an electric field." Faraday's law really distinguishes between two types of electric fields: (1) those attributed to electric charges and (2) those associated with changing magnetic fields. The curl of an electrostatic field is given by the differential form of Faraday's law is:

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad [1]$$

where $\nabla$ is the del operator, E is the electrostatic field, B is the magnetic flux density, and t is time.

An electric field diverges away from a (positive) charge while the magnetic field line curls around a current as shown in Figure 2. Electric field lines originate on positive charges and terminate on negative ones; magnetic field lines do not begin or end anywhere because to do so would require a non-zero divergence. Ampere first speculated that all magnetic effects are attributable to electric charges in motion (currents). It takes a moving magnetic field to generate a magnetic field, and it takes another moving electrical charge to "feel" a magnetic field.

The electric charges can be calculated using Coulomb's law and the magnetic field is calculated using a combination of Faraday's law and Ampere's law.

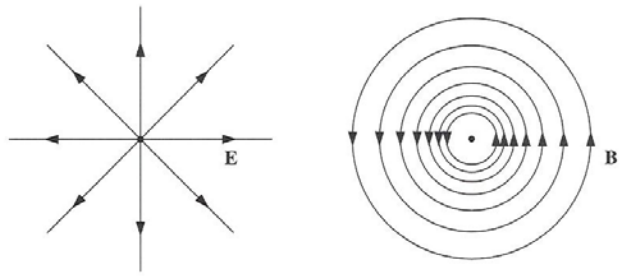


Figure 2: (a) Electrostatic field of a point charge. (b) Magnetostatic field of a long wire.

### 2.2.2. Eddy Currents (Electromagnetic Power)

Eddy Current analysis is a technique utilized to find near surface defects in alloy parts, normally in non-ferrous alloys. The ferromagnetic behavior of steel causes a significant change in the steel's impedance, which hinders the determination of cracks, but should serve as an excellent indicator for diffusible hydrogen content in the near surface region of the steel. Since diffusible hydrogen donates its electron to the d-band of steel, which is the same band that contributes to the ferromagnetic behavior, the induced current in the steel will experience the change in impedance due to the hydrogen and cause perturbation in the eddy current signal. Eddy currents units have been designed and experimentally proven for flaw, cracks, and thickness examination of large diameter pipelines through coatings and insulation [Griffith et al, 1997].

In eddy current testing, a high frequency electromagnetic (EM) field is generated in a conductor by an alternating current. When placed in close proximity of a material, the generated EM field induces currents (eddy currents) within the inspected material. In response, the eddy currents induced in the inspected material generates a magnetic field. The EM fields from the induction coil and the inspected material must be detected either by electromagnetic induction in a coil, by a system of coils, or by sensors such as the hall element. In many cases the same coil is used both to excite the eddy currents, and also to detect their fields.

A significant advantage of the eddy current technique is that it can be performed at a stand off distance and through the pipeline coating. The first step in using the eddy current testing practice is to select all of the controllable parameters in such a way as to optimally detect the desired material parameter. For the proposed hydrogen sensing investigation the initial part of the effort will be to determine the optimum set of controllable parameters.

When the circuit contains both inductance (L) and capacitance (C), the most general form of the impedance, Z, is:

$$Z = ((\omega L - 1/\omega C)^2 + R^2)^{1/2} \quad [2]$$

and the phase angle, $\phi$, between the current in and voltage across the circuit is given by:

$$\tan \phi = (\omega L - 1/\omega C)/R \quad [3]$$

It can be seen that the possibility arises that, if $\omega L = 1/\omega C$, then Z reduces to just R, and $\phi$ becomes zero degrees. This condition is known as resonance, and many circuits are designed to operate at or near such a condition. In eddy current probe work, generally $\omega L >> 1/\omega C$.

The eddy current density, and thus the strength of the response from a flaw, is greatest on the surface of the metal being tested and declines with depth. It is mathematically possible to define the "standard depth of penetration" where the eddy current is 1/e (37%) of its surface value. The following expression gives the relationship of the standard depth of induced current to the applied frequency.

$$\delta = 50\sqrt{\rho / (f \cdot \mu r)} \quad [4]$$

where *r* is resistivity in *mW.cm* and *f* is frequency in *Hz*. With charging frequency the hydrogen profile relative to the pipe surface can be assessed. Figure 3 illustrates the eddy current density as a function of depth.

Through thickness hydrogen measurements in the coated pipeline will require a large coil at a very low frequency (below 10 kHz). Frequencies of this magnitude are not commercially available. An eddy current unit is being specially designed by CANDET to achieve these necessary low frequencies. This non-contact probe approach has high potential to determine the diffusible hydrogen content in a very convenient way.

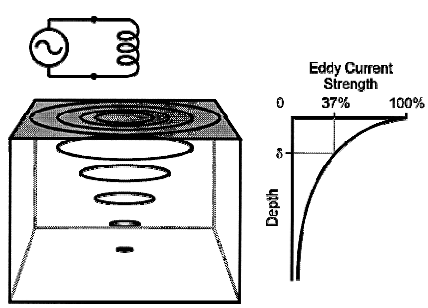


Figure 3: Schematic illustration of eddy current density declines with depth [Reference].

### 2.3. Electromagnetic Acoustic Transducer

EMAT's are devices that essentially consist of a stack of wires and magnets to excite and detect ultrasonic waves in electrically conductive material (magnetic or non-magnetic). When the EMAT transmitter is placed near an electrically conducting specimen, ultrasonic waves are launched into the material through the reaction of induced eddy currents and static magnetic fields. EMAT's allow examination of properties without contact at elevated temperatures and in remote locations. EMAT's can also generate and detect ultrasound through coated materials.

EMAT's can be used to assess the temperature of the steel in the line pipe being assessed. The use of EMAT produces an elastic wave pulse, which can travel through the steel. Its velocity can be determined by pulse echo or transducer to transducer measurements. The speed of sound depends upon the type of medium and its state given as:

$$V_S = \sqrt{\frac{E}{\rho}} = f(T) \qquad [5]$$

where $V_s$ is the speed of sound, E is the elastic modulus, ρ is the density, and T is temperature.

Each specific hydrogen content will have it's own unique speed of sound. The elastic modulus and density are both a function of temperature, thus the speed of sound accounts for variations in the pipeline temperature. If the affect of temperature in the pipeline is unaccounted for, the eddy current analysis for hydrogen content could be erroneous if the standardization practice if temperature is not a characterized feature of the standardization practice.

## 2.4. Magnetic Barkhausen Noise

Magnetic barkhausen noise is applicable to ferromagnetic metals and alloys and is dependent on the Barkhausen effect, which takes place when a magnetic field is swept in a ferromagnetic specimen along a hysteresis loop. Two types of high frequency signals are generated: (1) the Magnetic Barkhausen Noise (MBN) due to irreversible changes in magnetic moments during the hysteresis and (2) Magnetomechanical acoustic emission (MAE) is due to elastic deformations associated with magnetic domain activities during irreversible changes in magnetization. MBN signals are acquired by a sensor coil, while a MAE signal is acquired through a piezoelectric transducer. Both MBN and MAE are sensitive to microstructure and stress conditions [Raj et al, 2000].

At temperatures below the Curie temperature, the magnetic moments of different atoms are parallel within a certain restricted area called a domain. In the de-magnetic state, the domains of the structure are arranged in such a way that the sum of the magnetic moments, the net magnetization, is zero. In single crystals and poly-crystals the arrangement of domains are different as shown in Figure 4.

The domain wall is the transition region between two domains. The domain walls moves due to applied external magnetic field. In an ideal case, the domain wall movement can be quite continuous, while in the case of a single crystal or polycrystal, the movement of the domain walls can be discontinuous. Lattice discontinuities such as grain boundaries, precipitates, etc. tend to hinder the motion of the domain walls. With increasing magnetic field strength, local segments of domain walls abruptly break free from the pinning sites and move forward until they encounter the next pinning site. The abrupt microscopic changes in flux due to discontinuous wall motion are referred to as the barkhausen effect. As a result, the hysteresis loop is not smooth and continuous, but discontinuous as shown in the magnified onset of Figure 5 (a). The local and abrupt changes in magnetic flux within the material also gives rise to a spectrum of voltage pulses of varying heights. A typical barkhausen spectrum for an ultralow carbon steel sample for one complete hysteresis loop is shown as a function of time in Figure 5 (b) [Chopra et al, 2001].

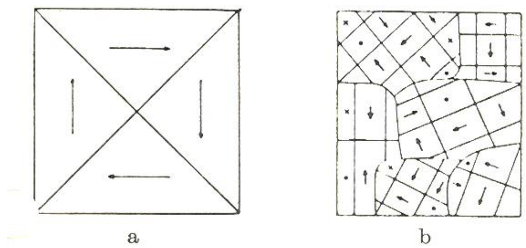


Figure 4: The arrangement of magnetic moments: (a) in a single crystal and (b) in a polycrystal.

Magnetic barkhausen noise is most often used for detection of microstructural changes such as carburized case depth, pearlite lamellar spacing, and texture. In this investigation, MBN will be used to classify the steel being measured as having specific combinations of chemical composition and microstructural features. Since each still will have its own eddy current signature it is important to classify these features to use of a specific set of standard in order that the hydrogen signal can be assessed without interference. Also magnetic barkhausen noise can be utilized for testing of surface defects that may involve changes in both stress and microstructure [Chopra et al, 2001]. Eddy currents are used to perturb the material and the electromagnetic acoustic transducers measure the magnetic barkhausen noise.

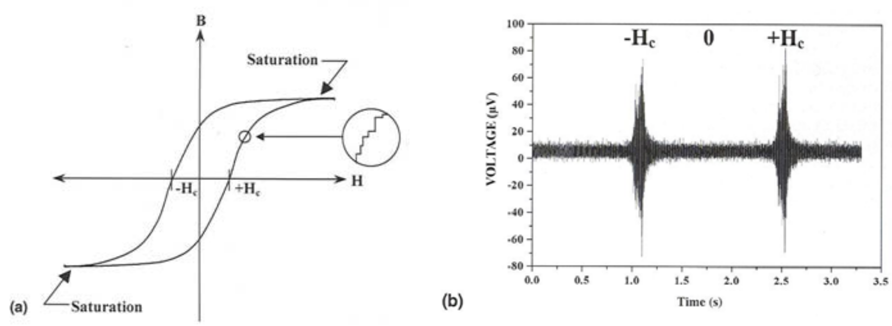


Figure 5. (a) The hysteresis loop of a ferromagnetic material, when magnified, shows that the magnetization increases are abrupt due to the barkhausen jumps. (b) A typical barkhausen spectrum for one complete hysteresis loop plotted as a function of time. [Chopra et al, 2001]

### 3. Methodology

The physical and chemical experiments for this hydrogen research is described in the following sections.

### 3.1. Physical and Chemical Experiments

Development of a non-destructive tool to measure diffusible hydrogen in coated linepipe steel involves extensive calibration of each electromagnetic technique. The specimen preparation and calibration techniques are discussed in the following sections.

The design of this non-contact electromagnetic tool is being performed in collaboration with CANDET (Canadian Non-Destructive Evaluation Testing). CANDET has agreed to build an electromagnetic box unit containing eddy current analysis, magnetic barkhausen noise analysis, and electromagnetic acoustic transducer analysis in one box unit as shown in Figure 6.

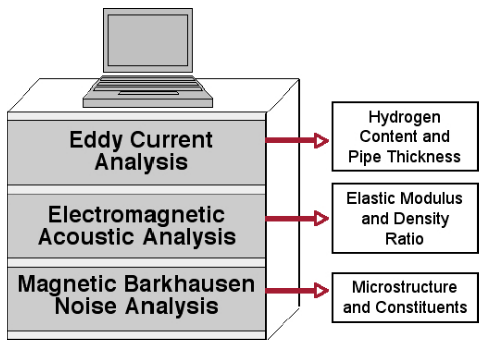


Figure 6: Schematic illustration of box unit containing three different analyses.

#### 3.1.1. Specimen Preparation

Two different sizes of cylindrical specimens are machined out of X80 linepipe steel with dimensions of 4 cm length with a diameter of 0.5 cm and 1 cm length with a diameter of 0.3 cm. Two different X80 specimen sizes are necessary because the specimens will undergo chemical analysis and electromagnetic analysis requiring different specimen sizes. The smaller cylindrical X80 specimens will be used for chemical analysis. Throughout this research, the Leco Hydrogen Determinator will be utilized for calibration and determination of hydrogen content in the smaller specimens. The larger cylindrical X80 specimens will be used for calibration and standardization of the electromagnetic tools. The specimens will be hydrogen charged to different levels of hydrogen contents utilizing a hydrogen charging system located at the Colorado School of Mines.

After the specimens have been hydrogen charged, the specimens are immediately placed into liquid nitrogen to keep the hydrogen from quickly diffusing out of the specimen. The hydrogen content in the specimen must be maintained during standardization and calibration, which necessitates a sample poisoning method. Different poisoning methods will be utilized and experimentally tested to determine the best method for maintaining the hydrogen content in the steel specimens. The poisoning techniques under investigation include cupric sulfate and nickel phosphate coatings and cadmium electroplating. The coated and electroplated samples will be held for 48 hours to allow for hydrogen homogenization. Before electromagnetic analysis, the coatings or electroplating may or may not be removed dependent upon whether the chosen coating effects the electromagnetic measurements.

### 3.1.2. Calibration

The eddy current, EMAT's, and magnetic barkhausen noise analyses require proper calibration. Eddy current analysis will be used to measure the linepipe thickness and hydrogen content. EMAT's will be used to measure the speed of sound as a function of temperature. Magnetic barkhausen noise measures the microstructural features giving elastic release as a function of frequency. The calibration of each tool will be briefly described. It is important to specify that during calibration of each technique, hydrogen is the variable. If any other variables exist during calibration and are unaccounted for, the calibration will be invalid.

Eddy Currents

Eddy currents will be used to analyze both the hydrogen content and the pipeline thickness. Eddy current calibration for determination of hydrogen content involves charging the larger cylindrical specimens to various hydrogen levels and creating a map or database of the change in phase lag with hydrogen shown in Figure 7 (a). Calibration of the eddy current unit for determination of pipe thickness will require eddy current measurements made at various pipe thicknesses to create a map or database for the particular wall thickness at a specific phase lag as shown in Figure 7 (b). The phase lag is important for the determination of hydrogen and thickness, however the phase lag has a complex functionality being a function of conductivity, which directly affects the electron concentration, the effective mass, and scattering sites, but it is also a function of thickness, and alloy content. With knowledge of the presence of these variables it is necessary to employ complimenting techniques to eliminate the variables associated with the linepipe.

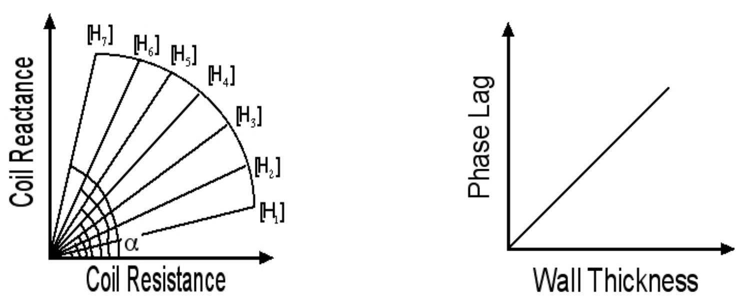


Figure 7: (a) Schematic diagram of coil reactance as a function of coil resistance showing the change in phase lag, $\alpha$, with variations in hydrogen concentration in linepipe steel. (b) Schematic diagram for eddy current measurements of phase lag as a function of wall thickness.

Electromagnetic Acoustic Transducers

EMAT's are to be used for the determination of the speed of sound in the pipeline, which is temperature dependent. The EMAT will be calibrated using the same hydrogen charged specimens discussed earlier in the eddy current section. Hydrogen adsorption affects both the density and the elastic modulus, which are in turn effected by temperature. Each specific hydrogen content will have its own signature temperature-dependent speed of sound, which is then collected into the database.

Magnetic Barkhausen Noise

Magnetic barkhausen noise analysis measures the microstructural features giving elastic release as a function of frequency. There are two ways to perform magnetic barkhausen measurements. The eddy current coil can be used to induce magnetic domain movement and the EMAT can be utilized to listen to the acoustoelastic signal. Another option is to use the magnetic flux generated by the "smart pig", which is already producing its own magnetic barkhausen noise. To calibrate the magnetic barkhausen noise analysis, specimens will be charged to various hydrogen contents and then the magnetic barkhausen noise measurement is made giving a microstructural characterization of the material at the various hydrogen contents. Once again, the data received will be put into an overall database.

So as the eddy current, EMAT, and magnetic barkhausen noise analyses have been performed, the received data is input into the database, which characterizes the steel for its hydrogen content, thickness, speed of sound, and microstructural features. Figure 8 illustrates a plot of the results from the EMAT and magnetic barkhausen noise analyses. From these two analyses, the steel is classified as A, B, C, etc.

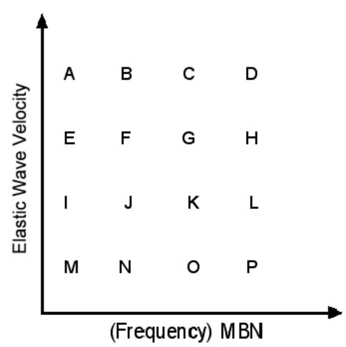


Figure 8: Schematic diagram of linepipe characterization through the elastic wave velocity (from EMAT) as a function of the product of frequency (from MBN) and magnetic barkhausen noise.

The box unit (Figure 6) will be designed to simultaneously perform measurements resulting in an accurate determination of hydrogen content for a given steel class A, B, C, etc. Then the results from Figure 9 will factor out the temperature and microstructural dependence of the phase shift for each particular steel class, so that the hydrogen content can be predicted from the phase shift as shown in Figure 9.

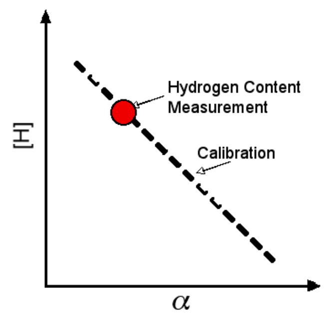


Figure 9: For a given steel class from Figure 9, the hydrogen content is determined from a plot of hydrogen content as a function of the phase shift.

**4. Literature Review**

- **Beachem, C.D., <u>Hydrogen Damage</u>, American Society for Metals, Metals Park, Ohio (1977) pp. ix-xxiii.**

Beachem provides a thorough overview of the most important papers associated with hydrogen damage. The mechanisms of hydrogen assisted cracking are systematically compared and critiqued.

- **Braid, J.E.M., Hyatt, C.V., and Olson, D.L., Vigilante, G.N., <u>Hydrogen Management for Welding Applications</u>, Proc. of Intl. Workshop, Ottawa, Ontario, Canada, (1998), pp.**

<u>Hydrogen Management in Welding Applications</u> is the proceedings of an international workshop on hydrogen. This book includes the latest technology and development of hydrogen detection, consequences, and solutions for weldments.

- **Chopra, H.D., Hicho, G.E., and Swartzendruber, L.J., "Review of the Jumpsum Based Nondestructive Testing Method for Evaluating Mechanical Properties of Ferromagnetic Materials", Materials Evaluation, October, (2001), pp. 1215 – 1222.**

Chopra et al. have provided evidence of the use of magnetic barkhausen noise for evaluation of material properties. This paper is important because once again it experimentally proves the use of MBN for property measurements.

- **Crouch, A.E. and Beuker, T., "In-line Stress Measurement by the Continuous Barkhausen Method", Proc. Of the IPC 2004, Intl. Pipeline Conf., Alberta, Canada, October, (2004), To be published.**

Crouch et al provides a very important aspect for hydrogen research. This paper experimentally proves that magnetic barkhausen noise is capable of stress inspection in coated pipelines. Since these non-destructive tools are based on standardization and calibration, magnetic barkhausen noise can also be utilized for hydrogen assessment in coated linepipe steel. Hydrogen is a form of stress because as hydrogen is induced into the metal matrix it distorts the lattice causing residual strain (stress).

- **Goldstein, L., Klein, R., and Strasser, A., "Evaluation of Nondestructive Hydrogen Detection Methods in Zirconium Alloys", Technical Report, EPRI-TR-100753, Jun 01 (1992).**

Goldstein et al presents the use of eddy currents for determination of hydrogen content in zirconium alloys. This paper is especially important to this research because it provides evidence and support of the use of eddy currents for hydrogen detection.

- **Griffith, J.C., Krotke, R.G., and Everett, B.L., "Large Diameter Piping Examination Using Eddy-Current", Materials Performance, January (1997), pp. 58-63.**


Griffith et al. provides evidence that eddy currents can be utilized for detection of cracks and defects in large diameter piping. This research is important because eddy currents are a function of depth. Larger diameter pipelines will require the use of much lower frequencies that are not yet offered commercially.


- **Lynch, S.P., "Mechanisms of Hydrogen Assisted Cracking – A Review", Intl. Conf. on Hydrogen Effects on Material Behavior and Corrosion Deformation Interactions, Moran, Wyoming, September 16-21, (2001).**


Lynch has played a very important role in hydrogen research. He has provided numerous contributions to the role and mechanisms of hydrogen assisted cracking. This paper is an updated version of his earlier work..


- **Mandal, K., Dufour, D., and Atherton, D.L., "Use of Magnetic Barkhausen Noise and Magnetic Flux Leakage Signals for Analysis of Defects in Pipeline Steel", IEEE Trans., Vol. 35, No. 3, May, (1999), pp. 2007-2017.**


The work of Mandal et al. provides a very important contribution to non-destructive testing research. This paper presents experimental evidence of the use of magnetic Barkhausen noise for defect analysis in pipelines steel. This proves that magnetic Barkhausen noise can be utilized in pipelines and with proper calibration and standarization magnetic barkhausen noise can be utilized for assessment of hydrogen in pipeline steel.


- **Murayama, R., Nakata, Y., Wakibe, Y., Wada, H., Imagawa, Y., and Hayashi, T., "Long Distance Inspection of Pipes Using Electromagnetic Acoustic Transducer for Cylindrical Wave", Materials Volo. 270-273, (2004), pp. 612-618.**


Murayama et al. provides experimental evidence of the use of EMAT's for inspection of gas pipelines. Evidence is provided of the use of cylindrical waves for non-destructive inspection because they can travel long distances through the pipeline without distance attenuation. This research is signficant because it provides support for the use of EMAT's for pipeline inspection, which if properly calibration and standardized can be used for hydrogen detection.


- **Raj, B., Subramanian, C.V., and Jayakumar, T., Non-Destructive Testing of Welds", ASM Intl., Narosa Publishing House, New Delhi, India, (2000), pp. 104-106, 179-185.**


Raj and Jayakumar provide a wealth of knowledge about the latest technology and parameters for non-destructive testing of welds. Many of the same non-destructive techniques can be applied for non-destructive testing for both welds and pipelines.

## 5. Schedule/Time Table

| | TASKS | BEGIN DATE | END DATE |
|---|---|---|---|
| **1** | Hydrogen charging of specimens and determination of the best coating for maintaining hydrogen in X80 steel. | **March 15, 2005** | **April 15, 2005** |
| **2** | Development of box unit containing eddy current, EMAT, and MBN with ANDEC | **Feb. 1, 2005** | **May 1, 2005** |
| **3** | Visit LANL for course on NDT | **June 1, 10025** | **July 1, 2005** |
| **4** | Calibration of eddy current unit for thickness and hydrogen content | **May 1, 2005** | **June 1, 2005** |
| **5** | Calibration of EMAT unit for elastic modulus and density ratio as a function of temperature | **May 1, 2005** | **June 1, 2005** |
| **6** | Calibration of MBN unit for microstructure and constituents | **May 1, 2005** | **June 1, 2005** |
| **7** | Begin measurements on X80 steel cylindrical specimens | **June 1, 2005** | **August 1, 2005** |
| **8** | Thesis Defense | **Dec. 2005** | **-** |
| **9** | Begin measurements on in-service X80 steel pipelines | **Jan. 1, 2006** | |

**Fundamental Questions**

- Can electromagnetic non-destructive, non-contact techniques be developed to assess the hydrogen content in high strength pipeline steel?
- Will it require a combination of techniques to achieve this non-destructive hydrogen assessment due to the many dependent variables e.g. temperature, microstructure, etc.?
- What will be the limitations to implementing NDE non-contacting electromagnetic tools for in-service oil and gas pipelines e.g. weight, robustness of electronic tools, operator skills, variations in steel product, service environment?
- What level of data acquisition will be required for either active or passive electromagnetic sensing?