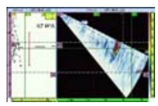
Corrosion

Discovery and Assessment Using Non-Destructive Techniques and Methods





Presentation Outline

- Essentials for developing a corrosion monitoring program.
- The need for a comprehensive corrosion monitoring program.
- Tools for monitoring corrosion.
- Example of a corrosion monitoring program.

Program Development

- Essentials for developing a corrosion monitoring program.
  - Understanding of the process stream.
  - Identification of known and potential contaminants.
  - Identification of known and potential degradation mechanisms.
  - Assessment of metallurgy, configuration, design, and other mechanical properties that may impact corrosion severity and its location.
  - Assessment of actual and/ or anticipated upset conditions that may effect corrosion type, severity and location.

Why monitor corrosion?

- The need for a comprehensive corrosion monitoring program:
  - Safety
  - Reliability
  - Extension of asset life (increased ROI)
  - Flexibility of fixed assets
  - Planning
  - Overall management of HSE risk

Tools: Presentation Format

- Tools to be used in a corrosion monitoring program discussed as follows:
  - Basic Theory
  - Application
  - Discovery / Assessment Capability
  - Cost
  - Conclusion
  - Discussion of degradation mechanisms that tool is effective in monitoring and applications in the oil sands industry.

UT Thickness

- Tool:
  Digital Ultrasonic Thickness Gauge
  - Theory
    - Apply voltage pulse to piezoelectric material
    - Induce energy (sound wave) and listen for the echo
    - Time of flight indicates thickness
    - Factors: Temperature, consistency, curvature

UT thickness

- Application
  - Metals, plastics, composites, ceramics, and glass.
  - On-line or in-process measurement of extruded plastics and rolled metal is often possible, as is measurement of individual layers or coatings in multilayer fabrications.
  - Liquid levels and biological samples can also be measured.
  - Materials that are generally not suited for conventional ultrasonic gauging include wood, paper, concrete, fiberglass, and foam products

UT thickness

- Discovery/ Assessment
  - Corrosion Type:
    - General/ Uniform Wall Loss
      - Discovery: Locate and measure general / uniform wall loss.
      - Assessment: Provides quantitative data for assessment of corrosion severity.
    - Localized Wall Loss
      - Discovery: Ineffective for detecting localized corrosion. When combined with a comprehensive corrosion assessment program discovery capability can be greatly increased.
      - Assessment: Provides quantitative assessment of identified locally corroded areas.
    - Mid-Wall:
      - Discovery - Limited capability to discover and/ or assess mid- wall conditions.
      - Assessment – Limited assessment capability.

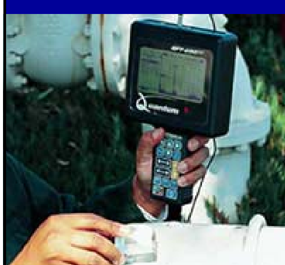
UT thickness

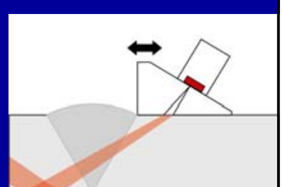
- Cost:
  - Very low in basic application, increases proportional to complexity.
- Conclusion:
  - The basic building block for any comprehensive corrosion monitoring program designed to evaluate large volumes of surface areas of all types of plant equipment.
  - Effectiveness largely dependant on level of supporting input.
  - Simple technique can be employed by technicians with minimal experience and basic training (level I).

UT Flaw Detection

- Tool
  - Ultrasonic Flaw Detector
    - Theory – Usually uses angle beam (shear wave) for better sensitivity
    - Application - detect and evaluate flaws inside component
    - Weld examination

UT Flaw Detection





UT Flaw Detection

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      - Assessment: Provides quantitative assessment of identified locally corroded areas.
    - Mid-Wall:
      - Discovery - Detection of voids, cracks, lack of weld fusion, incomplete weld filling, etc.
      - Assessment – Provides quantitative measurement / estimate of depth and size of flaw.

UT Flaw Detection

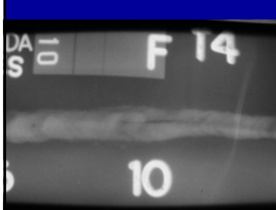
- Cost:
  - Low in basic application, increases proportional to complexity.
- Conclusion:
  - An excellent tool to assess small to moderately sized areas.
  - Ability to scan and query using a variety of probes.
  - Requires more experienced technician (level II) to adequately/ accurately evaluate/ size/ classify.

Radiographic Testing (RT)

- Tool
  - Conventional Radiographic Testing (Industrial Radiography)
    - Theory
      - Photon source (high energy photons penetrate test material)
        - » Isotope (Ir-192, Co-60, Cs-137, others)
        - » X-Ray Tube
      - Film exposed by penetrating photons
        - » Image represents amount of radiation emerging from opposite side of test piece
        - » Image intensity used to measure thickness/ identify defect
      - Image Negative
        - » White = more radiation
        - » Black = less radiation

Radiographic Testing (RT)

- Application
  - Can be used on any and all materials



Radiographic Testing (RT)

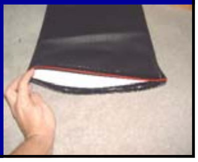
- Discovery/ Assessment
  - Corrosion Type:
    - General/ Uniform Wall Loss
      - Discovery: Good tool for locating general/ uniform wall loss.
      - Assessment: Acceptable tool for assessing wall loss provided proper procedures are strictly adhered to. Provides qualitative-to- semi-quantitative data for the assessment of corrosion severity.
    - Localized Wall Loss
      - Discovery: Good tool for detecting localized corrosion.
      - Assessment: Acceptable tool for assessing wall loss provided proper procedures are strictly adhered to. Provides qualitative-to- semi-quantitative assessment of identified locally corroded areas.
    - Mid-wall
      - Discovery: Limited
      - Assessment: Limited

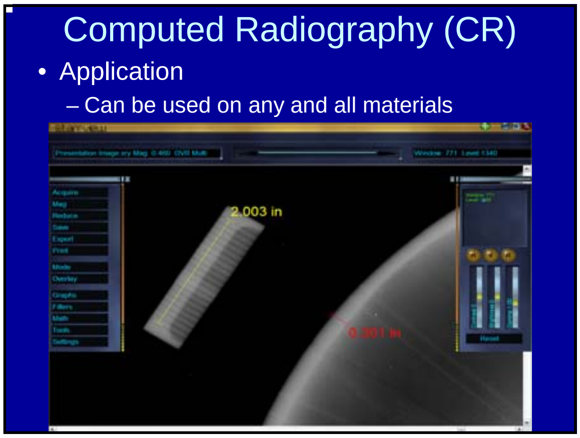
Radiographic Testing (RT)

- Cost:
  - Low-to-moderate in basic application.
- Conclusion:
  - Good tool for examining areas of potential localized corrosion.
  - Provides actual picture (film negative) of item/ area inspected.
  - Quantitative results generally require supporting methods (manual UT) for qualitative assessment of findings.
  - Large area must be evacuated due to radiation concerns.
  - Safety concerns surrounding the use of nuclear source.
  - Generally performed at night due to need for evacuation, increasing safety concerns and cost.
  - Relatively slow due to radiation control and film processing.
  - Size limitations.
  - The following quote is from an OSHA HSE study:
    - "Industrial radiography appears to have one of the worst safety profiles of the radiation professions, possibly because there are many operators using strong gamma sources (> 2 Ci) in remote sites with little supervision when compared with workers within the nuclear industry or within hospitals."

Computed Radiography (CR)

- Tool
  - Computed Radiography (Digital Radiography)
    - Theory
      - Photon source (high energy photons penetrate test material)
        - » Isotope (Ir-192, Co-60, Cs-137, others)
        - » X-Ray Tube
      - Image plate exposed by penetrating photons
        - » Image represents amount of radiation emerging from opposite side of test piece
        - » Image intensity used to measure thickness/ identify defect
      - Image Negative or Positive




Computed Radiography (CR)
• Application
– Can be used on any and all materials
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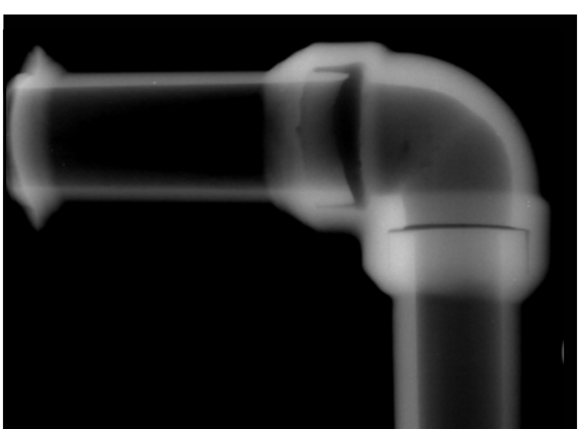
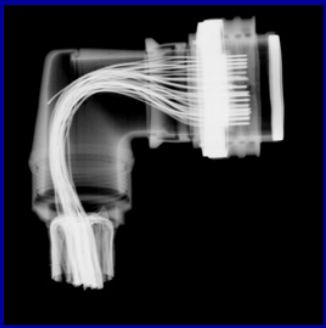


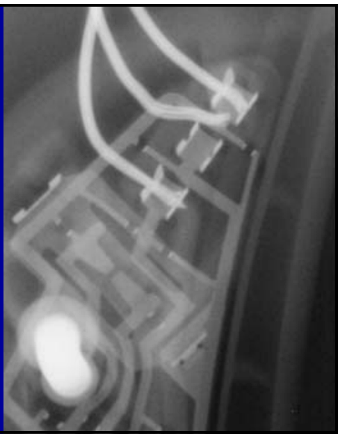
Computed Radiography (CR)

- Discovery/ Assessment
  - General/ Uniform Wall Loss
    - Discovery: Good tool for locating general/ uniform wall loss.
    - Assessment: Acceptable tool for assessing wall loss provided proper procedures are strictly adhered to. Provides qualitative-to- semi-quantitative data for the assessment of corrosion severity.
  - Localized Wall Loss
    - Discovery: Good tool for detecting localized corrosion.
    - Assessment: Excellent tool for assessing wall loss provided proper procedures are strictly adhered to. Provides qualitative-to- semi-quantitative assessment of identified locally corroded areas.
  - Mid-wall
    - Discovery: Acceptable
    - Assessment: Good

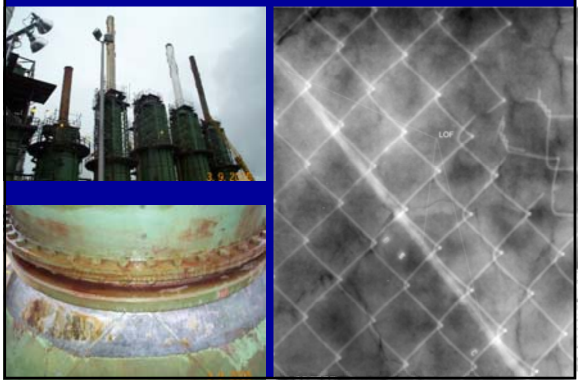
Computed Radiography (CR) Broken wire



Computed Radiography - Wire Separation



Computed Radiography - Stack

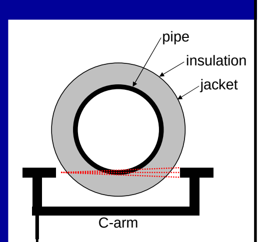


Computed Radiography (CR)

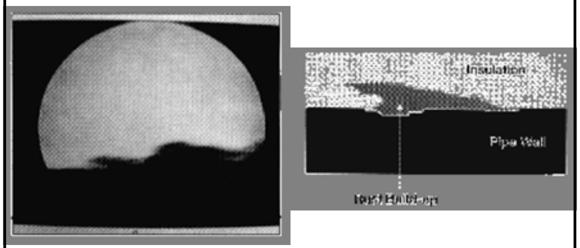
- Inspection Method: Computed Radiographic Testing
  - Cost: Low-to-moderate in basic application (comparable to film radiography).
  - Conclusion:
    - Requires less exposure time.
    - In many instances production with CR will be greater than with conventional radiography.
    - Image can be viewed as a whole.
    - Tools allow for quantitative assessment.
    - Electronic archiving.

Real-time Radiography (RTR)

- Tool
  - Real-Time Radiography
    - Theory – Same as for conventional and digital radiography, except that image is captured "real time" and displayed on a monitor.
    - Application – Can be used on insulated lines and very thin wall components.



Real-time Radiography (RTR) Corrosion Under Insulation



Source:
Inspection Techniques for Detecting Corrosion Under Insulation
by Michael Twomey, *Materials Evaluation*, Vol. 55, No. 2, Feb 1997, pp. 129–132.

Real-time Radiography (RTR) - Security

Real-time Radiography (RTR)

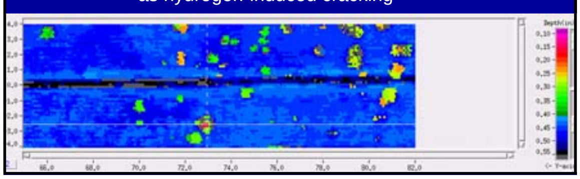
- Discovery/ Assessment
  - General/ Uniform Wall Loss
    - Discovery: Little to no ability to locate general/ uniform wall loss.
    - Assessment: Little to no ability to assess general/ uniform wall loss.
  - Localized Wall Loss
    - Discovery: Good tool for detecting localized corrosion – external only.
    - Assessment: Good tool for assessing external localized corrosion. Assessment is strictly qualitative.
  - Mid-wall
    - Discovery: None
    - Assessment: None

Real-time Radiography (RTR)

- Cost: Moderate
- Conclusion:
  - Very good tool for inspecting piping for corrosion under insulation.
  - Excellent tool for locating welds under insulation.
  - Image can be viewed in real time.
  - Image can be archived electronically.

Automated UT (AUT)

- Tool
  - Automated Ultrasonics (C-Scan)
    - Theory
      - Computer-controlled scan
      - Measure thickness over a surface
      - Use shear wave to detect smaller defects such as hydrogen-induced cracking



Automated UT (AUT)

- Application
  - Pipes, vessels, tanks
  - Corrosion mapping (0-degree thickness)
  - Laminations, corrosion, cracking
  - Bond integrity
  - Shear-wave for plate and welds
  - Multi-channel for advanced HIC and other service-related damage

Automated UT (AUT)

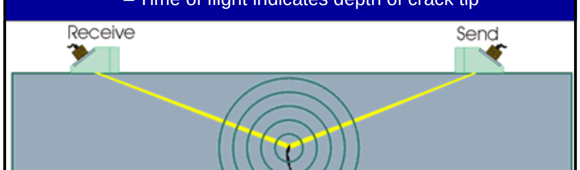
- Discovery/ Assessment
  - General/ Uniform Wall Loss
    - Discovery: Locate and measure
    - Assessment: Quantitative
  - Localized Wall Loss
    - Discovery: Locate and measure. For thickness measurement, need a flat reflector face. Shear wave (angle beam) more sensitive.
    - Assessment: Quantitative
  - Mid-wall
    - Discovery: Locate and measure
    - Assessment: Quantitative

Automated UT (AUT)

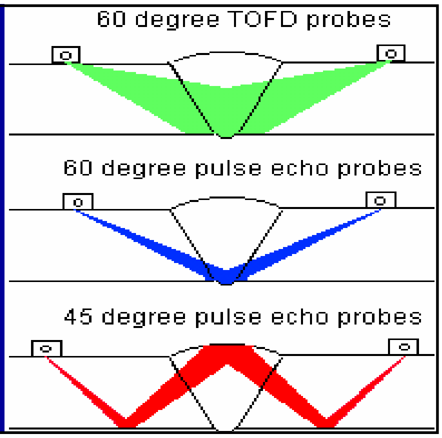
- Cost:
- Conclusion:
  - Complete coverage
  - Recorded data
  - Trending of thickness and crack growth
  - Repeatable year by year

Time of Flight Diffraction (TOFD)

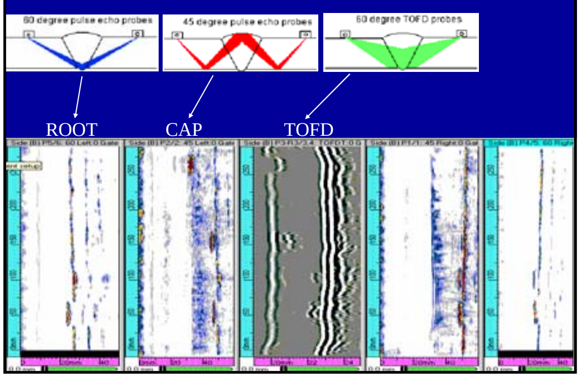
- Tool
  - Time of Flight Diffraction
    - Theory
      - Two probes in send-receive configuration
      - Crack tips emit a diffracted signal
      - Time of flight indicates depth of crack tip



TOFD / Pulse-Echo probe combos



TOFD P/E Weld Data



Time of Flight Diffraction (TOFD)

- Application
  - Developed for the British Nuclear Industry
  - Used for sizing and trending cracks in welds
  - Works for OD, ID, and mid-wall cracks
  - Wall thickness > ½ inch
  - Pressure vessels and tank walls
  - Used in conjunction with pulse-echo to cover root & cap

Time of Flight Diffraction (TOFD)

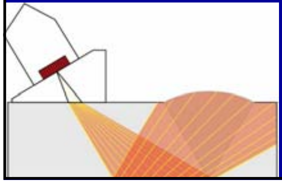
- Discovery/ Assessment
  - General/ Uniform Wall Loss
    - Discovery: Detectable using TOFD
    - Assessment: Accuracy comparable to conventional UT
  - Localized Wall Loss
    - Discovery: Detectable by reflection from top face
    - Assessment: Accuracy comparable to conventional UT
  - Mid-wall
    - Discovery: More sensitive than conventional UT
    - Assessment: Flaw depth and size typically within 0.5 mm in through-wall direction.

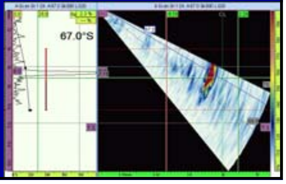
Time of Flight Diffraction (TOFD)

- Cost:
  - Cover a typical 50-foot weld in one day (RT two days)
- Conclusion:
  - Magnetic buggy runs probes along length of weld
  - Accurate and sensitive weld examination

Phased Array Ultrasonics

- Tool
  - Phased Array Ultrasonics
    - Theory
      - Beam is steered electronically
      - Instantly floods weld with sound
      - Creates a sector scan (slice view)

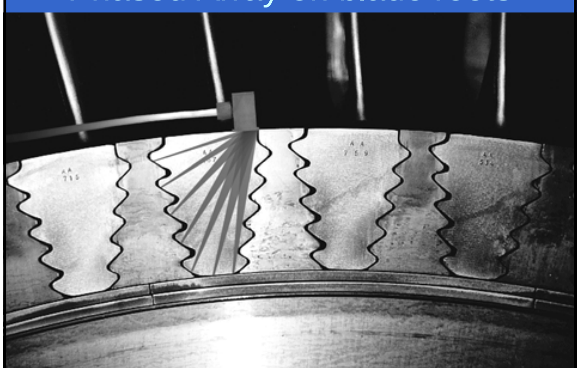




Phased Array Ultrasonics

- Application
  - Weld examination in piping and fabrication
  - Hydrogen-Induced Cracking
  - Complex geometries e.g. turbine blade roots

Phased Array on blade roots



Moles and Zhang, Materials Evaluation Jan 2005

Phased Array Ultrasonics

- Discovery/ Assessment
  - General/ Uniform Wall Loss
    - Discovery: Set beam at 0° for detection
    - Assessment: Quantitative measurement
  - Localized Wall Loss
    - Discovery: Sensitive and effective
    - Assessment: Evaluate flaw on Sector-scan
  - Mid-wall
    - Discovery: Sensitive and effective
    - Assessment: Evaluate flaw on Sector-scan

Phased Array Ultrasonics

- Cost:
  - Productivity approximately 1.5 times that of RT.
- Conclusion:
  - Weld examination with no need to evacuate area as with RT
  - Requires UT level II technicians with advanced training

Guided wave UT

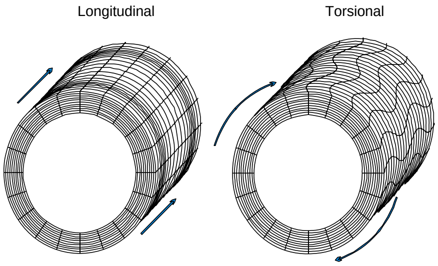
- Tool
  - Long / Guided Wave Ultrasonics
    - Theory
      - A "Guided wave" is an ultrasonic beam restricted to within a thin object such as a pipe wall
      - Collar is applied to pipe, sends ultrasonic beam along pipe
      - Can also send beam through bottom of pipe from top position
      - Problem areas: fittings, corrosion shadow, high-density bonded coating, packed earth or concrete, sleeves

Guided wave UT

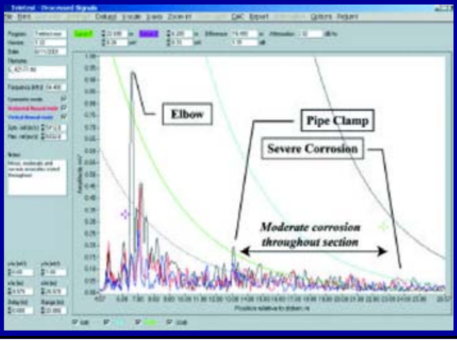
Guided wave UT

Wavemaker Pipe Screening System by Guided Ultrasonics Ltd.

Guided wave UT- modes



Guided wave UT



Guided wave UT

- Application
  - thermally insulated, coated, and buried pipe work; road-crossings
  - corrosion under pipe supports
  - detection of hidden welded joints
  - petrochemical process pipe work
  - oil and gas transmission lines
  - jetty lines
  - power station boiler tubes.

Guided wave UT

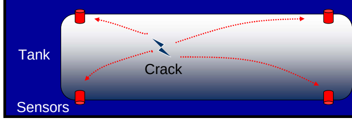
- Discovery/ Assessment
  - General/ Uniform Wall Loss, Localized Wall Loss, and Mid-wall:
    - Discovery: Damage with more than 5% loss of cross-sectional area returns reflection
    - Assessment: Operation and interpretation highly operator dependent

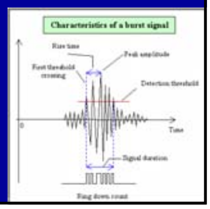
Guided wave UT

- Cost:
- Conclusion:
  - No need to remove paint
  - Only need to remove a narrow ring of insulation for transducer application
  - Up to 50 meters tested to either side of a transducer ring
  - Typically 100 meters of pipe inspected from a test position

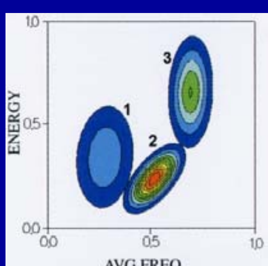
Acoustic Emission

- Tool
  - Acoustic Emission Testing
    - Theory
      - Changing applied load causes crack deformation at high-stress areas - "AE events"
      - Sound propagates from "AE events" to sensors
      - Defect position obtained by triangulation
      - Defect type obtained by "fingerprint" on energy vs. frequency plot (next slide)



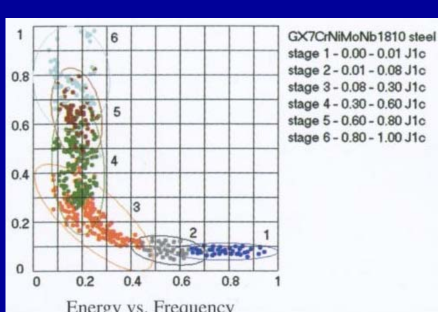


Acoustic Emission "fingerprinting"



1. Creep
2. Background noise
3. Micro crack

Acoustic Emission Danger-Level evaluation



Acoustic Emission

- Application
  - NDT of heavily mechanically stressed components or complete structures
  - Tank floors
  - Plant lines: hot reheat, main steam, cold reheat, water feed
  - Hangers and support performance
  - Monitoring line integrity

Acoustic Emission

- Discovery/ Assessment
    - General / Uniform Wall Loss
    - Localized Wall Loss
    - Mid-wall
    - Early stage detection for most failure mechanisms

Acoustic Emission

- Cost:
  - As low as 10% of current NDE Cost for some jobs
- Conclusion:
  - In-service examination
  - Inspection of entire line length
  - No scaffolds
  - No insulation removal

Tubular Electromagnetic NDE

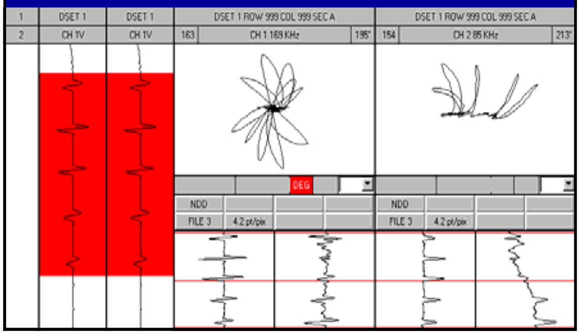
- Tool
  - Eddy Current / Remote Field/ Magnetic Flux Leakage Testing
    - Theory
      - Magnetic field is applied to tube wall.
      - Defects create a response field
      - Response is measured for amplitude and time lag to characterize depth or volume of metal loss

Tubular Electromagnetic NDE

- Application
  - Eddy current testing (ECT)
    - Heat exchangers.
    - Non-ferromagnetic materials such as copper, brass, cupronickel
  - Remote field testing (RFT)
    - Heat exchangers and boilers. Steel tubes and pipes
    - Interpretation challenging due to inconsistent magnetic properties of pipe
  - Magnetic Flux Leakage (MFL)
    - Steel tubes and pipes (generally less accurate than RFT)

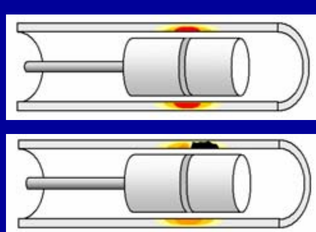
Tubular Electromagnetic NDE

Tubular Electromagnetic NDE



Tubular Electromagnetic NDE

- Eddy current testing: crack interrupts flow of eddy currents



Tubular Electromagnetic NDE

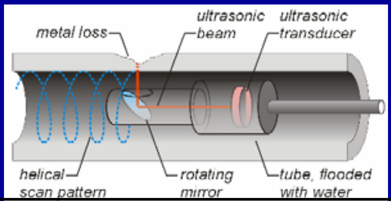
- Discovery/ Assessment
  - General/ Uniform Wall Loss
    - Discovery: Locate and measure
    - Assessment: Quantitative measurement with good reference standard
  - Localized Wall Loss
    - Discovery: Eddy current very effective. Remote field and flux leakage adequate.
    - Assessment: Quantitative with eddy current. Volumetric with remote field and flux leakage
  - Mid-wall
    - Discovery: Only volumetric flaws. Eddy current, when flaw interrupts circumferential currents.
    - Assessment: Qualitative

Tubular Electromagnetic NDE

- Cost:
- Conclusion:
  - Pull speed
    - eddy current 2 - 5 foot per second
    - remote field 1 fps
  - Plug damaged tubes to keep component operating at peak

Internal Rotating Inspection System

- Tool
  - Internal Rotating Inspection System (IRIS)
    - Theory
      - Rotating mirror directs ultrasonic beam into tube wall



Internal Rotating Inspection System

- Application
  - Metallic tubes, ID 0.5 to 8 inches
  - Compared to electromagnetic methods, very slow but very accurate (pull speed 1 inch per second, wall thickness accuracy ± 0.005 inch)

Internal Rotating Inspection System

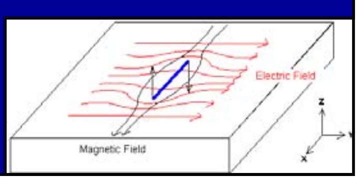
- Discovery/ Assessment
  - General/ Uniform Wall Loss
    - Discovery: locate and measure thickness or cracks oriented right-angles to beam
    - Assessment: quantitative
  - Localized Wall Loss
    - Discovery: insensitive to small pits
    - Assessment: measures depth of reflectors
  - Mid-wall
    - Discovery: locate and measure
    - Assessment: quantitative

Internal Rotating Inspection System

- Cost:
- Conclusion:
  - Commonly used as a follow-up to remote field testing on selected tubes (e.g. 10 out of 1000)
  - For IRIS, tubes must be cleaned to bare metal
  - Supply of clean water required to flood tubes

Alternating Current Field Measurement

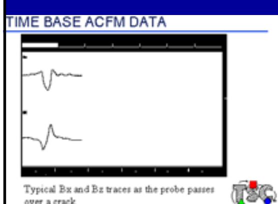
- Tool
  - Alternating Current Field Measurement (ACFM)
  - Theory
    - Induce surface eddy currents in steel with coil
    - Surface-breaking cracks disrupt flow of eddy currents
    - Measure magnetic field to obtain depth of crack

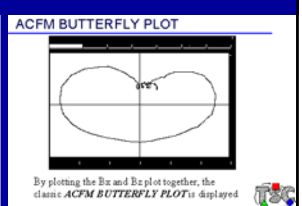


Alternating Current Field Measurement

- Application
  - Developed for offshore & underwater NDE
  - Detect surface-breaking cracks in welds in metals
  - Works through coating
  - Often replaces wet flourescent magnetic particle
  - Industries: civil engineering, nuclear, offshore, petrochemical, power, theme parks

Alternating Current Field Measurement





Alternating Current Field Measurement

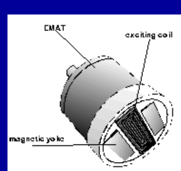
- Discovery/ Assessment
  - General/ Uniform Wall Loss
    - Discovery: Insensitive
    - Assessment: none
  - Localized Wall Loss
    - Discovery: Sensitive to surface-breaking cracks
    - Assessment: Quantitative measure of crack depth along crack face (less accurate for slanted cracks)
  - Mid-wall
    - Discovery: Insensitive
    - Assessment: none

Alternating Current Field Measurement

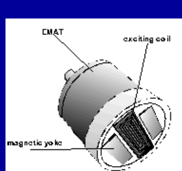
- Cost:
- Conclusion:
  - Fast compared to magnetic particle: welds done at hand-scanning speed
  - Sizes cracks of depth from 0.125 to 1 inch
  - Recorded data
  - Most common application: steel.
  - High-frequency probes available for titanium, stainless steels, etc.

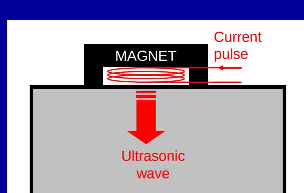
Electromagnetic Acoustic Transducer

- Tool
  - Electromagnetic Acoustic Transducer (EMAT)
    - Theory
      - Probe with magnet and coil applies an electromagnetic pulse to steel which creates an ultrasonic wave.
      - Return ultrasonic wave (echo) creates electromagnetic pulse, which is detected.



Electromagnetic Acoustic Transducer





Electromagnetic Acoustic Transducer

- Application
  - Thickness Measurement
  - Weld inspection
  - High temperature inspection
  - Automated inspection
  - Inspection with rough surfaces or minimal surface preparation

EMAT FST gauge®

Electromagnetic Acoustic Transducer

- Discovery/ Assessment
  - General/ Uniform Wall Loss
    - Discovery: Locate and measure
    - Assessment: Quantitative
  - Localized Wall Loss
    - Discovery: Locate and measure with shear wave
    - Assessment: Quantitative
  - Mid-wall
    - Discovery: Locate and measure with shear wave
    - Assessment: Quantitative

Electromagnetic Acoustic Transducer

- Cost:
- Conclusion:
  - Requires no couplant
  - High speed scanning
  - Non-contact; rough surfaces OK; minimal probe wear
  - Variety of wave modes
  - Thickness in ferromagnetic and bimetallic tubes
  - Hydrogen damage detection
  - Pit detection and sizing
  - Corrosion fatigue crack detection

Corrosion Monitoring: an Example

- Example of a well developed corrosion monitoring program:
  - Sour Water Corrosion Monitoring:
    - Facts:
      - Relatively benign in low velocity, constant temperature stream where a protective sulfide film forms on the line to protect from corrosion.
      - Corrosion rates significantly increase with increasing stream velocity – at velocities > 20 ft./second corrosion rates may increase by the measure of 1 X 10^{4}.
      - Carries suspended particles that may fall out of solution when changes to stream occur.
      - More severe in vapor phase.
      - May cause secondary corrosion in the form of:
        - » Erosion and Erosion/ Corrosion
        - » Under Deposit Pitting
        - » Corrosion in Condensed Acids

Corrosion Monitoring: an Example

- Corrosion Monitoring Program for Sour Water Equipment:
  - Assess process stream velocity, pressure, and temperature.
  - Assess mechanic design and determine areas where:
    - localized elevated stream velocities may occur.
    - Temperature changes may occur.
    - Process flow may be disrupted (I.e. localized turbulence or cavitation)
    - Pressure may change.
  - Assess previous inspection history or industry data on similar streams.

Corrosion Monitoring: an Example

- Straight Run: Assign random points along areas with low velocity and minimal turbulence. Predominant focus in vapor phase.
- Elbows: Locate elbows where sweep results in localized increases in velocity. Assign multiple points at areas with localized velocity increase (erosion and erosion-corrosion). Assign bands of points upstream of elbow (turbulence – erosion and erosion-corrosion and UDP from solids released during pressure drop).

Corrosion Monitoring: an Example

- Other fittings – similar to elbows.
- Stagnant areas and dead legs: Assign multiple points or grids (corrosion in condensed acids, UPD)
- Areas where there are external attachments and supports. Assign multiple points, grids or scans in vicinity (corrosion in condensed acids).
- When there is evidence of, or history of corrosion, closely examine potential collection areas in equipment downstream due to potential high levels of FeO_2 (UDP, CICA)

Wrap-up

- No tool is a "do it all"
- Tools are mutually supporting and should be used in combinations that allow the greatest return on inspection dollars invested.
- The consequence of failure will generally drive the complexity of the corrosion monitoring program.
- The NPRA estimates the cost of scheduled vs. unscheduled downtime to be 1:16.
- Properly developed and executed corrosion monitoring programs, utilizing the appropriate tools can reduce unscheduled downtimes and reduce SHE exposure.
- Properly developed and executed corrosion monitoring programs, utilizing the appropriate tools are a good investment with potential returns on investment of $16 for every $1 invested.