Magnetostrictive Transducers for Guided Wave Testing and SHM of Pipes, Tank Walls, Tank Bottoms, Steel Ropes, Buried Anchor Rods and Heat Exchanger Tubing

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International Conference and Exhibition on NDE

Corinthians Club & Resort, Pune, India

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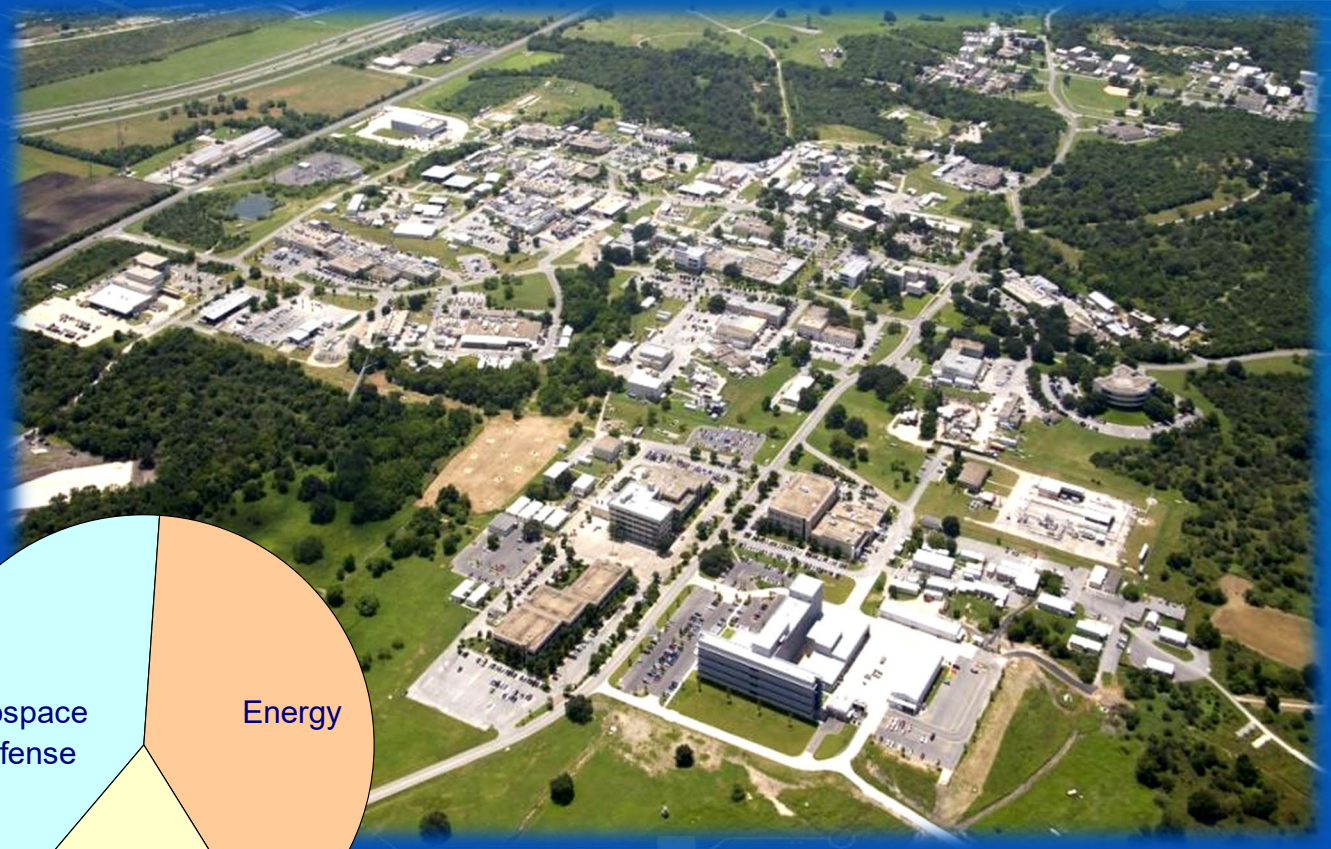
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Agenda

- Southwest Research Institute Overview
- Long-Range Ultrasonic Guided Wave Introduction
- Magnetostrictive Sensors Physics
- Application Examples of Magnetostrictive Sensors
  - Steel Ropes
  - Pipe Inspection
  - SHM of Pipes
  - SHM of Pipes Operating at Elevated Temperature
  - Buried Anchors
  - Boiler Tubes
  - Automated Scanners for Storage Tanks Walls
  - Omni-Directional Scan of Buried Electrical Poles
  - Heat Exchanger Tube Inspection
  - Storage Tank Bottom Inspection

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SwRI® Overview



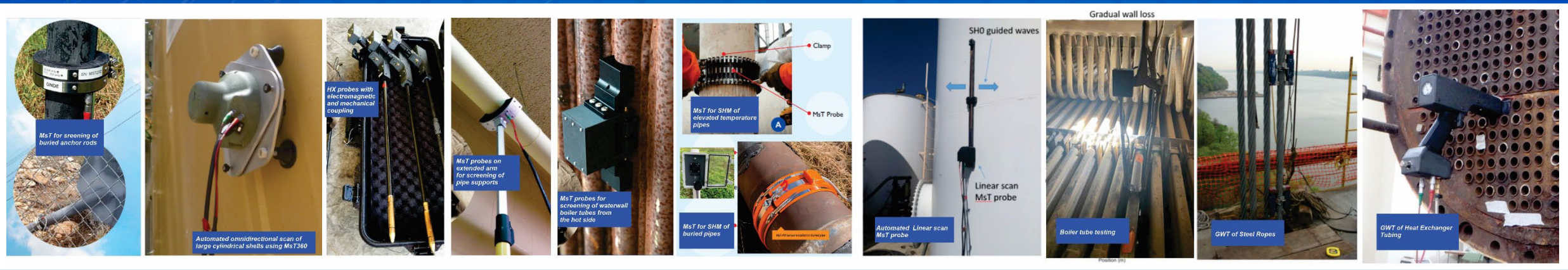
- Founded in 1947
- Nonprofit
- Today over 3,000 employees
- Revenue in 2022: $726 million
- Over 1,200 acres / 4.86 km^2 facility in San Antonio, Texas
- 2.2 million ft^2 / 204,400 m^2 of laboratories & offices
- Over 1,235 patents
- 40 *R&D 100* awards
- Applied RDT&E services
- Physical sciences & engineering
- Broad technological base
- Capital intensive operation

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NDE Using Long-Range Ultrasonic Guided Waves

- Guided waves are special types of waves that exist when the wavelength is on the order or larger than one of the principle component dimensions (e.g., plate thickness)
  - Allows the structure to act as a wave guide, meaning the wave propagation is guided by the structure boundaries
  - Waves propagate along the structure and can go around curves
  - Typical test frequencies in the range of 10 – 1000 kHz

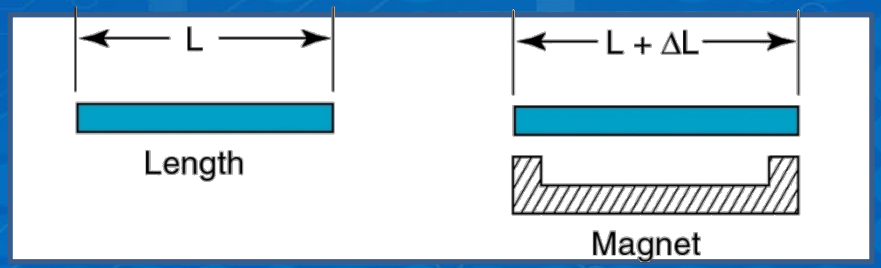
- Use of guided waves for NDE began only in the last few decades
  - Better understanding of wave mechanics and increase computing power available allowed their adoption
  - New transducer designs resulted in more mode selectivity to simplify analysis
  - Also, it triggered development of a large number of niche guided wave applications



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Magnetostrictive Sensor Physics: Joule Effect

- Magnetostriction is the physical phenomena of some materials to change shape when magnetized
  - Joule magnetostriction – Length change in same direction as field

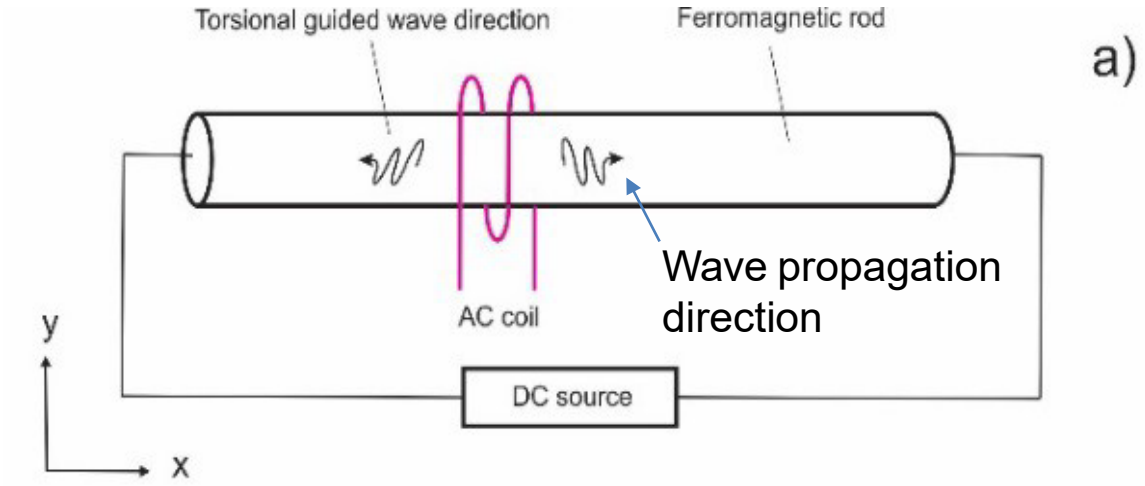


- Other strain directions (torsional) and inverse effects exist known as Wiedemann effect (WE)
- Alternative implementations of WE:
  - Permanent circumferential field (propagation perpendicular to this bias) – the conventional WE
  - Time-varying circumferential field (propagation parallel to the axial bias) – a reversed WE
- What makes the difference in sensor design is how these two coils are oriented in the wave propagation direction.

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Magnetostrictive Sensor Physics: Wiedemann Effect

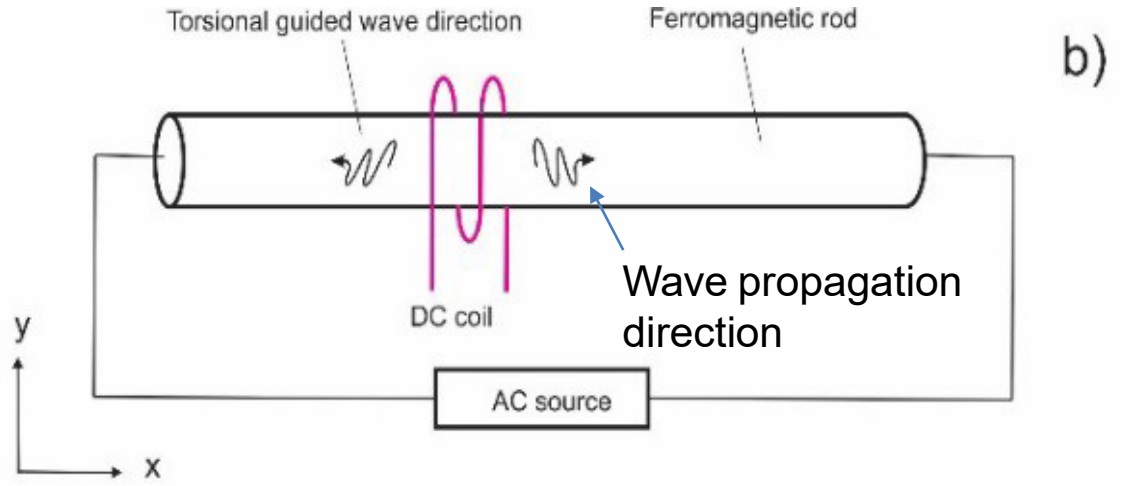
Direct Wiedemann Effect



Mutual orientation of torsional wave and magnetic fields under direct Wiedemann effect

	Permanent magnetic bias direction	Time-varying magnetic field direction
Direction of Torsional wave propagation	Perpendicular	Parallel

Reversed Wiedemann Effect

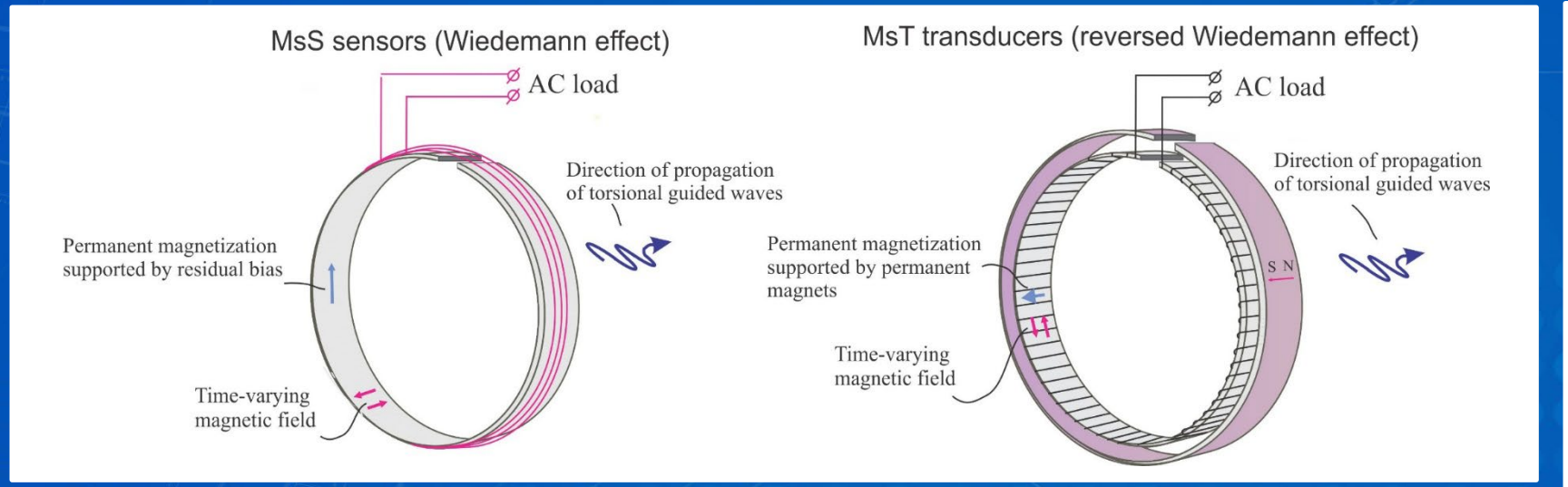


Mutual orientation of torsional wave and magnetic fields under reversed Wiedemann effect

	Permanent magnetic bias direction	Time-varying magnetic field direction
Direction of Torsional wave propagation	Parallel	Perpendicular

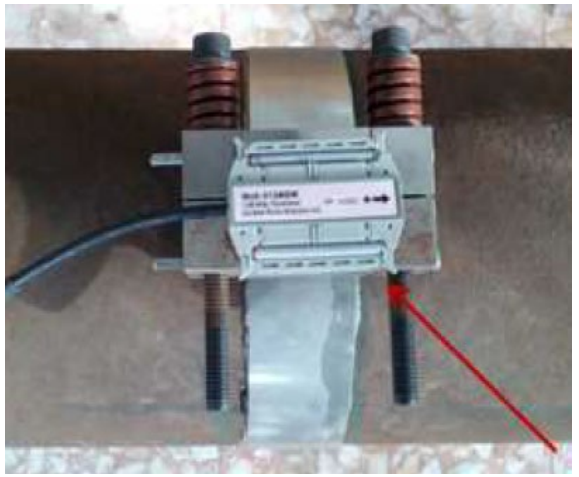
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Magnetostrictive Transducers Design for Pipe Applications



- AC coil wound around FeCo strip
- Array of small permanent magnets or residual biasing provides in-plane static magnetization of strip
- Coil generates high amplitude AC magnetic field
- 10 – 500 kHz frequency range for Torsional guided wave modes
- Known and stable beam characteristics
- Applicable to magnetic and non-magnetic materials

MsS for Pipes



MsTs for Pipes



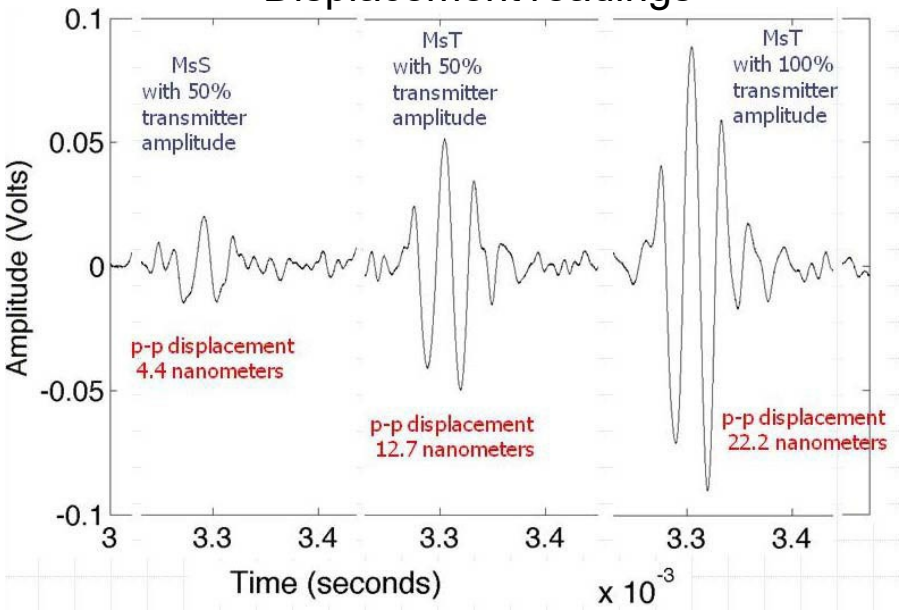
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Unique Features of Reversed Wiedemann Effect Transducers (MsT)

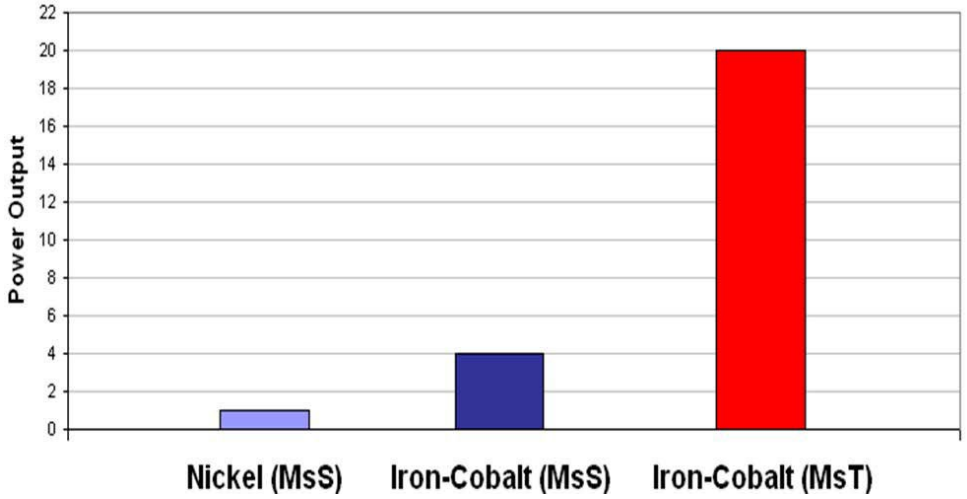
Sensors test



Displacement readings



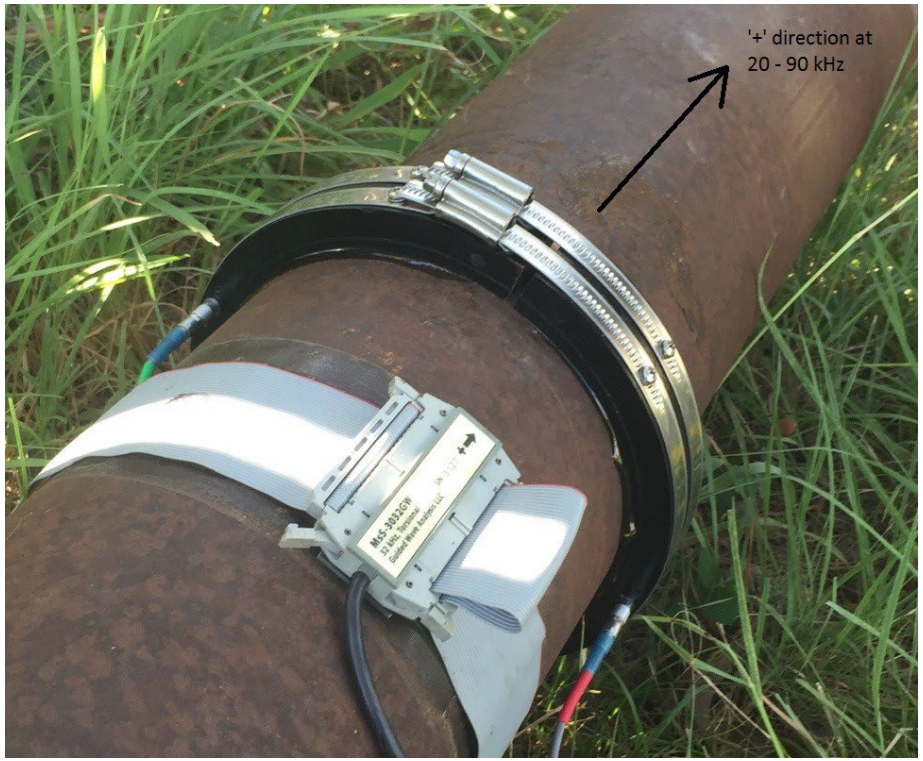
Amplitude gain MsS - MsT

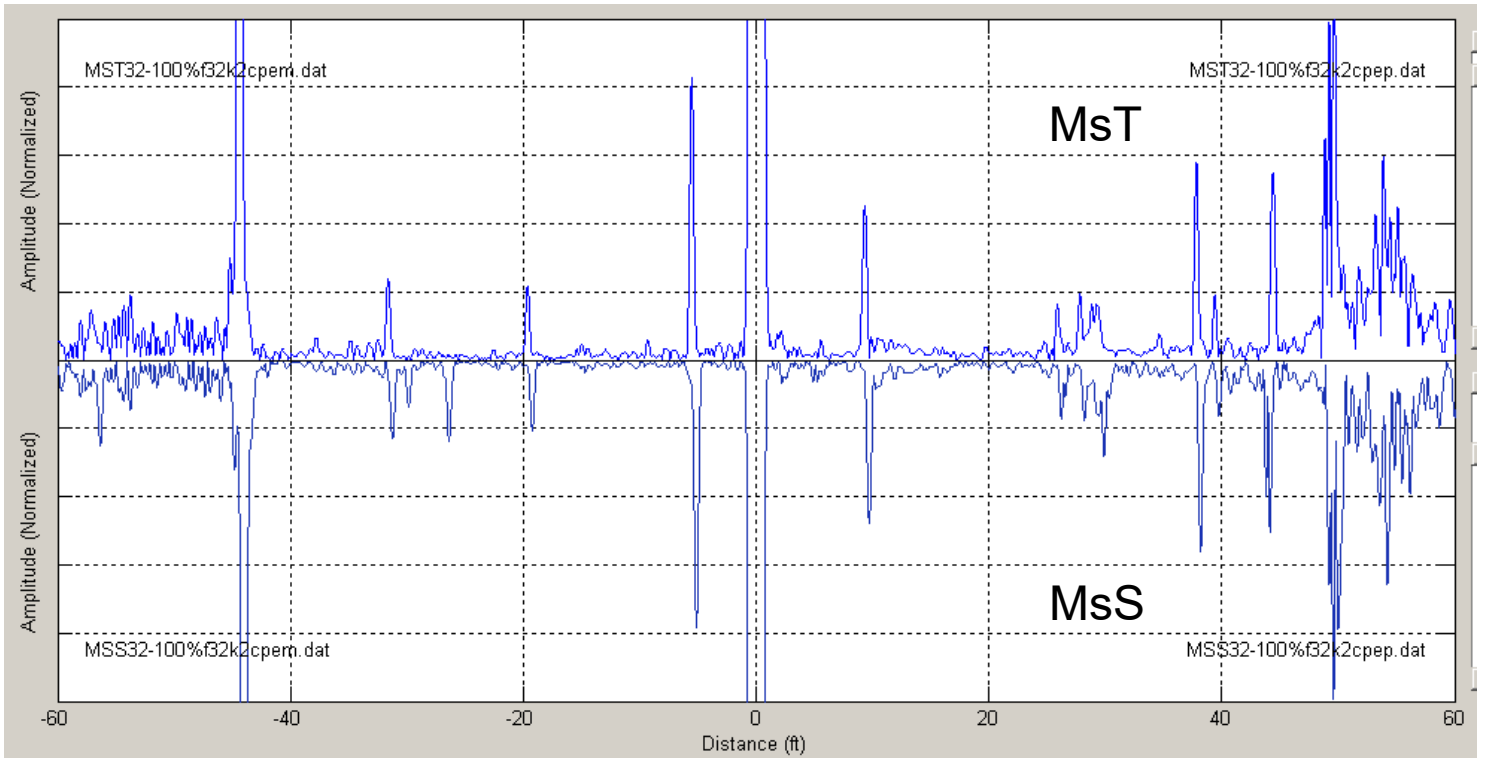


- MsT transducers are quite complicated in fabrication, but exhibit a number of unique features compared to the direct Wiedemann sensor such as:
- Use of small rare earth permanent magnets to achieve large, uniform, and self-sustained bias field strengths
- Use of more efficient electric coil arrangements to induce a stronger time-varying magnetic field for a given coil impedance (this resulted in 4 – 10 times increased signal amplitudes depending from the probe size)
- Beneficial nonlinear operating characteristics given the efficiency improvements in both magnetic fields
- Ease of using a segmented coil design for determining location of anomaly around pipe circumference.

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Rigid MsT Collars with Small Footprint





- Latest MsT transducers are only 1.1 inch wide and require minimal amount of couplant for acoustic coupling
- Exhibit the same directionality in frequency range 20 – 90 kHz and 170 – 250 kHz (no adaptor change is needed)
- Similar performance when compared to conventional 2” wide MsS ribbons
- Extremely robust clamp on design, suitable for quick mount / dismount using couplants or bladders
- Latest versions allow segmented operation and synthetic focusing (SAFT)

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Application Examples of Magnetostrictive Sensors

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Magnetostrictive Sensors for Cables and Ropes

- Starting in the early 1990s, SwRI developed sensors using magnetostriction
- An early application was inspection of stranded suspension bridge cables
  - Cables made of wound steel wires (steel exhibits magnetostriction)
  - Low-order longitudinal guided wave used
    - No coatings or other fluids to worry about
    - Bias direction and time-varying fields both in the axial direction
  - Two coils worked in tandem to steer sound in one direction (similar to phased array)
  - Successfully used to detect breaks in individual wires in bundle

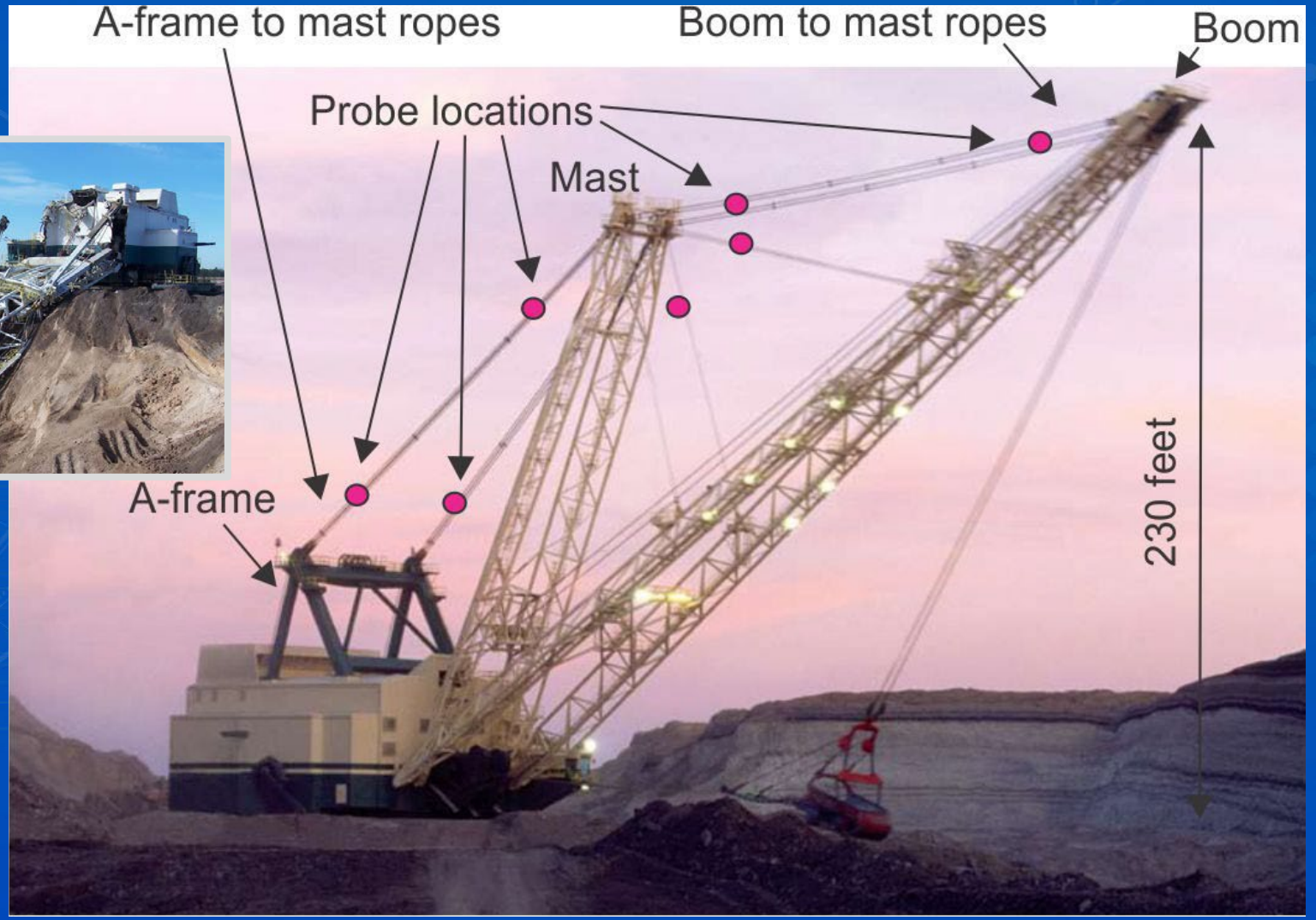




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Dragline Ropes Inspection





Pendant rope cross-section
(up to 4” OD, up to 260 wires)



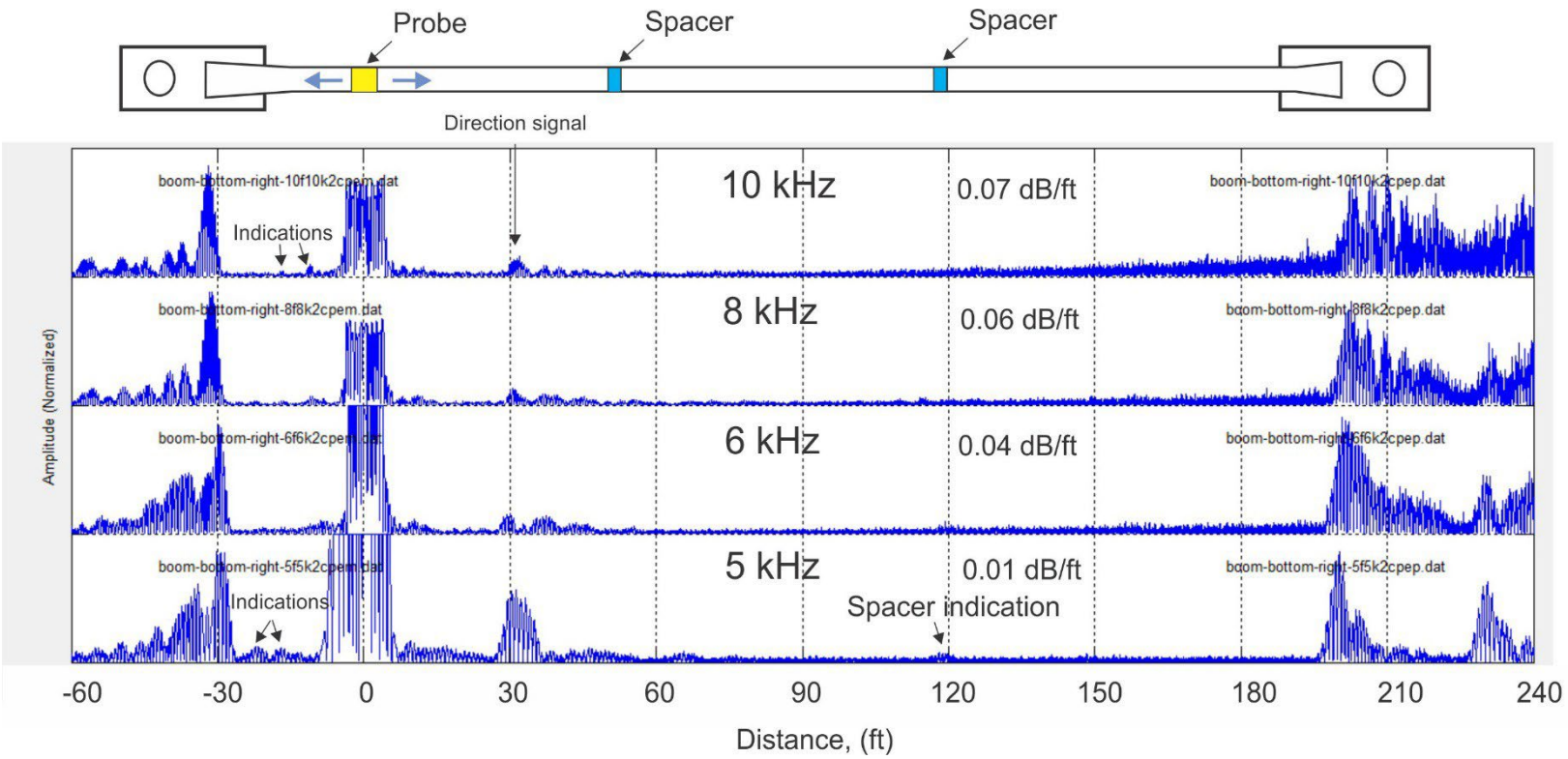
Area of most frequent failure
(first 3 feet next to a socket)



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Dragline Ropes Inspection Example



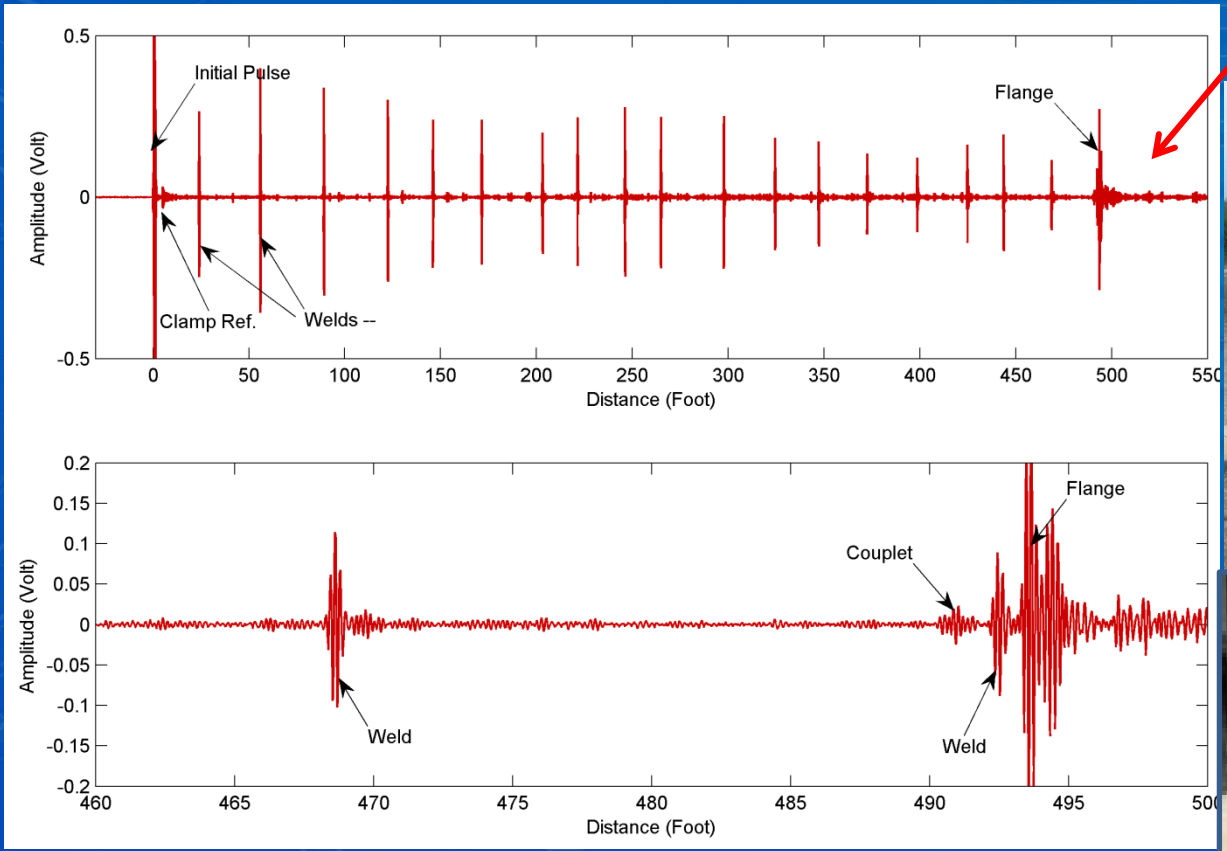


- Results obtained from multiple dragline ropes indicated that up to 300 feet of rope can be inspected from one probe position in the frequency ranges 4 - 16 kHz
- The range of coverage with a satisfactory signal to noise ratio is dependent on test frequency and rope condition
- If multiple broken wires are presented the test range can be as short as 30 feet

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Example of Guided Wave Pipe Testing

16-inch Gas Transmission Line



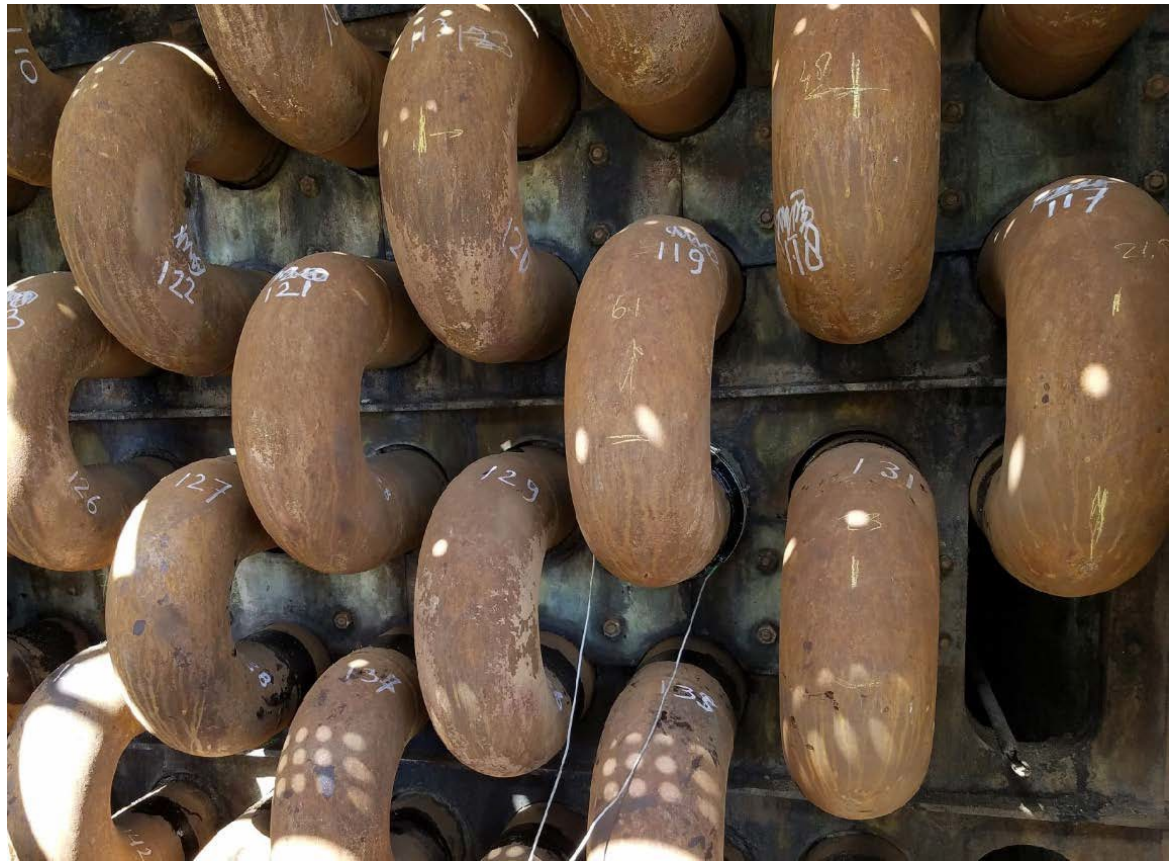
Guided wave easily
Propagates 500 ft (150m)

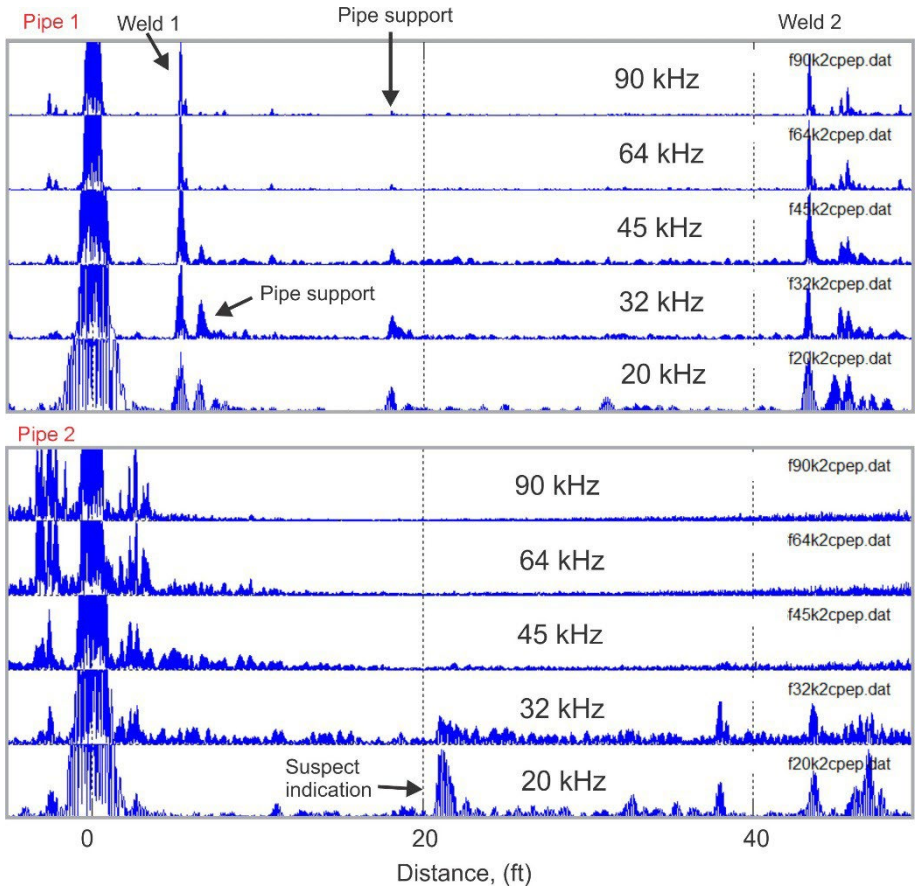


Guided Wave MsS Probe

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Multi - Frequency (20 – 90 kHz) Testing of Boiler Pipes Using MsTs

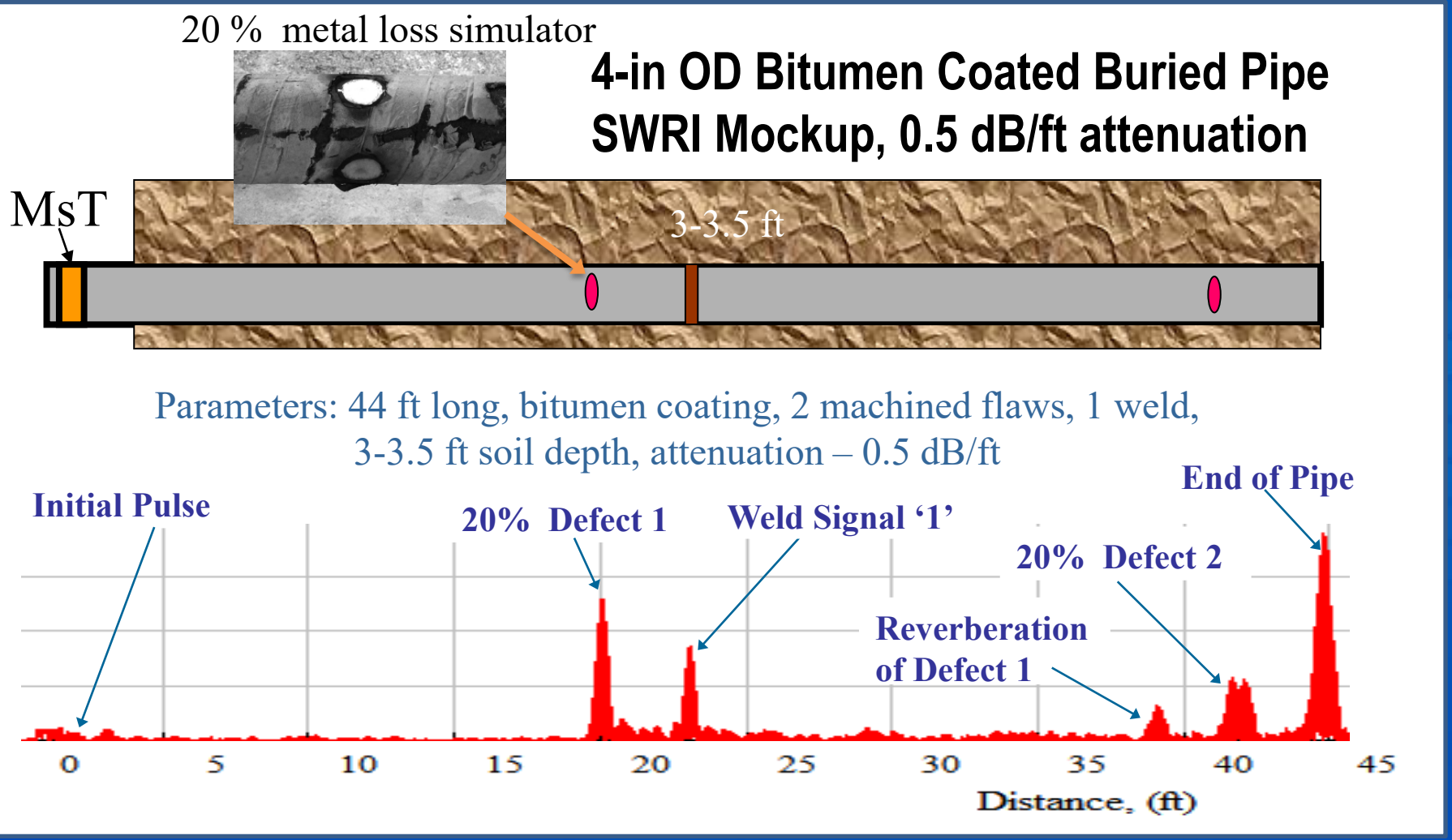




- After MsT is coupled to a pipe, data can be acquired at multiple frequencies without changing coil adaptors
- Higher frequencies (60-90, 180-250 kHz) can be used for finding pitting corrosion and checking conditions under pipe suppor
- Lower frequencies (20 – 50 kHz) are more suitable for finding generalized corrosion

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Buried Pipe Example







Buried pipeline inspection introduces new challenges: detection classification will shift to 5 -10% instead of 2-5% CSA

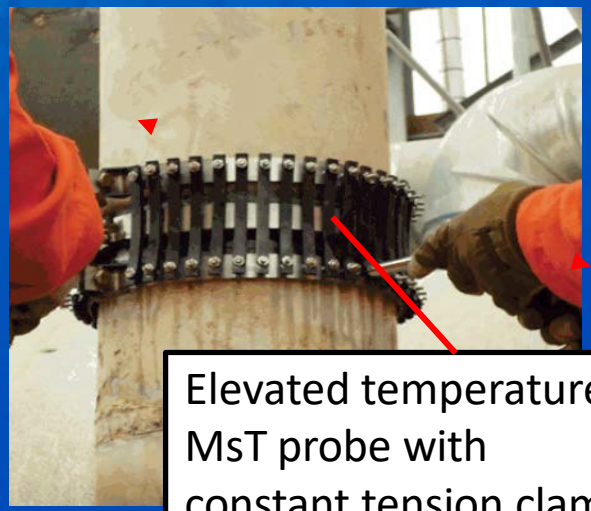
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Structural Health Monitoring (SHM)

- All of the preceding examples were based on the inspection concept
  - Data collected at one time / inspection report generated based on that data only
  - Comparison between historical inspections possible, but usually only using reports
- A monitoring approach has been developed in recent years to expand the capability of guided wave testing
  - Usually involves permanent installation of the sensor
  - Explicitly process the data using past data acquired on the structure
- Major advantages of monitoring versus inspection
  - Periodically acquire data more often than inspection-based strategy
  - Large reduction in labor costs (only single sensor installation process)
  - Advanced signal processing can improve detection sensitivities
- MsT technology uniquely suited for permanently installation because sensor can be designed to support higher temperatures and harsher environments.



MsT probe for SHM of buried pipes

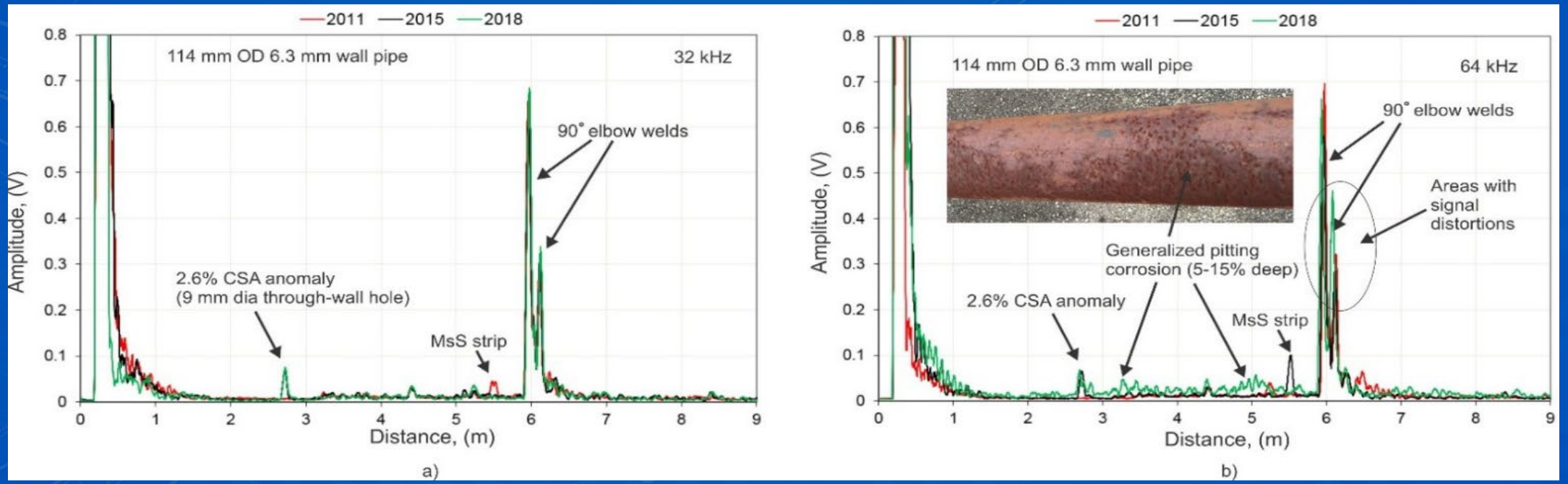


Elevated temperature MsT probe with constant tension clamp

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Seven Years Monitoring of 4’’ OD Schedule 40 Pipe

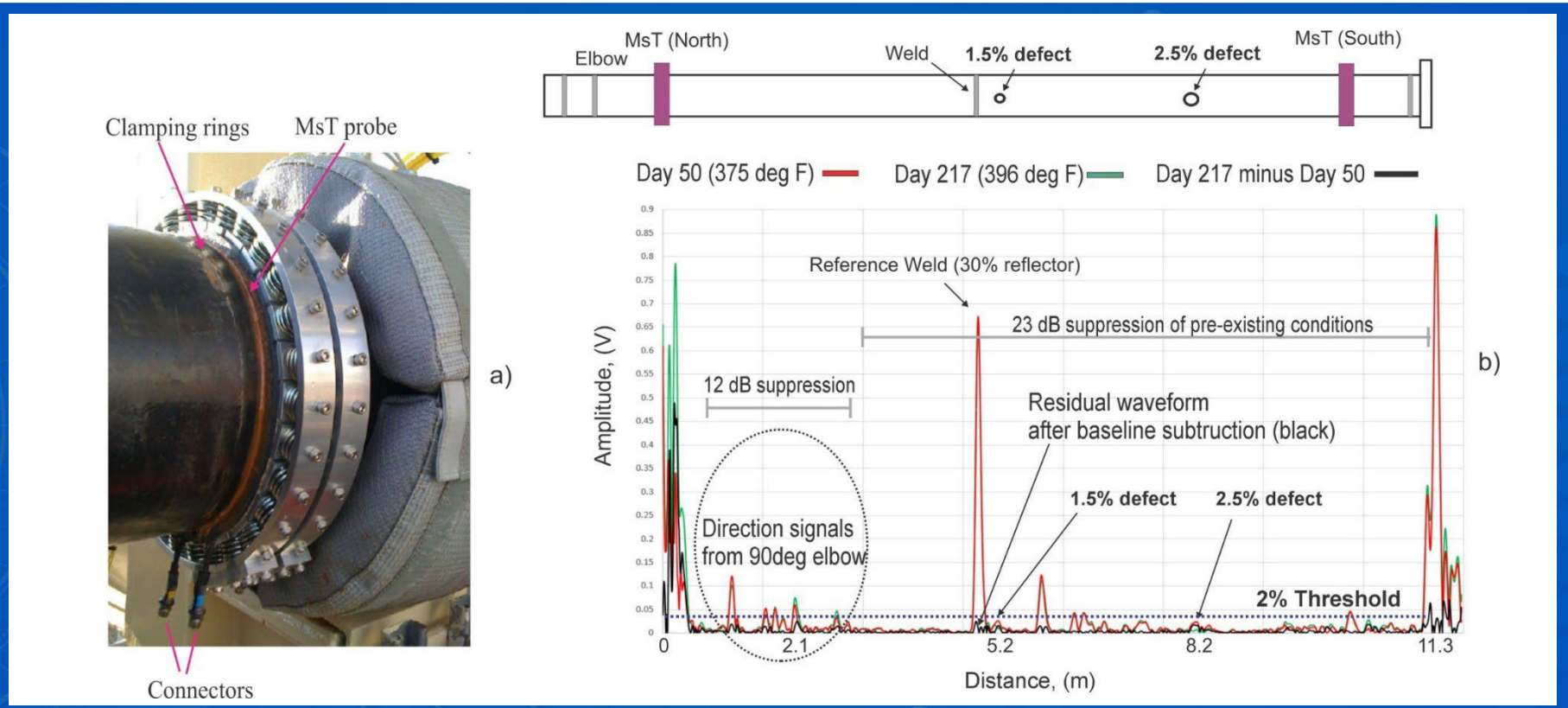
Effect of generalized corrosion on guided waves propagation



- Simulation of extended generalized corrosion is difficult task
- This matter was investigated during a 7-year long test conducted at SwRI
- In 2011, an MsT probe was permanently installed on a 114 mm (4 inch) OD pipe exposed to natural environmental conditions
- High sensor reliability and high reproducibility of traces was observed
- The results of this test also indicated that in the presence of generalized corrosion, use of lower frequencies (20 – 40 kHz) is more appropriate in terms of reproducibility of traces.

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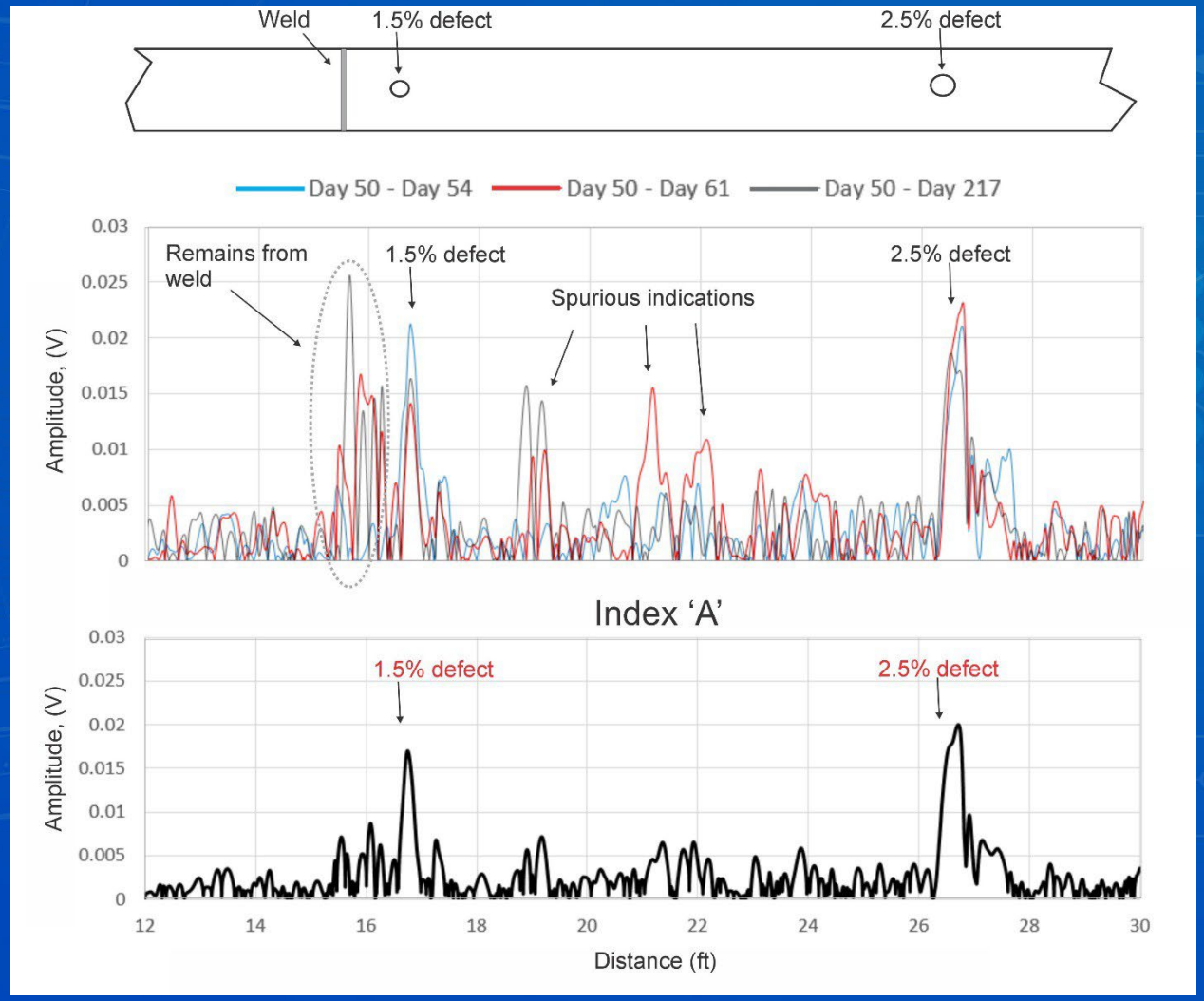
SHM of Pipes at 200° C: Test Results



- Testing was conducted during 270 days with variable temperatures and multiple thermal cycles applied to the probe
- Detection of a 1.5% cross-sectional area anomaly in an open span of the pipe before applying the baseline subtraction algorithm (BSA) was demonstrated.
- Applying BSA allowed suppression of the majority of signals related to pre-existing conditions by 23 dB
- The lowest background noise after applying BSA was at 0.4%, setting a practical limit for the sensitivity of the method for selected frequency range (64 kHz) at about 0.8% cross sectional area.

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SHM of Pipes at 200° C: Utilizing a Pool of BSA Traces



- Additional method is to use a pool of BSA traces to sort out indications that are intermittent
- These indications could be relevant to actual pipe condition at the moment data were acquired, but not relevant to condition of the pipe metal (for example, variations in clamping forces produced by pipe supports)
- For sorting out steady indications an index 'A' was defined as a n-th root of multiplication of n-th traces:

$$\text{Index A} = \sqrt[n]{A1 * A2 * A3 * An}$$

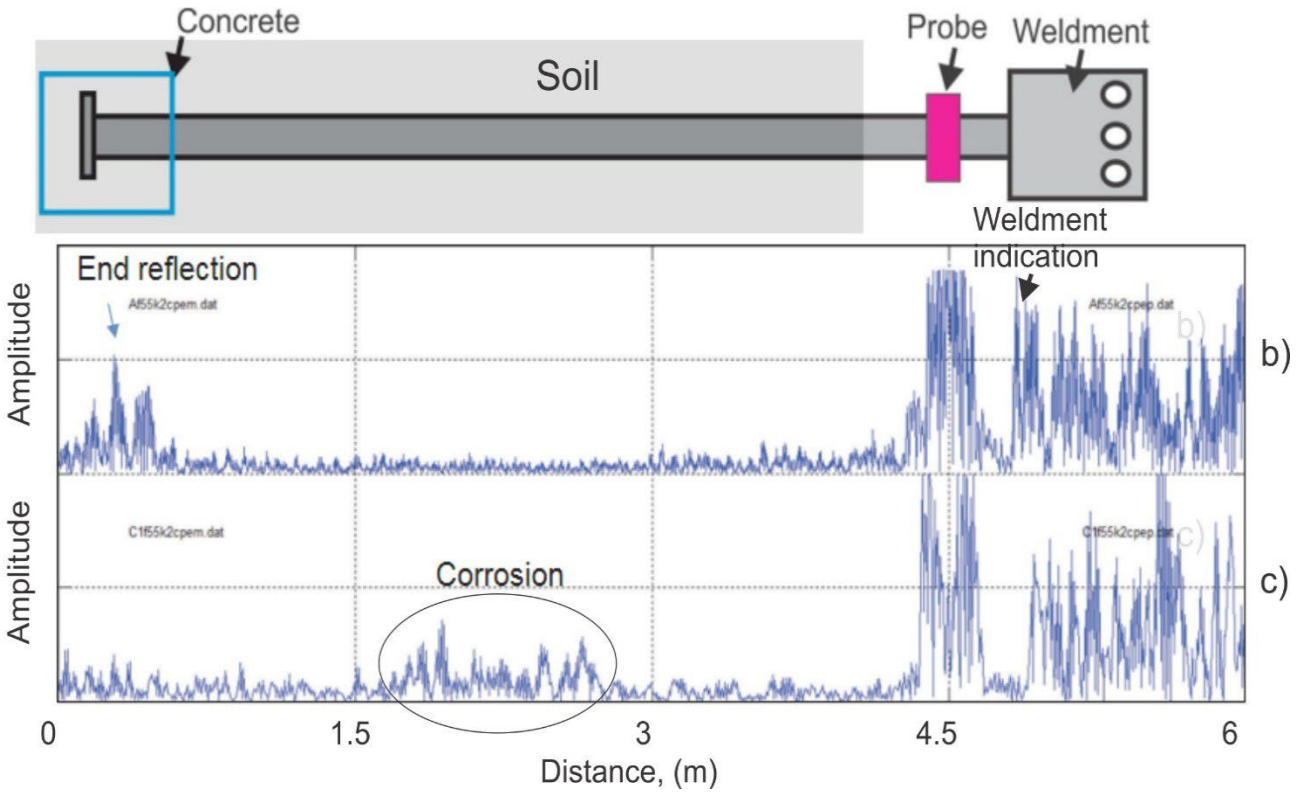
Where *A - baseline traces*

n - serial number of the last baseline trace in the pool of baseline traces

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GWT of Buried Anchors using MsTs







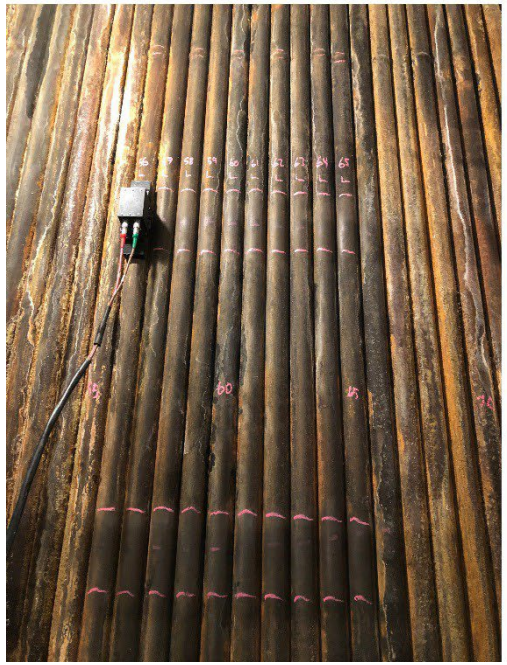
- These anchors had the OD 2 inches and had a concrete attachment near the bottom
- The anchor on (b) produced clear bottom reflection and no other relevant indications were found
- The anchor on (c) did not produce the end reflection and a number of indications can be observed in the middle section (the condition was visually identified as a sharp bend)
- The method is qualitative, allowing ranking into good, medium, and bad categories
- Due to high attenuation, anchors fully embedded into concrete might require alternative test method such as acoustic impact (tapping)

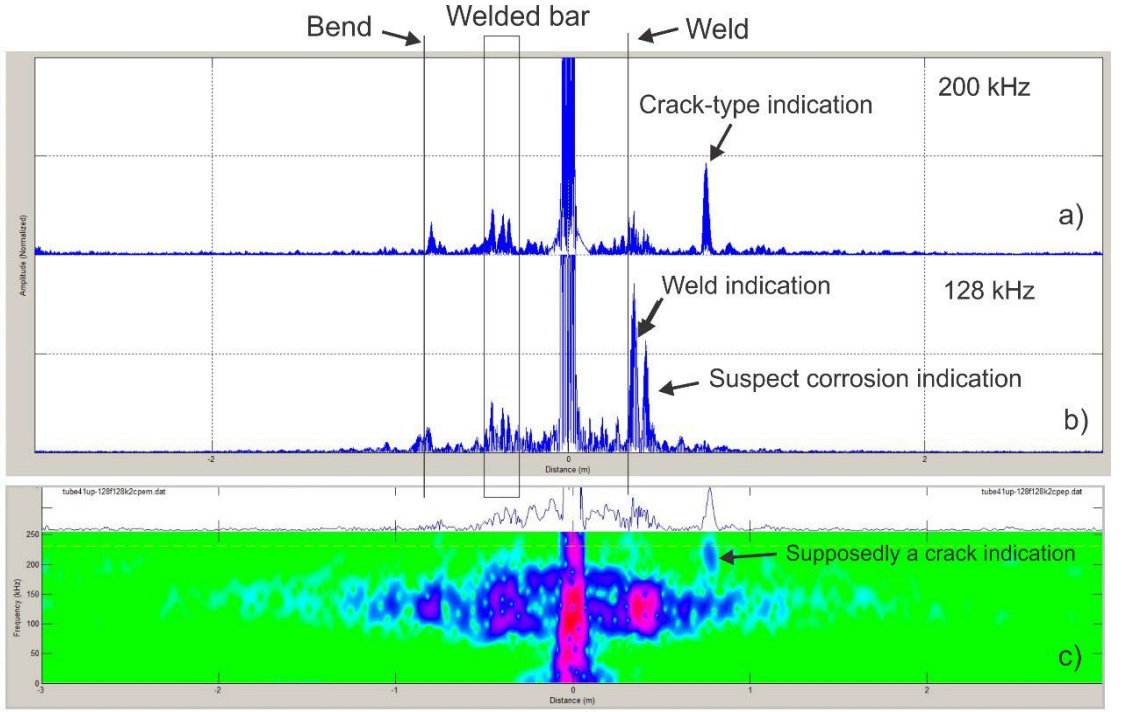
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MsT for GWT of Boiler Tubes

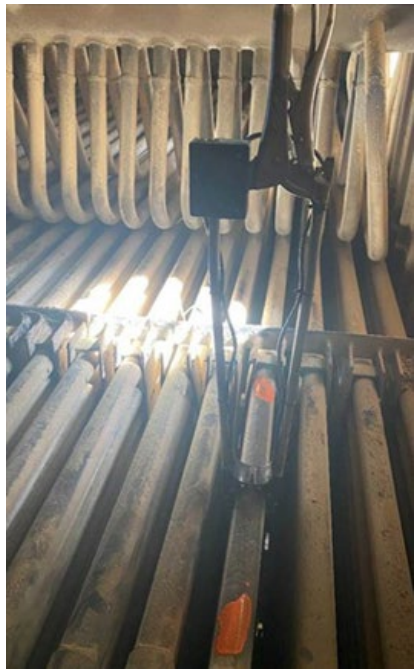
Side coupling MsT probe







Two-side coupling MsT probe

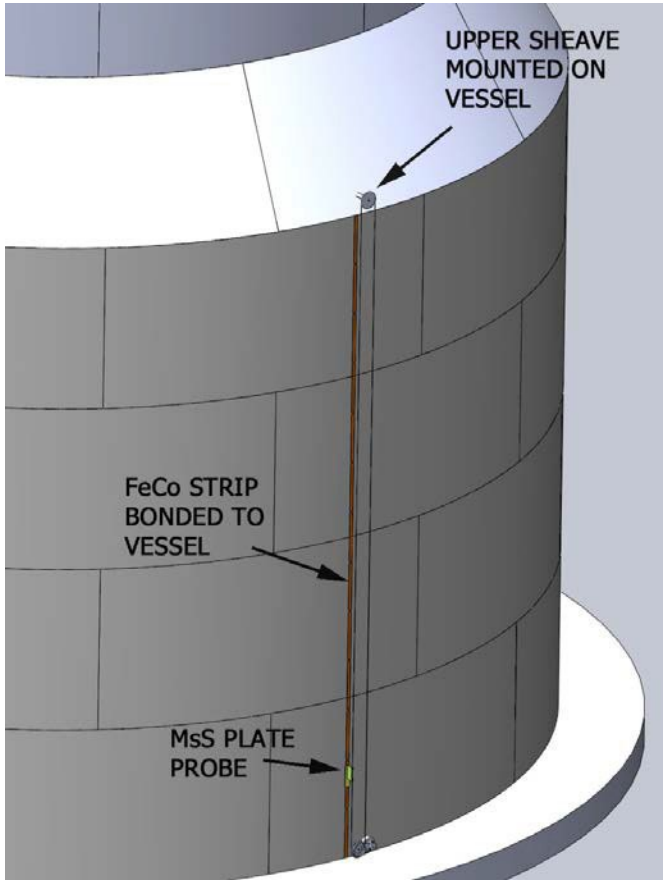


- MsT probe with side coupling is suitable for water-wall tubing when the only access is from the fire side
- Field test indicated that up to 12 foot of boiler tube (cold and hot sides) could be covered from one probe position with test time about 30 sec
- Two side coupling probe could be used on the tube bundles with the ability to clamp on the tubes from the 1st to the 6th row
- The average test range from one probe position is about 30 ft
- The first U-bend could be fully covered

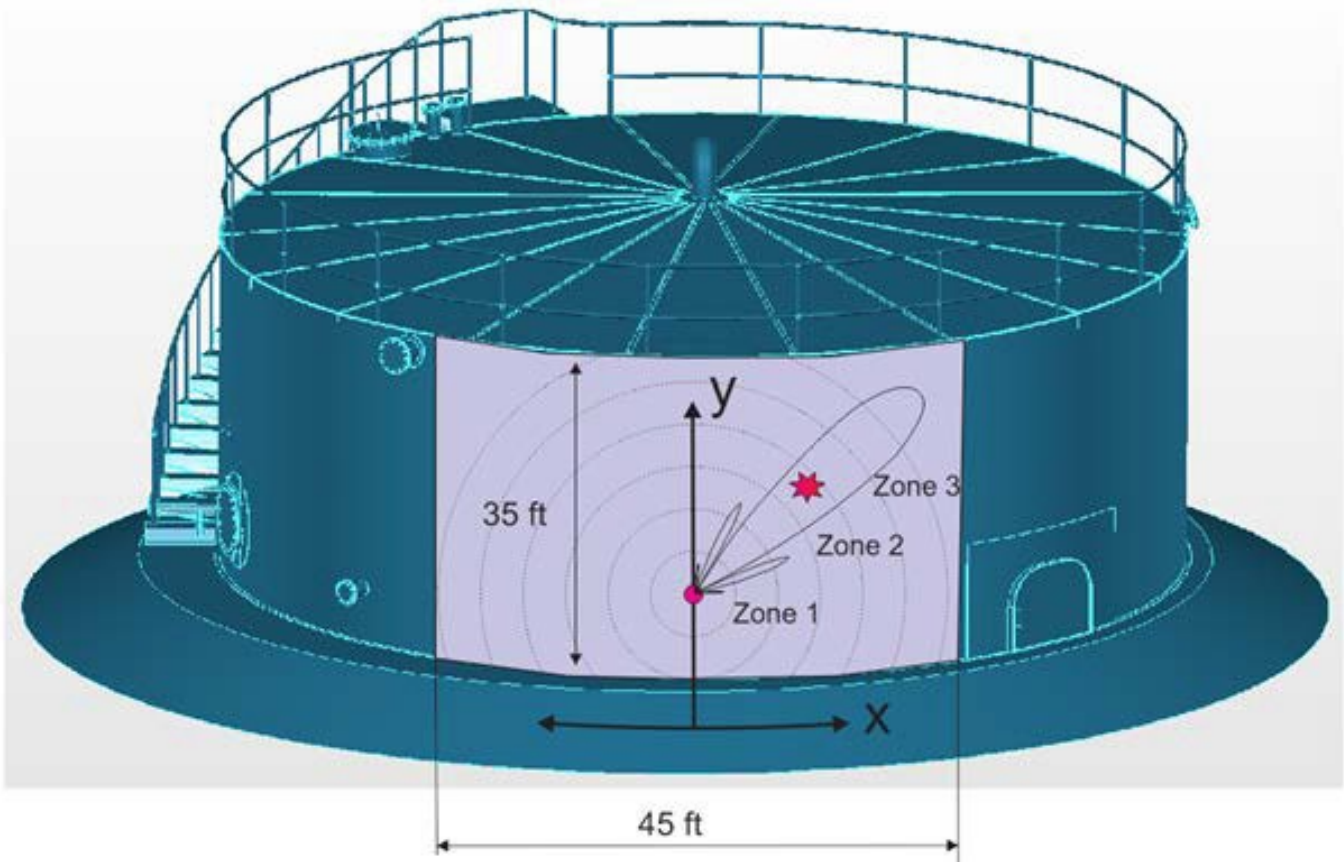
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GW Scan Options for Large Cylindrical Shells

Incremental scans using plate probe

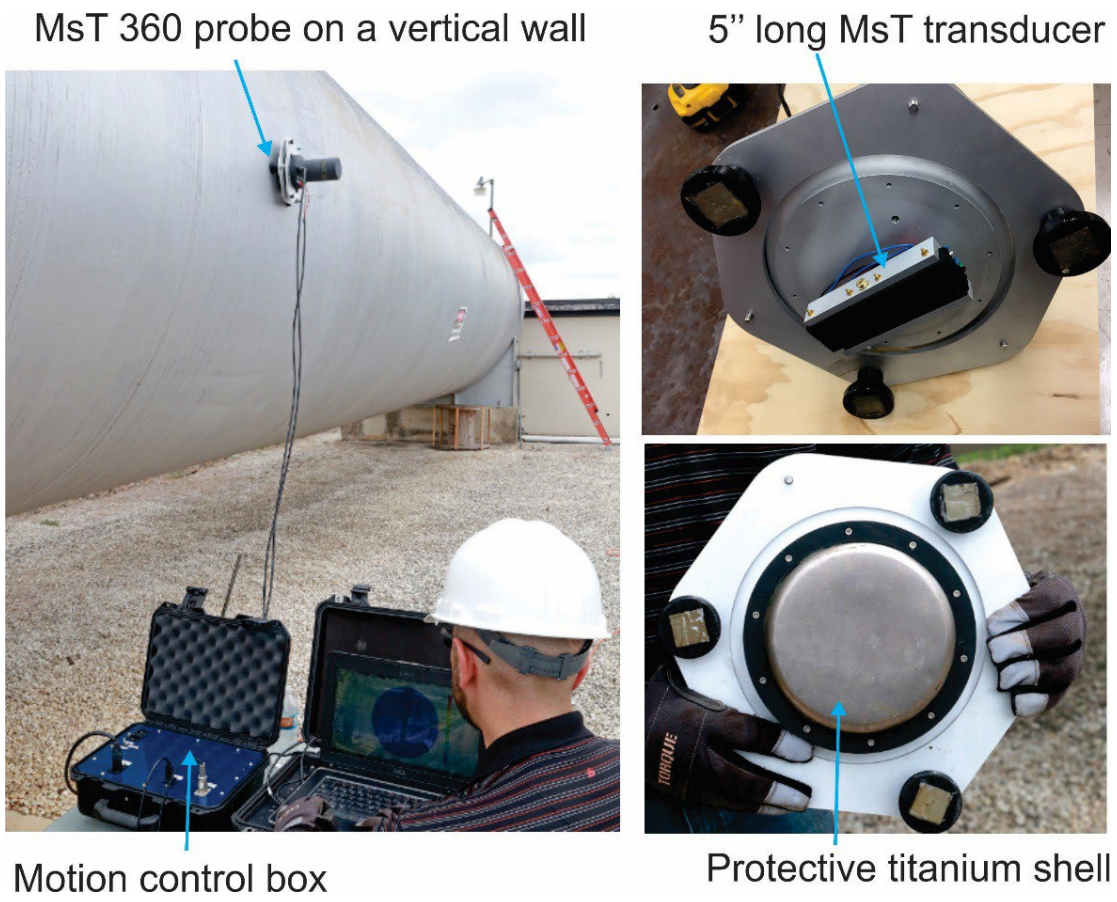


Omnidirectional scan using OMNI probe



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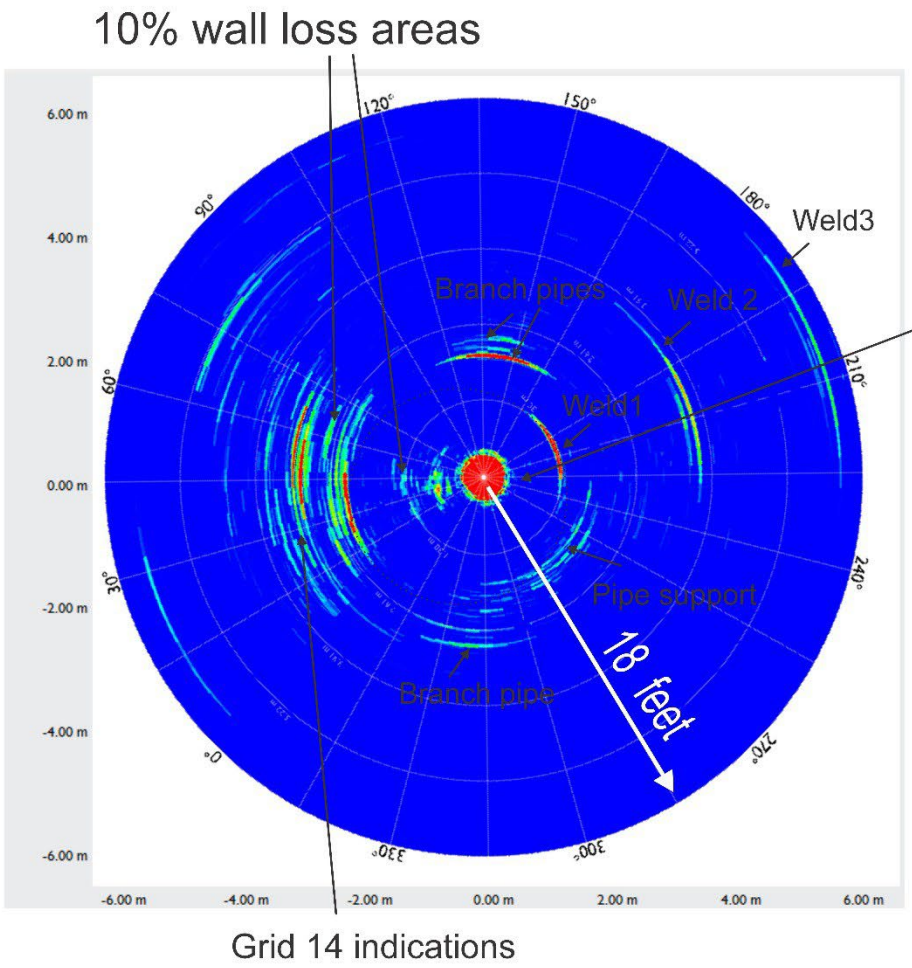
Omnidirectional Probe for Large Cylindrical Shells



- In this new probe design, a directed, plate-application probe with known characteristics was incorporated into an automated scanner
  - This scanner rotates the directed plate probe for data collection at regular intervals using a single or multiple frequencies
- Coupling of the transducer to the structure is accomplished using shear wave couplant (stainless steel materials can be tested)
- For tank walls operating at elevated temperatures (up to 120 deg C) a nickel patch could be bonded to the wall
- This probe was developed for automated guided wave scanning of large shells, such as storage tank walls and bottoms, with a target area of coverage of the order of 100 square meters from one probe position
- 30 – 300 kHz frequencies can be used

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MsT360 Omnidirectional Probe on Large Storage Tank



48 feet long, 10 feet diameter tank
5/8-inch head, 3/8-inch shell



Grid 14 corrosion profile

Grid #14 Thickness Measurements

8	0.298	0.356	0.301	0.284	0.350	0.378	
7	0.361	0.373	0.365	0.232	0.369	0.378	0.210
6	0.366	0.357	0.375	0.280	0.306	0.369	36.7
5	0.359	0.358	0.372	0.236	0.340	0.232	
4	0.365	0.234	0.305	0.210	0.235	0.319	
3	0.373	0.341	0.369	0.301	0.245	0.376	
2	0.375	0.373	0.372	0.289	0.365	0.355	
1	0.372	0.306	0.371	0.347	0.369	0.356	
	1	2	3	4	5	6	

Minimal wall (inches)

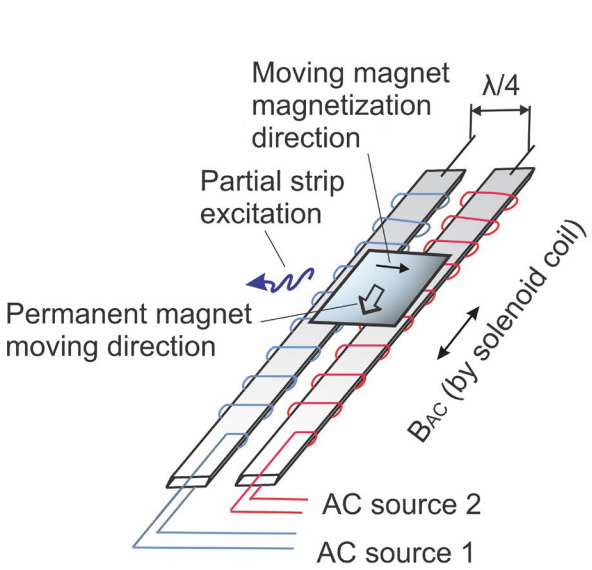
Wall loss (%)

- Data were acquired using 60, 70 and 80 kHz frequencies and 5 degree increment
- Data acquisition time was 15 minutes
- Welds produced indications up to about 18 feet distance mark
- Multiple branch pipes produced indications
- A number of suspect indications were identified and well correlated to known corrosion areas with the wall loss in the range 10 – 36%

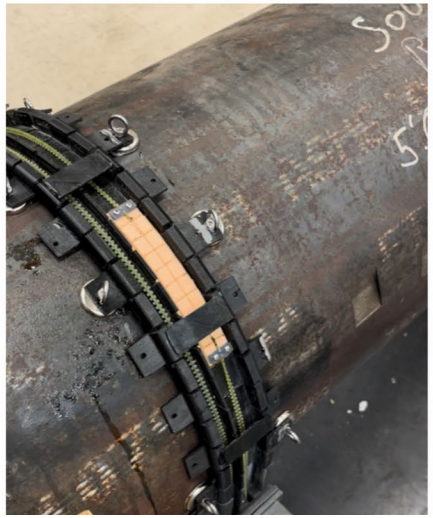
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Linear Scan MsT Transducer

- The linear scanning MsT probe utilizes a FeCo strip of a predefined length wound with RF coils and attached to the structure under test using a shear wave couplant
- A permanent magnet driven by a step motor is used to excite SH0 guided waves at predefined positions along the strip
- Manual manipulation of the probe is minimized, allowing significantly increased axial resolution and testing speeds
- Scan data from various aperture sizes can be obtained with minimal effort by using magnets of different lengths
- The ferromagnetic ribbon is encapsulated into a low-profile flexible casing.



Pipe supports scan



Storage tank supports scan



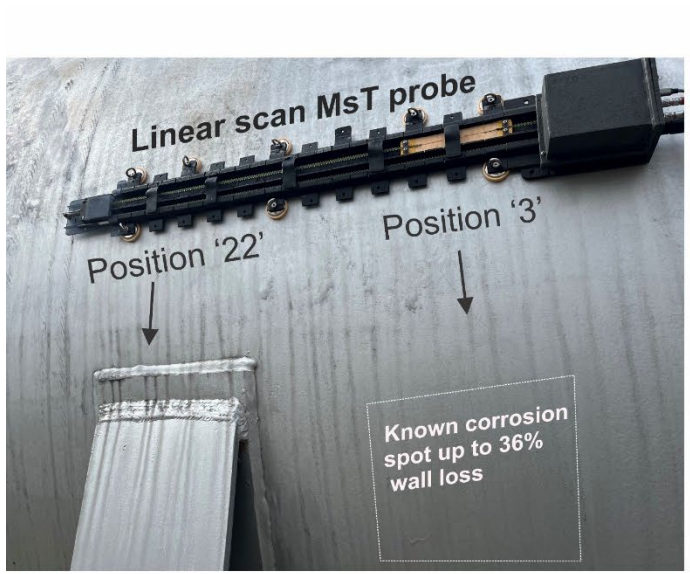
Storage tank walls scan

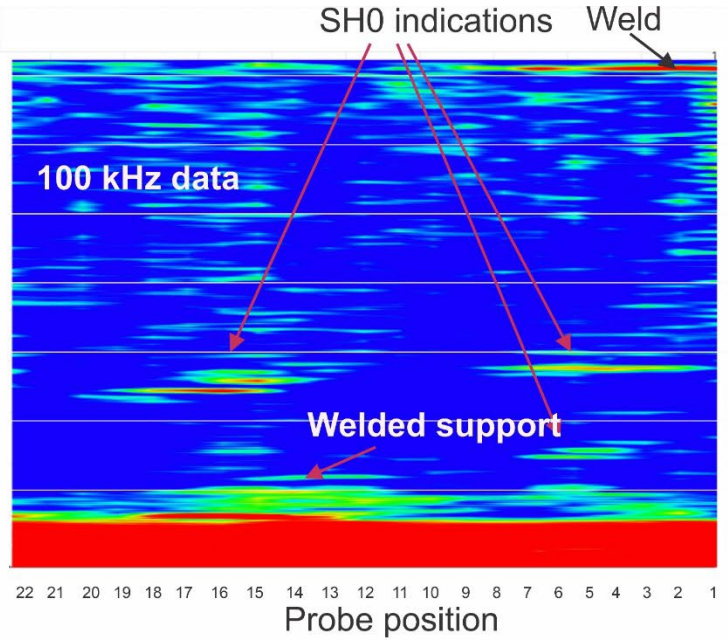


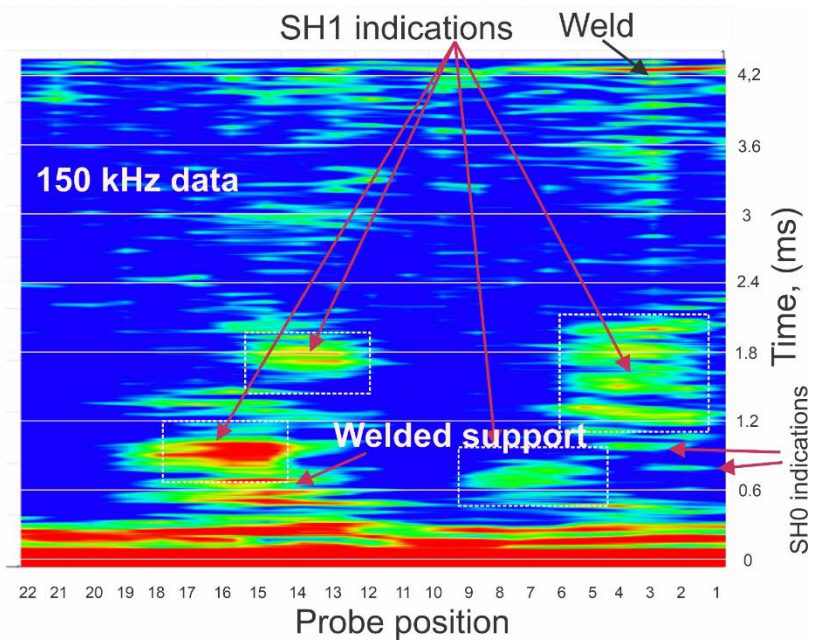
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Detection of Gradual Wall Loss in Storage Tank Walls

- Linear scan MsT probe was evaluated for detection of generalized corrosion in a storage tank with extended internal surface corrosion
- Probe was positioned on top of two areas of interest – welded pipe support and known corrosion spot with measured wall loss up to 36%
- At 100 kHz, a few SH0 mode indications were observed relevant to the welded support and to deepest anomaly
- At 150 kHz, multiple SH1 mode indications could be observed in both areas of interest
- The presence of multiple SH1 mode indications provided more realistic information about the defect morphology.





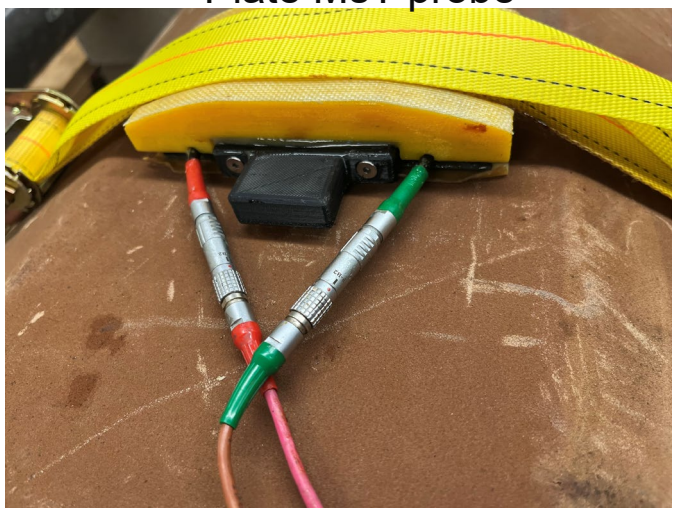


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Omnidirectional Probe on Buried Pole

- Guided wave inspection of poles embedded in the ground shares many of the challenges of guided wave testing of buried pipelines
- A plate magnetostrictive sensor transducer (MsT) probe can be utilized as a very effective pole-bottom finder due to its high power output
  - Due to large circumferences, screening the entire pole using this probe is labor intensive
- Another option is the MsT360 omnidirectional probe with automated data collection function
- The MsT360 utilizes a rotating EMAT head that generates transverse vibrations in the nickel cap
- The cap is acoustically coupled to the pole using shear wave couplant or permanent adhesive bonding
- This probe configuration allows the transmission of guided waves in many different directions including helical paths
- Data collection is automatic and results in a 360-degree polar plot showing pulse-echo data from the entire pole

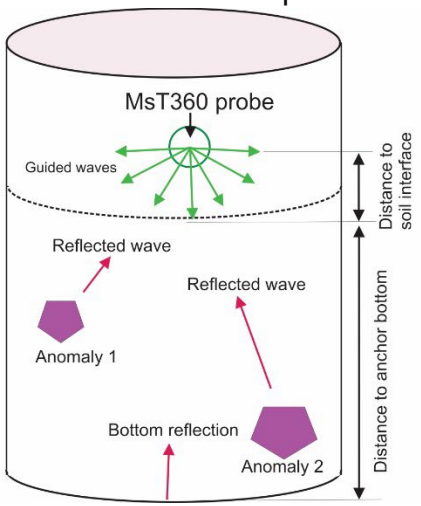
Plate MsT probe



MsT 360
Omnidirectional probe



OMNI scan Concept



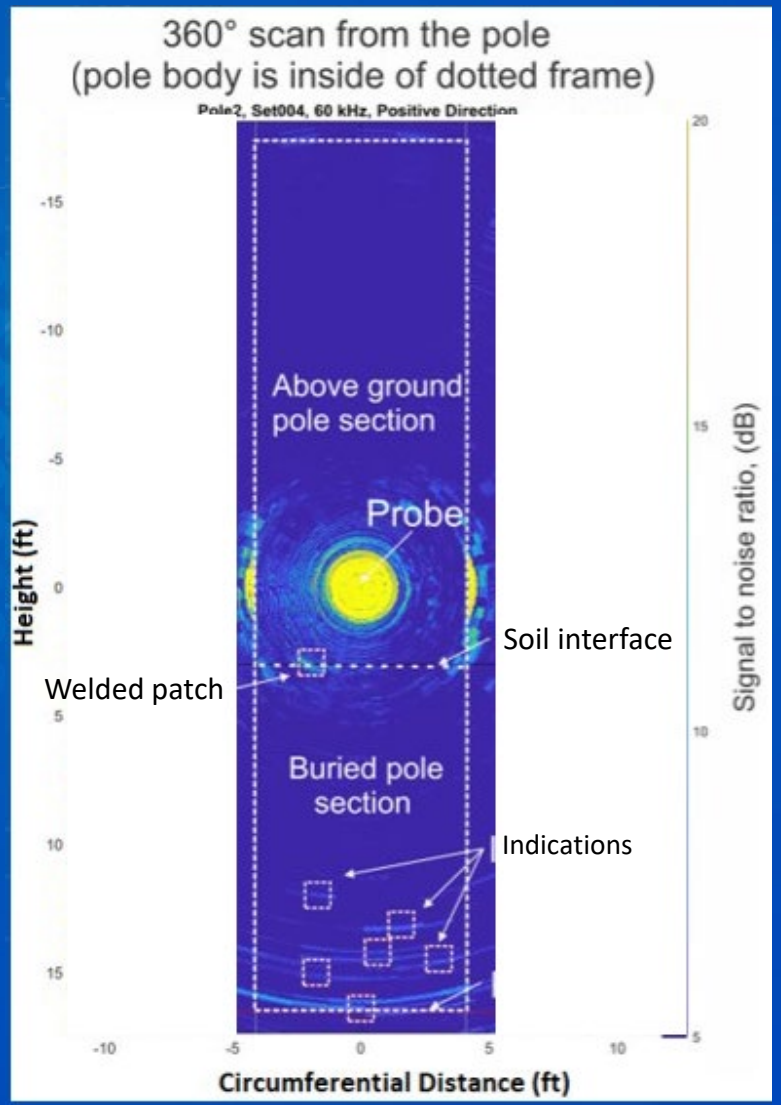
MsT 360 on pole



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Indication Plot From Buried Pole

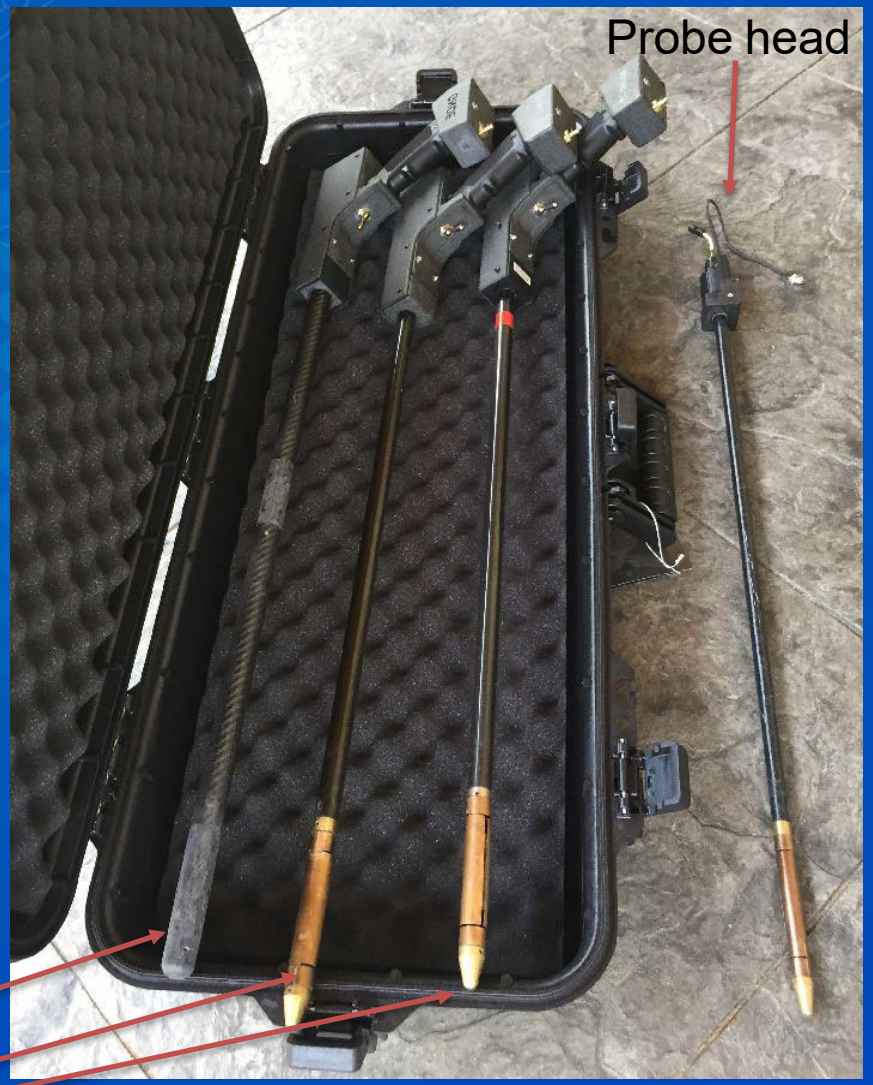
- Based on the amplitude of the bottom reflection at 16 ft, about 20 dB of signal amplitude was lost on the round trip to the pole bottom
- The average attenuation was estimated as 0.625 dB/ft
- Indications found on this plot include a welded patch at the soil-to-air interface and a set of indications near the bottom of the pole
- Some indications might be from defects, and some might correspond to geometry features or coating damage
- It is assumed that repetitive data acquisition over time could help to track the attenuation rate (for detection of generalized corrosion) as well as formation of new defects



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MsT for GWT of Heat Exchanger Tubes

- Since 2004, several different types of probes were developed for ferromagnetic and non-ferromagnetic tubing
- Field testing on carbon steel (CS) tubing indicated that higher frequencies (128 kHz) provided better penetration under tube support plates and better ability to penetrate past U-bends
- In CS heat exchangers indications produced by tube support plates (TSP) could be high amplitude and produce multiple reflections what makes analysis complicated
- Utilization machine learning and AI assisted reporting is on the way
- Overall, application of guided waves for screening of heat exchanger tubing was found to be very promising and challenging at the same time
  - the SNR can vary from excellent to poor depending on tube conditions

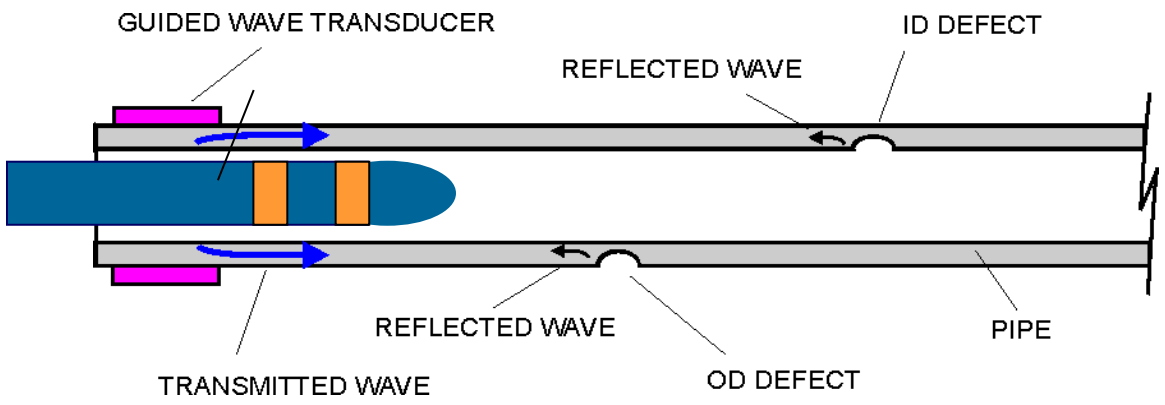


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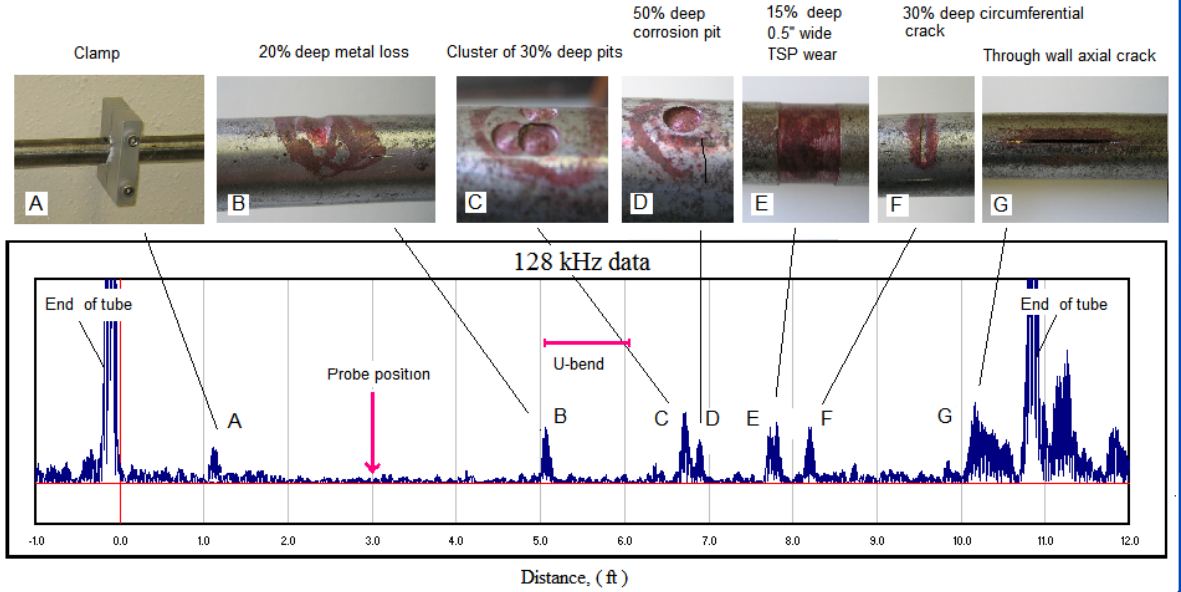
Guided Wave Testing of Carbon Steel Tube

- The concept of rapid screening of heat exchanger tubing using guided wave testing has utilized the capability of guided waves to travel long distances (up to 100 feet) in the components essentially without attenuation
- The guided wave is generated in the tube wall by inserting a probe into the tube from one end approximately 30 cm
- Guided waves generated by the probe are mechanically or electromagnetically coupled to the tube wall
- Conventional axially symmetric probe designs only allowed detection of axial position of anomaly and ranking based on amplitude information

Guided Wave Generation

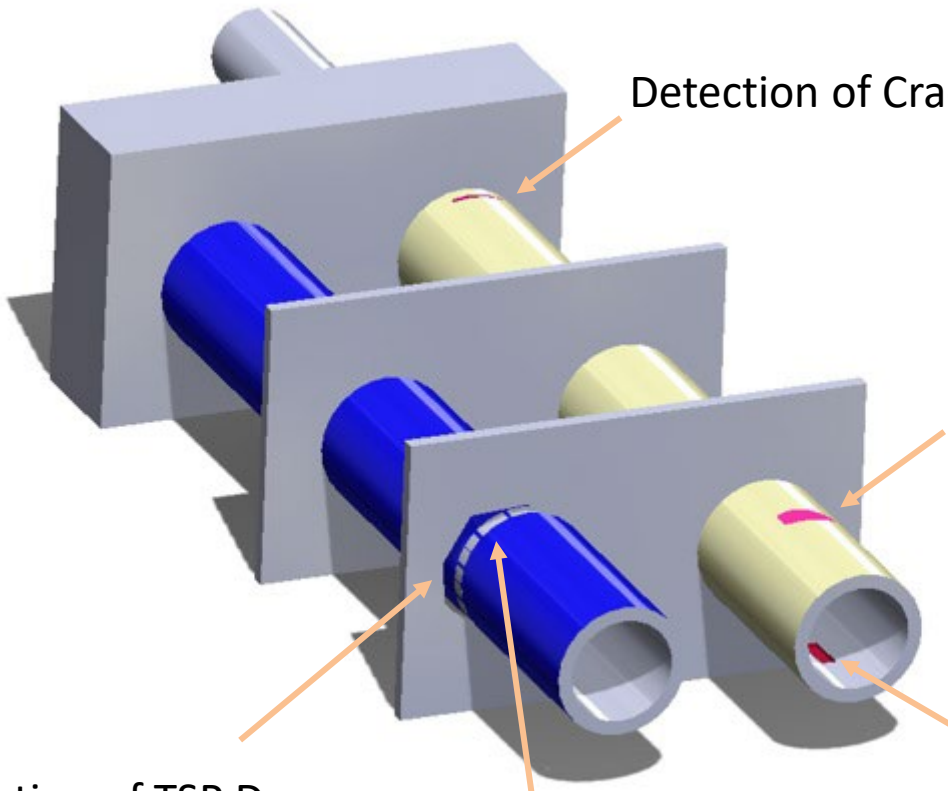


Example of Anomaly Detection at 128 kHz CS Tube



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Typical Damage in Heat Exchanger Tubes

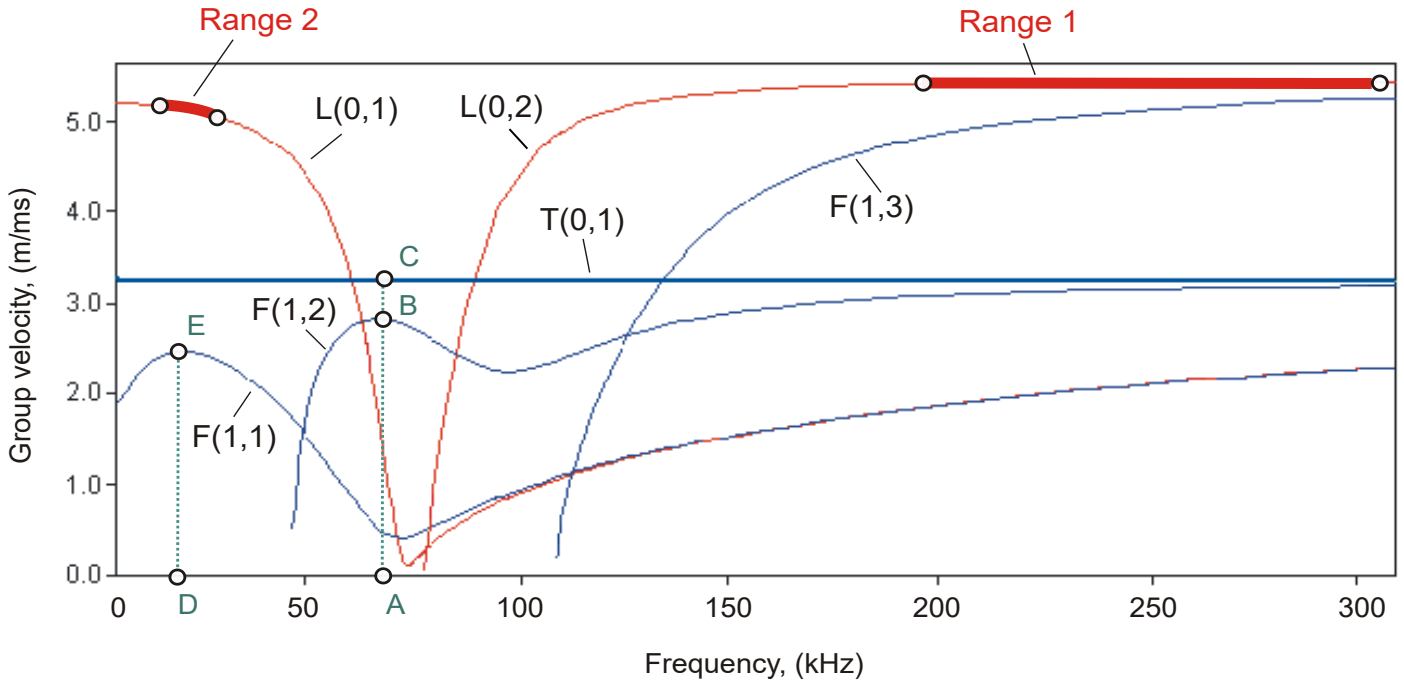


- Majority of anomalies in heat exchanger tubing are non axially symmetric
- Ability to quantify the circumferential extent of anomalies could help to sort them out from indications relevant to normal tube support plate (TSP) attachments

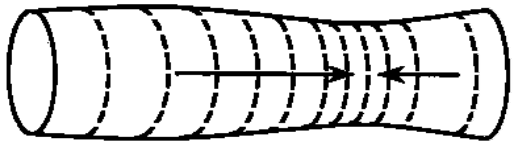
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Guided Wave Modes

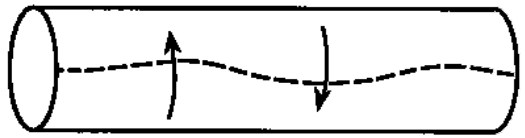
Dispersion Curves of Guided Waves in 1” OD Tubes



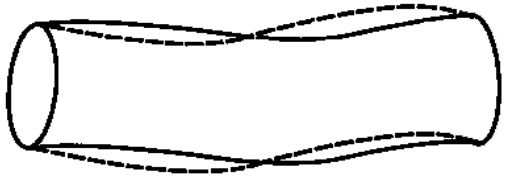
Longitudinal



Torsional



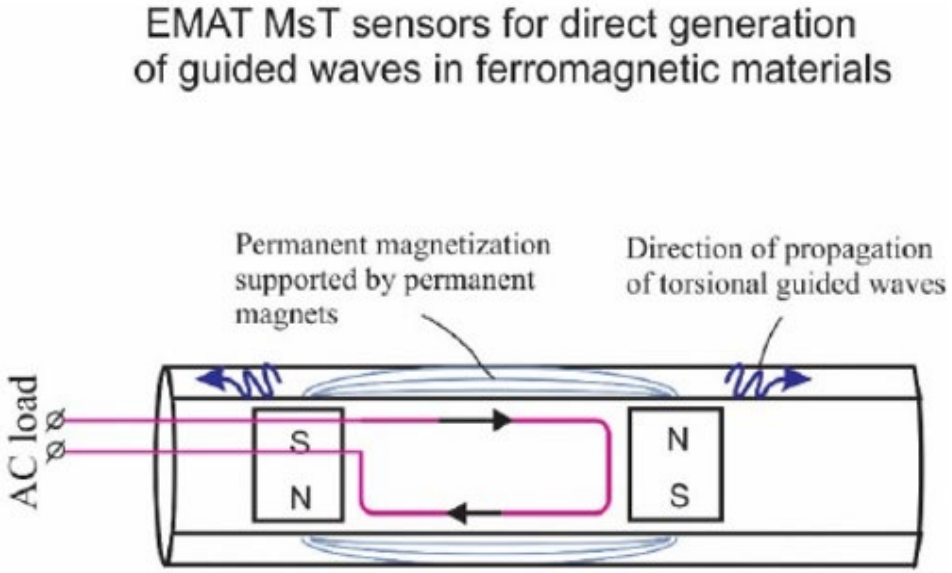
Flexural

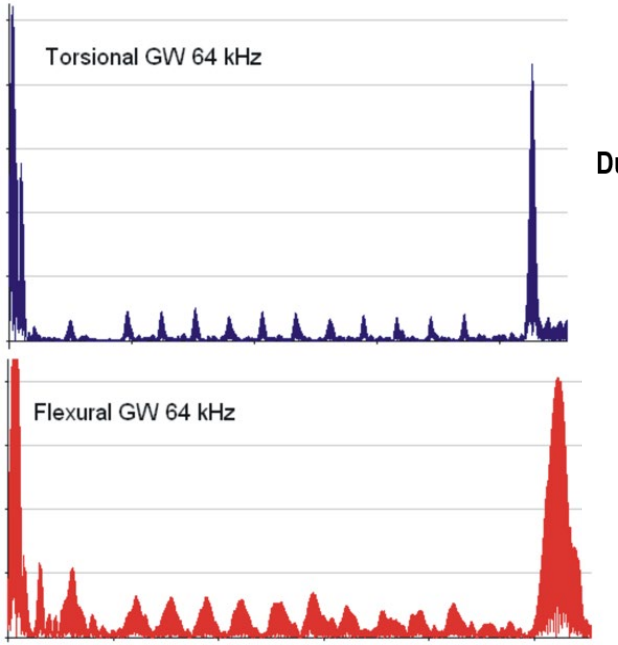


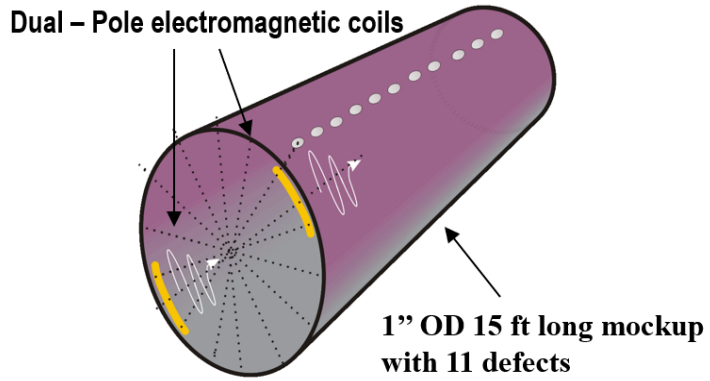
- Based on guided waves dispersion characteristics, a fundamental T(0,1) mode as well as L(0,1) and L(0,2) could be used for guided wave screening of heat exchanger tubes
- Utilization of flexural F(1,1) and F(1,2) modes was also found to be beneficial for applications when guided wave focusing function is required

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EMAT MsT Probe







- EMAT MsT probe can generate both axially symmetric torsional guided waves and flexural guided waves (US Patent N 10352909B2, "Paired Magnetostrictive Transducers for Non-Destructive Testing of Tubular Structures with Selective Torsional or Flexural Wave Modes", 2019
- T(0,1) mode demonstrated excellent signal to noise ratio and ability to propagate up to 100 feed distance in the presence of multiple anomalies
- Flexural guided waves also demonstrated the ability to propagate long distances but, the axial resolution was lower due to longer wavelength

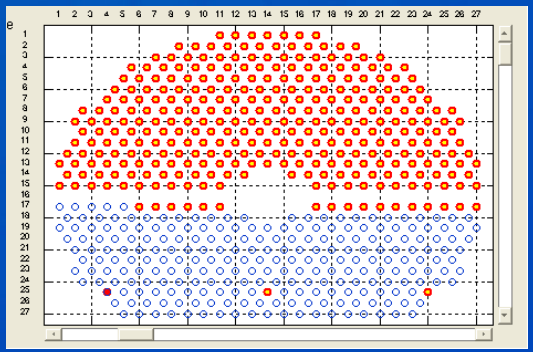
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Guided Wave Screening of Oil Lube Cooler Using MsT EMAT Probe

Guided waves screening of 5/8” OD Super-Ferritic SeaCure tubing was conducted at Nuclear Power Plant (Project was supported by EPRI)

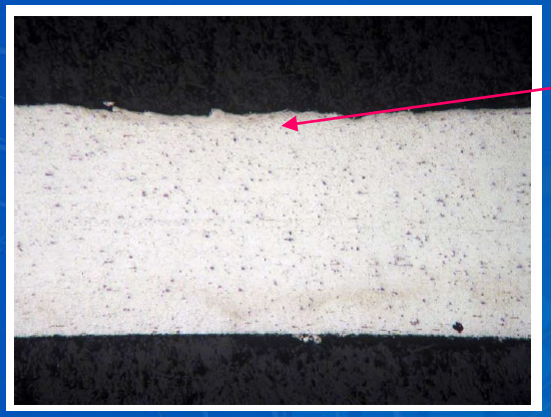
- 100 kHz torsional guided wave EMAT MsT probe was utilized for screening
- The highest accomplished speed of uninterrupted screening was approximately 3 tube/min
- 329 tubes total were inspected with 62 out of 329 tubes being inspected from
- both sides of the cooler for confirmation of the reading
- 308 tubes were found to be in good condition
- 21 tubes identified as having relevant indications including 4 tubes with relevant indications near the area of rolled expansion, indications near the tube support plate, and indications in the free span areas
- 4 of these tubes were pulled out for destructive testing and anomalies were confirmed in 3 tubes out of 4
- A false positive was caused by an indication produced by a tube support plate



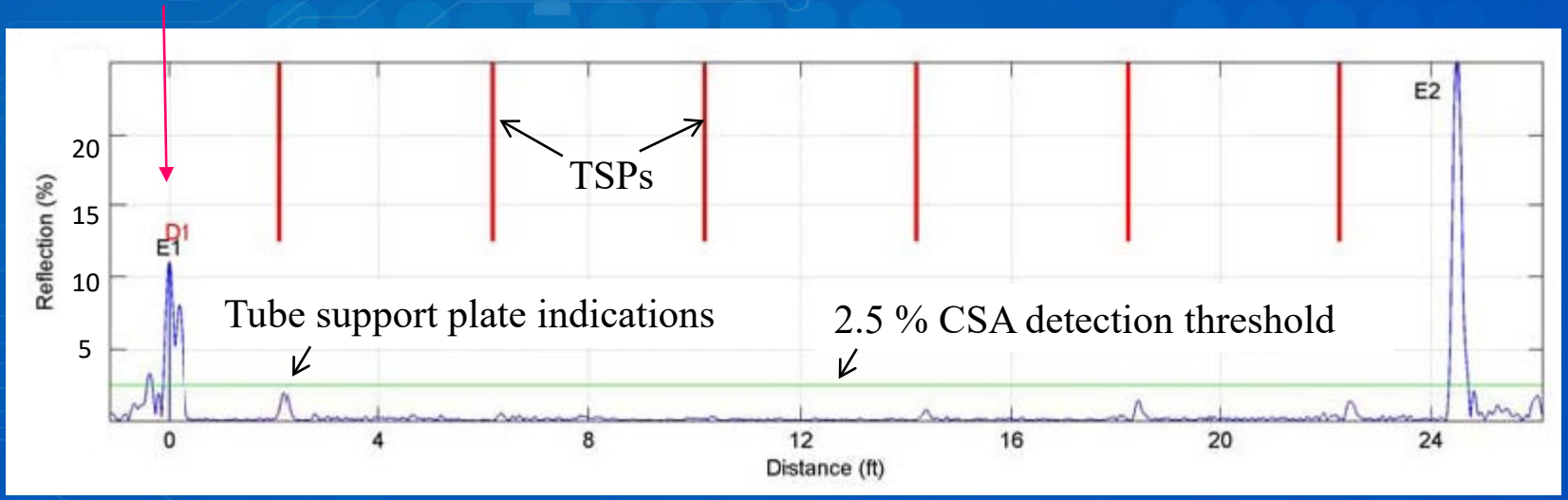


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Guided Wave Screening of Oil Lube Cooler Using Single Coil Probe



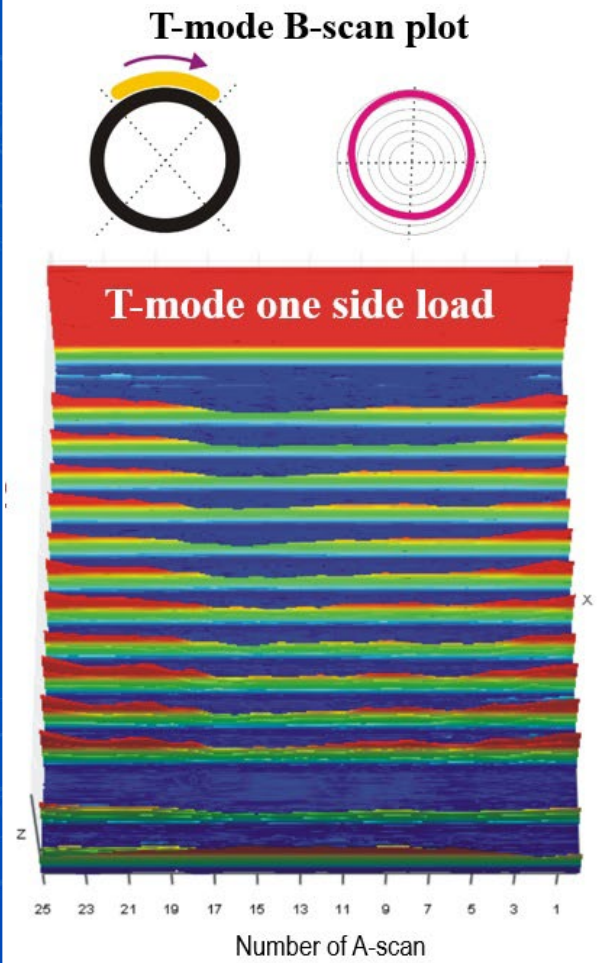
"Cross-sectioning reveals an elongated 0.001" to 0.0014" depression in the range of .055" – .060" long (50X acid etched). 494X magnification reveals plastic deformation typical of mechanical damage, OD of tube is at top.
(by Perry Holzman, "Comparison of Tube Pull Analysis Results to Guided Wave NDE Indications in SeaCure Tubing", 12th EPRI BOP Symposium, Avon, CO. 2012).

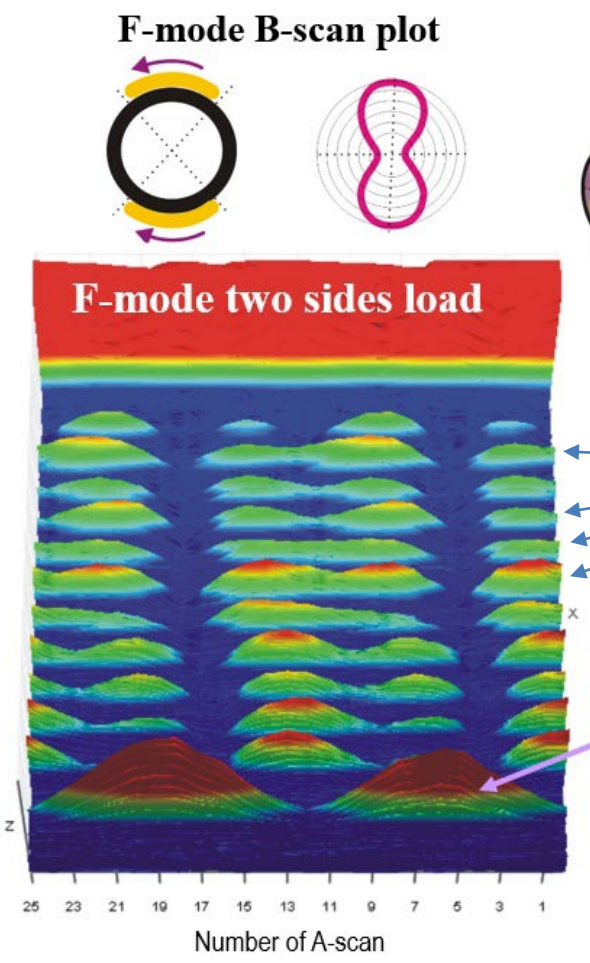


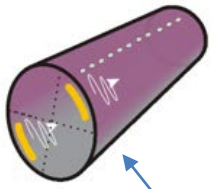
- An example of anomaly found near the rolled expansion area is presented
- The anomaly was equivalent to 3% cross-section metal loss and was overestimated partially due to lack of information about its circumferential extent
- Information about circumferential profile of indications produced by TSPs is also missing
- Clear need for a probe allowing receiving information not only about axial location of anomaly but also about its circumferential location was identified

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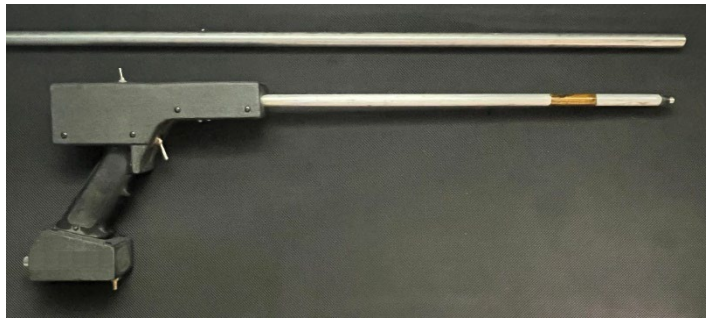
Rotating MsT EMAT Probe: T mode versus F Mode







Distribution of anomalies



Indications produced by 11 anomalies located on top side of the tube



Simulation of one side attachment produced by tube support plate (assuming that another side is not attached due to hole enlargement)

MsT EMAT probe with flexural mode function allowed obtaining information about circumferential position of anomaly

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Summary of GWT Method for HX Tubes

Advantages:

- The method allows testing of tubes that can not be tested using other methods due to deposits
- Only one foot area of the tube needs to be cleaned for probe insertion
- Full Coverage of U-bends
- Coverage of areas under TSP
- Detection of anomalies near tube sheet
- High speed ~ 30 sec / tube

Probes with focusing function allow:

- Enhanced flaw characterization including flaws under TSPs
- Early detection of TSPs hole enlargement.

Disadvantages:

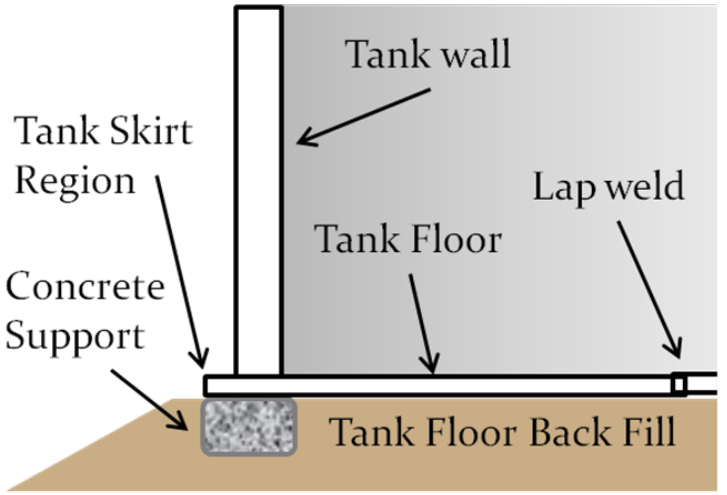
- Limited flaw depth sizing capability (ranking only)
- Inspection range depends on tube condition and some tube geometries might not support guided waves at all

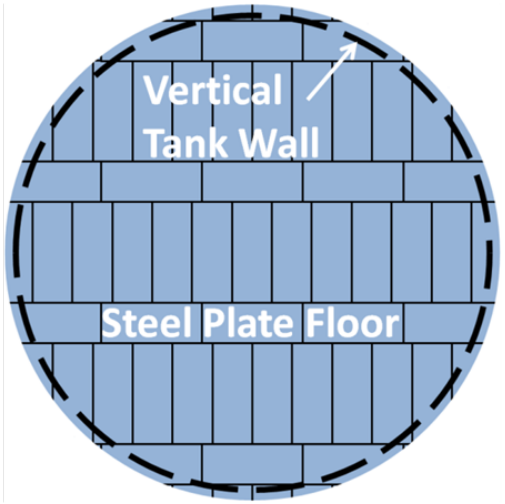
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Storage Tank Bottom Inspection

- Storage tanks can be found across many industries
  - Built by welding together a floor of plates
  - Vertical wall (shell) welded to create vessel
- Inspecting tank bottom is challenging as the vessel typically must be emptied to allow inspection
  - Time Consuming
  - Expensive
  - Unsafe



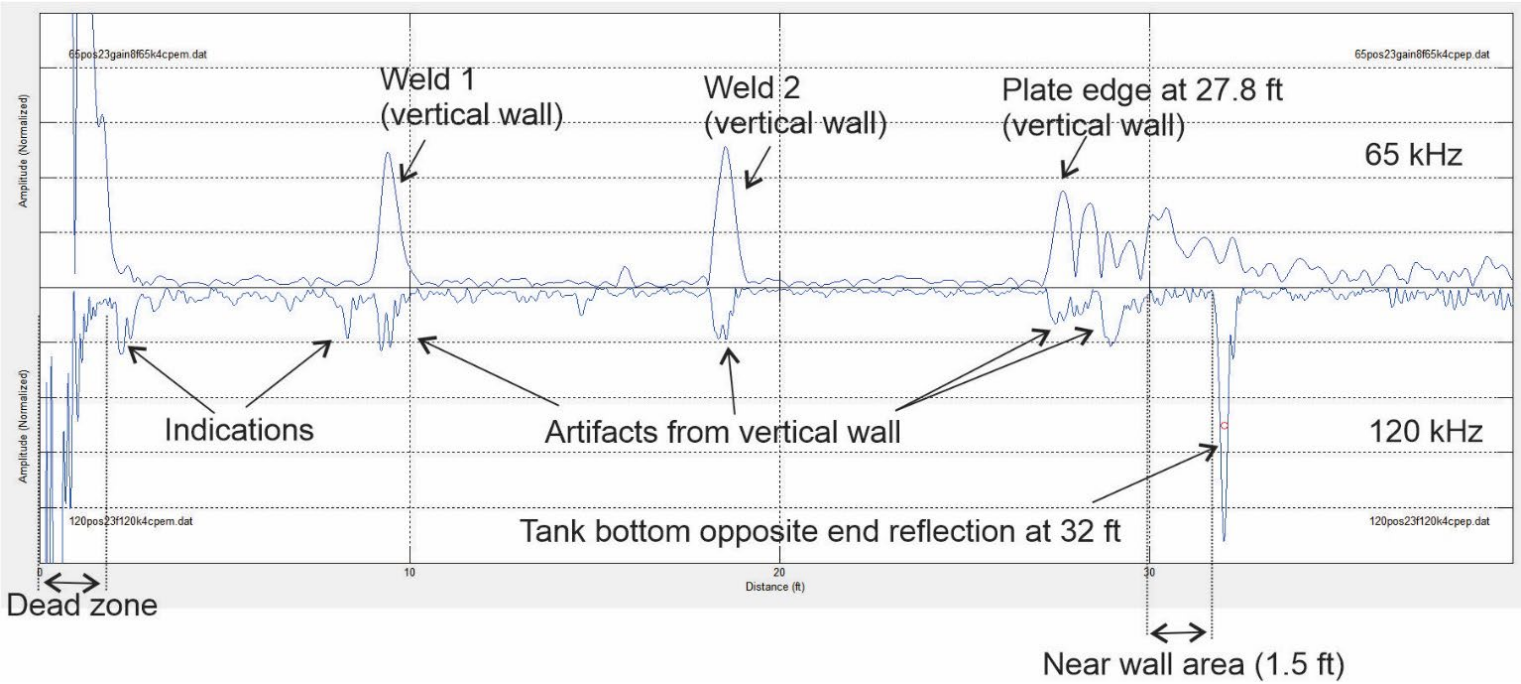


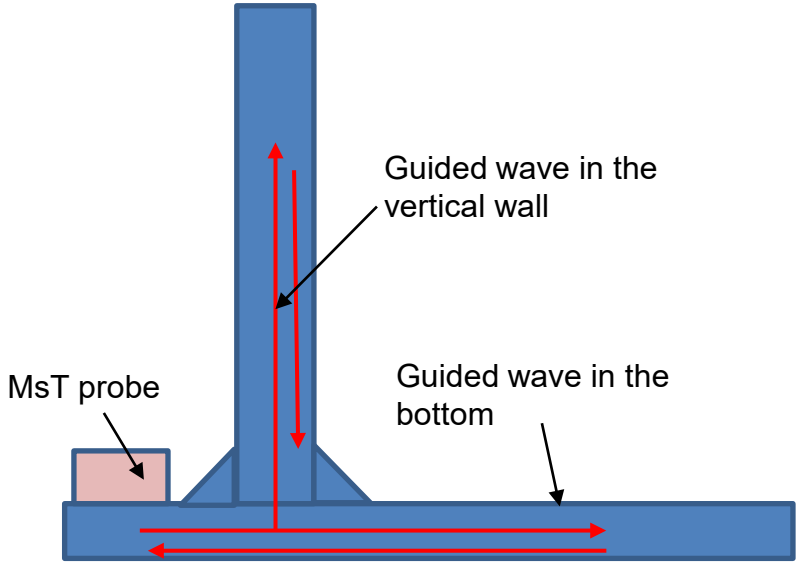


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Challenges of GWT of Butt-Welded Tank Bottoms

Data acquired from butt welded storage tank bottom at 65 and 120 kHz using SH0 mode

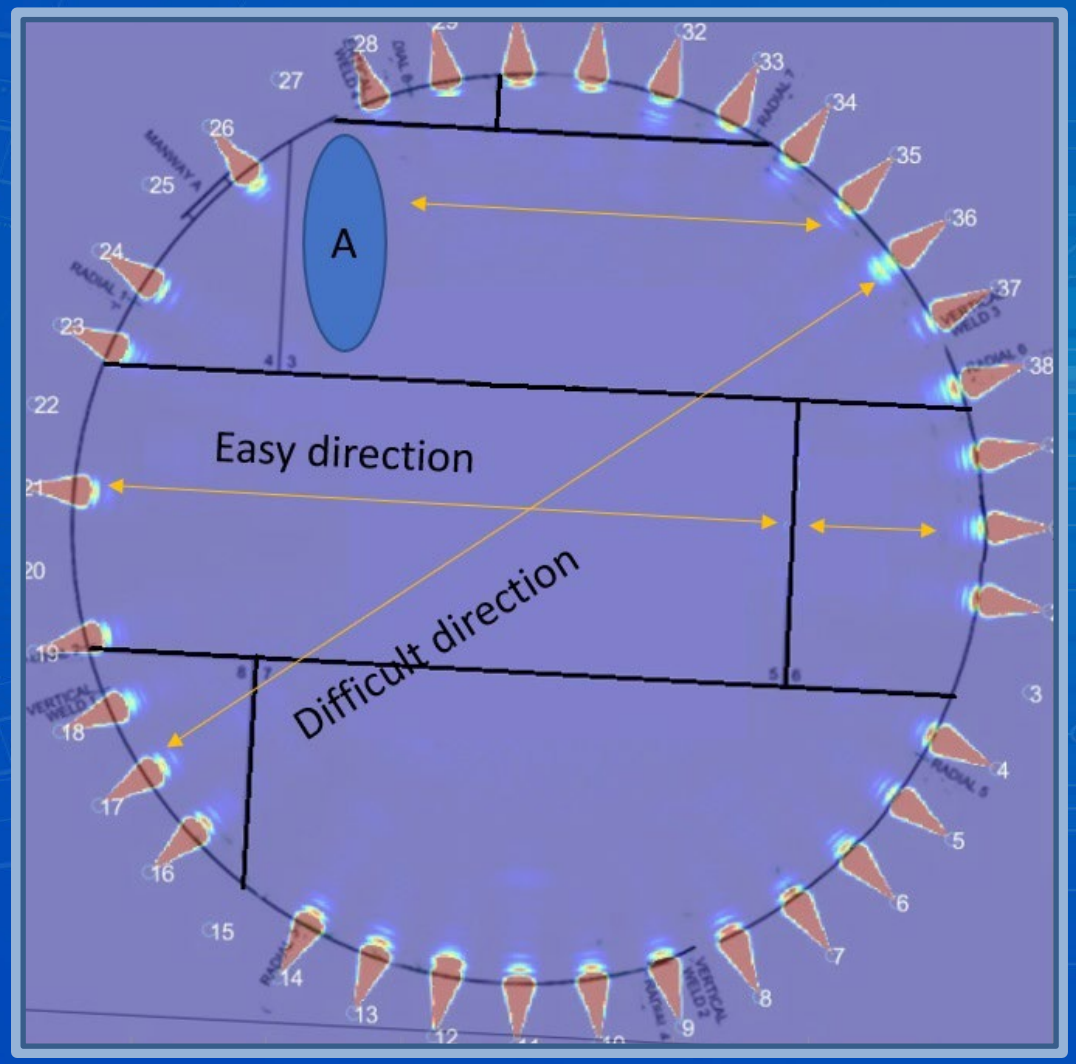




- In butt welded tank bottom guided wave covered the entire tank bottom side to side
- Guided wave energy propagates not only in the tank bottom but also in tank walls
- As a result, each A-scan has a mix of indications relevant to geometry features or anomalies
- Separation of reflections between the wall and bottom is needed to produce viable reports

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Challenges of GWT of Lap Welded Tank Bottoms

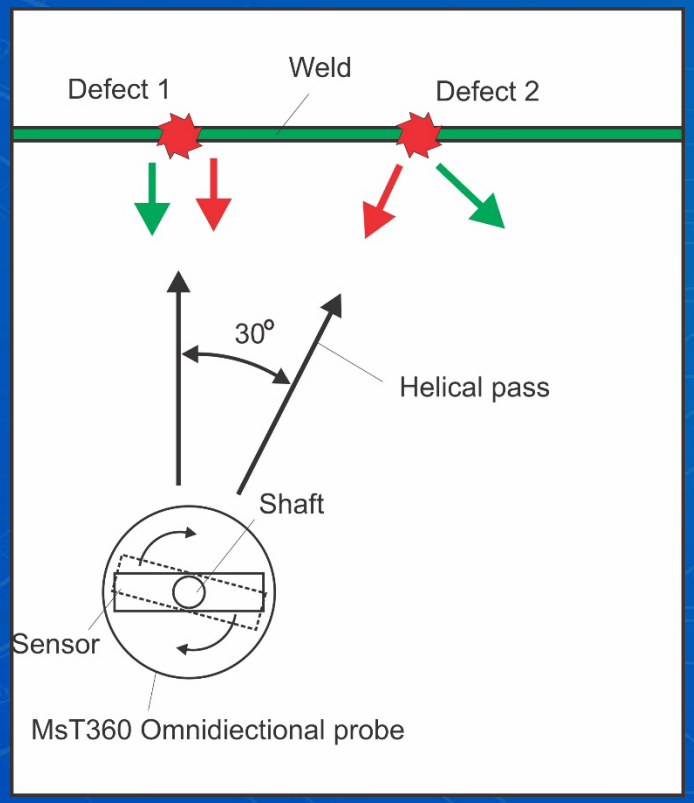


- Lap welds typically reflect the majority of guided wave energy, however larger anomalies could be detected past the first lap weld
- Beam direction avoiding lap weld crossings are marked as an ‘easy’
- Some other paths in this tank bottom could cross up to three lap welded joints (path 17 - 36) and these directions are difficult for utilization in reporting
- Full coverage of the plate could only be possible using a probe allowing beam steering or wide beam spread probe (example is area A and probe position 35)

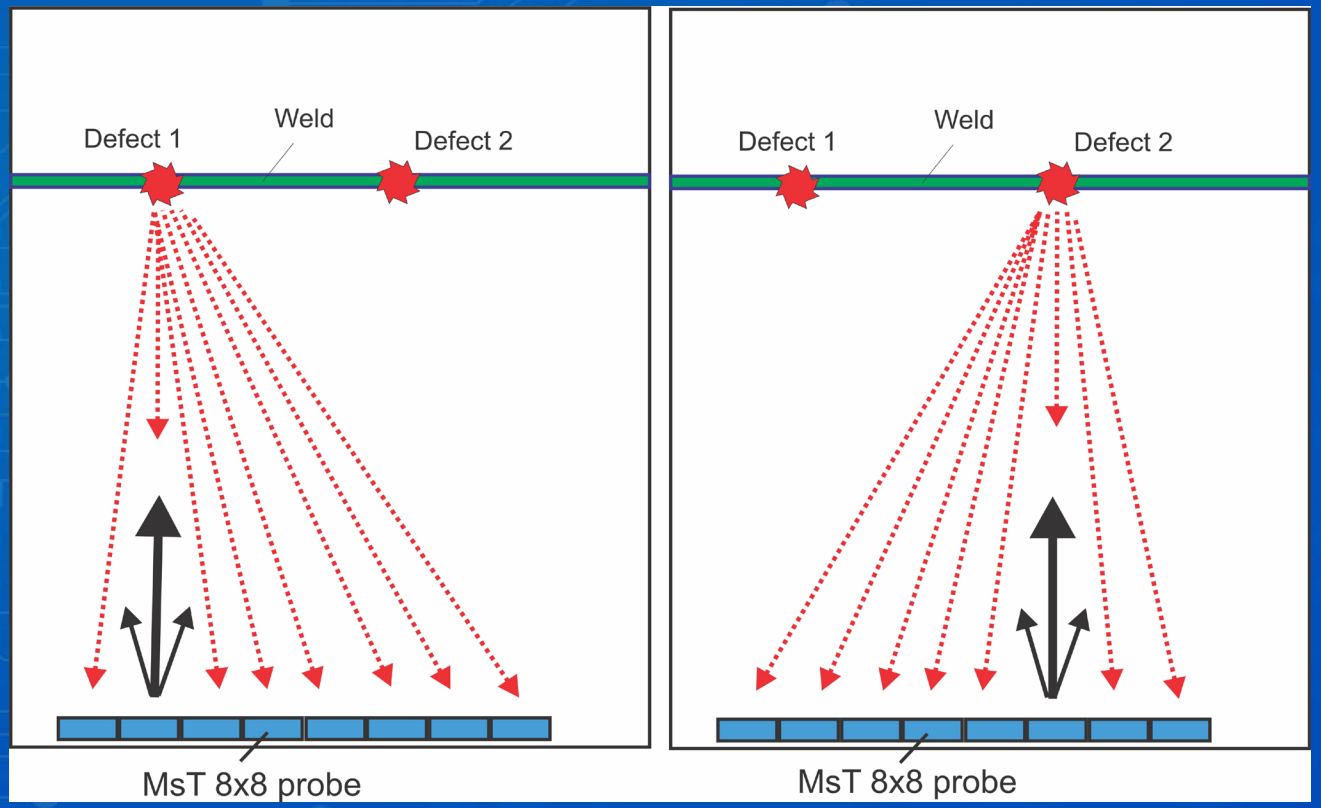
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Two Data Collection and Data Analysis Strategies

MsT 360 probe



MsT 8x8 probe with FMC/TFM function



- Strategy 1: MsT 360 probe sending sound to the inaccessible areas using rotating probe head
- Strategy 2: MsT 8x8 probe collect data in Full Matrix Capture mode and then process data using Total Focusing Method

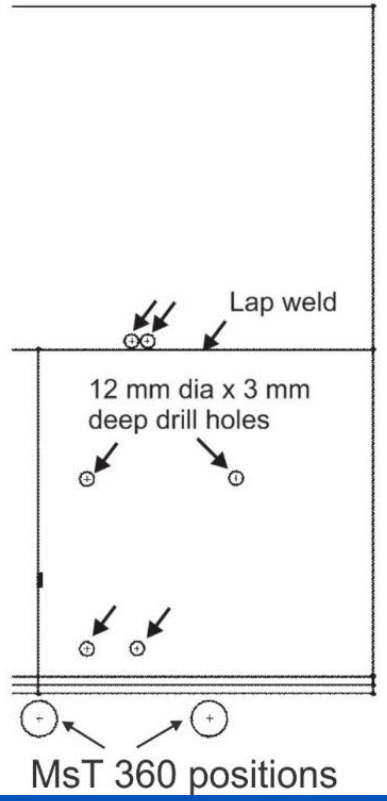
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MsT 360 Probe With Beam Steering Option

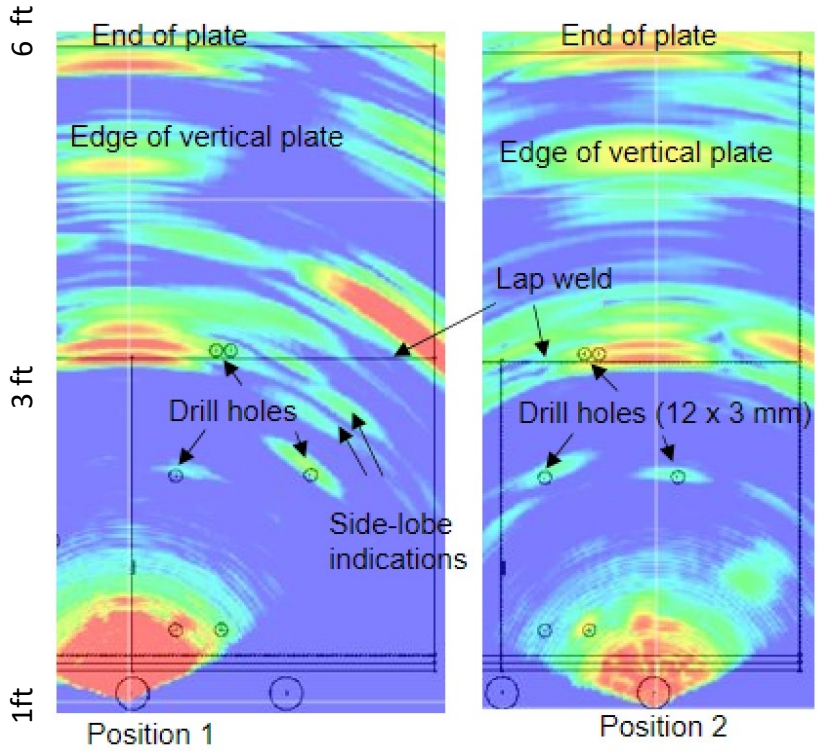
Mockup



Anomalies



Detection of anomalies in A-ring area



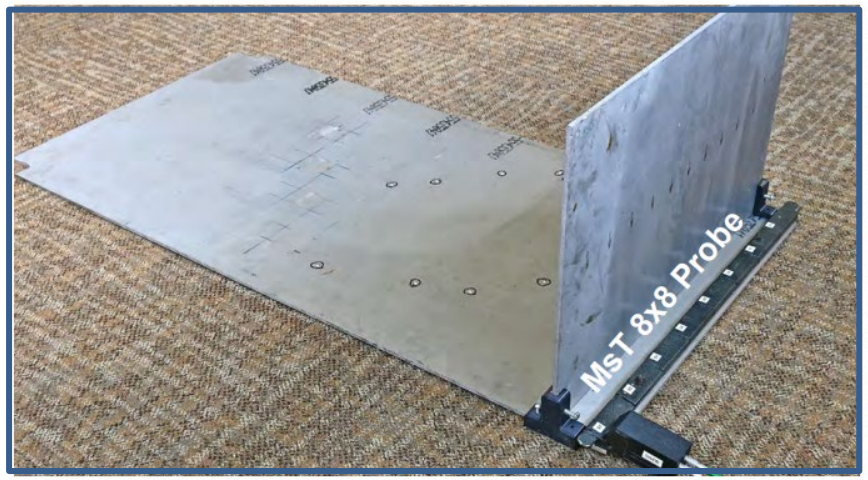
- The probe is coupled to a nickel platform coupled to the skirt using shear wave couplant
- The MsT 360 probe provides accurate beam steering with angle increment 1 – 10 degrees
- Avoids indications produced by vertical wall weld when the guided wave hits weld at angles of 20 – 40 degrees because these waves are not reflected back to the probe.

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MsT 8x8™ Probe with MsSRv5™ System

- MsT 8x8™ probe was developed specifically for tank bottom inspection from the skirt
- The MsT 8x8™ system consists of:

  - Multi-segment 8x8™ magnetostrictive transducer probe
  - MsSRv5™ guided wave instrument
  - Integrated signal multiplexer
  - Full matrix capture (FMC) acquisition software
  - Advanced analysis methods, including the synthetic aperture focusing technique (SAFT) and total focusing method (TFM)



MsT 8x8 positioned on the mockup outside the vertical wall



MsS FMC MUX Multiplexer unit

- 1:8 MUX on Receiver
- 1:8 MUX on Transmitter
- Each can be independently controlled to select any of the 8 sensor segments



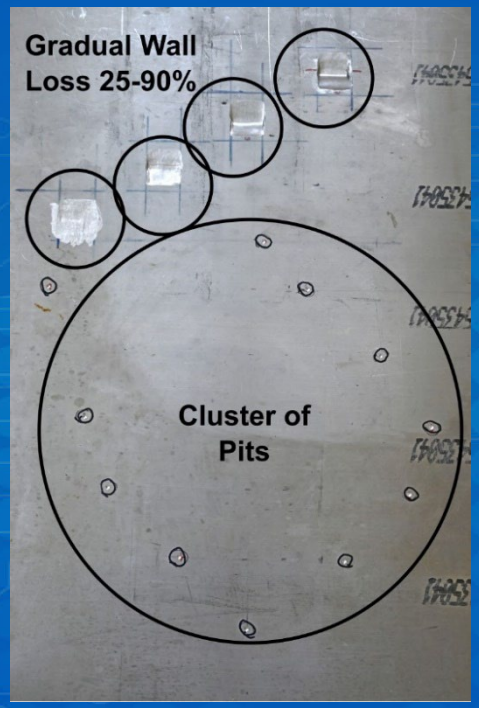
MsS RV5 pulser

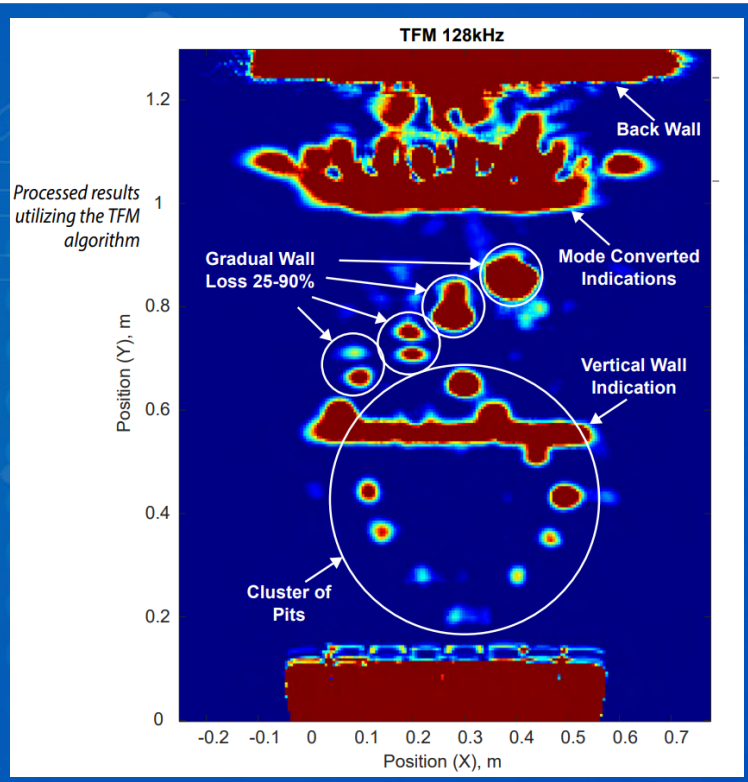
- 250 VPP Max
- 40 Amps current
- Up to 24 hours battery life
- Weight - 5 kG

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Defect Imaging in Plates Using MsT 8x8 and FMC/TFM Method







- MsT 8x8 positioned on the mockup outside the vertical wall locations
- Mockup was a 0.25 inch (6.4 mm) thick aluminum plate representing the tank floor and a second attached vertical plate representing the tank wall
- The bottom plate had a series of anomalies introduced, including 4 mm diameter 25% deep drilled holes and gradual wall loss defects, with maximum wall loss of 25% to 90%
- The probe demonstrated outstanding sensitivity to simulated pitting corrosion and gradual wall loss defects, as well as the ability to map the defect locations.

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Thank you!



Questions?

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