QUANTITATIVE MEASUREMENT OF MATERIAL DEGRADATION WITH SCANNING EMATS

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Abstract: The non-contacting and couplant-free nature of EMATs makes them particularly useful for inspections that require moving a transmitter/receiver pair over large objects in a field environment. Examples include the inspection of boiler tubes, buried pipelines, refinery piping and storage tanks. These inspections must produce a quantitative measurement of the remaining wall thickness under the deepest corrosion pit or stress corrosion crack. This implies a requirement for scanning the transducers over a considerable area to locate the most severe damage and then make a quantitative estimate of the severity of the defects. Because EMATs can be designed to excite and detect guided waves in plate or pipe structures, large areas can be inspected at the speed of sound by monitoring reflections from defects illuminated by a beam of acoustic energy directed from transducers operating in a pulse-echo mode. With this mode of operation, the scan direction will provide one coordinate of a C-scan type of image while the time-of-arrival of the echo provides the other coordinate. More important, however, several different guided wave modes can be used to form the beam of acoustic energy and the information contained in these modes can be combined to give more reliable information on the flaw dimensions. Examples will be presented to illustrate how illumination of a given flaw with different guided wave modes can be used to determine its dimensions. Supported in part by the Institute of Gas Technology and PG&E.

Introduction: Perhaps the most useful output of an ultrasonic inspection is a C-scan image that shows the location of possible flaws in a map format and displays the severity of the indications with a color scale. To perform such an inspection with conventional piezoelectric transducers requires precision mechanical bridge systems to maintain the alignment of the transducer over the surface to be inspected as well as a large water bath or squirter system to conduct the ultrasonic waves to and from the part. Non-contacting electromagnetic transducers (EMATs) can avoid much of this complexity because they launch and detect the ultrasonic waves *in the surface itself* and, therefore, are not sensitive to the exact alignment of the transducer axis and the normal to the surface. Thus, the EMAT probe can be mounted loosely on wheels or skids and simply dragged over the part in a nominal raster pattern to achieve 100% coverage *with no water bath at all.* In many applications, the structure to be inspected is a plate or pipe with its volume stretching out laterally from the sensor in one or all directions. Such a situation is an obvious candidate for Guided Wave Technology in which the acoustic energy propagates out from the transmitter in a beam trapped between the surfaces of the plate or pipe walls and is easily reflected by discontinuities in the thickness dimension such as found at corrosion pits or cracks. Since the time-of-arrival of an echo signal determines the distance between the transmitter and the reflector, it is a trivial exercise to generate a map that locates any reflector relative to the transmitter.

Figure 1 shows a basic configuration of EMATs suitable for implementing a guided wave inspection of a pipe. The transducer probe consists of a transmitter and a receiver EMAT attached to one another and separated by a fixed distance. The pair is scanned along a direction perpendicular to the line joining the transmitter and receiver– that is, perpendicular to the acoustic wave path. The output of the receiver shows a large signal arriving at a time equal to the separation distance between the transmitter and receiver EMAT divided by the group velocity of the guided wave in the plate. Signals arriving later than this Directly Transmitted signal can be interpreted as echo signals from flaws. If the amplitude versus time display (the A Scan) is drawn as the X-axis of a coordinate system, in which the receiver signal amplitude is represented by various colors corresponding to amplitudes, each sequential A-Scan can be plotted on the Y-Axis resulting in a visual representation that actually contains all of the amplitude-time information of an entire mechanical scan of a pipe.

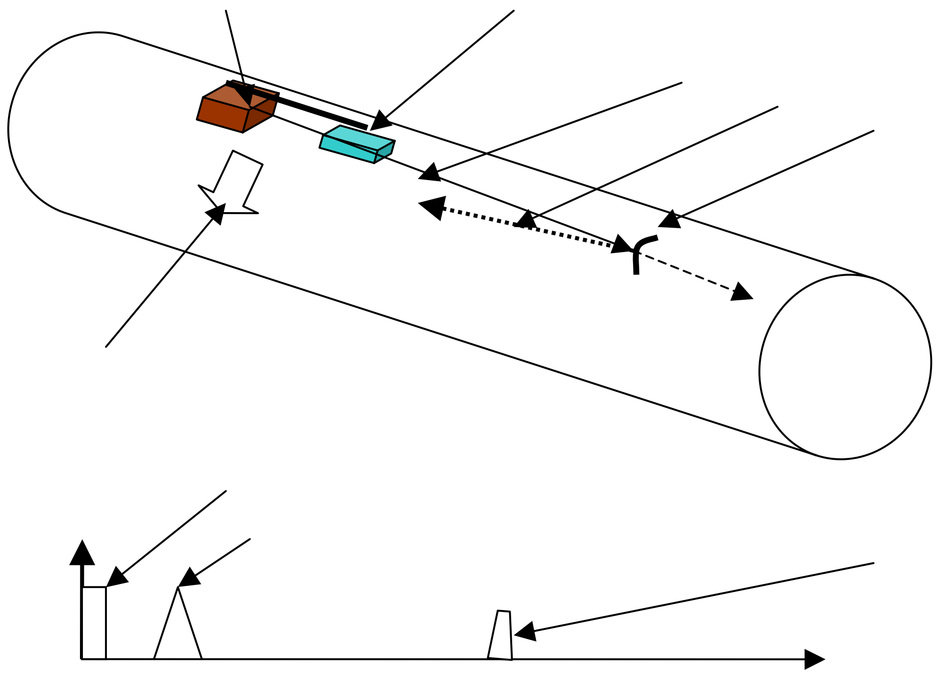

Figure 1. Schematic diagram of an EMAT system for inspecting a cylinder or pipe using guided waves propagating in an axial direction.

A two dimensional map can be created with the Y-axis of this coordinate system as the distance moved by the scanning mechanism between successive triggers of the ultrasonic system, and the acoustic arrival time as the X-axis. Areas that reflect acoustic energy will appear as colored areas at coordinates determined by the scanner position, Y coordinate, and the arrival time of the signal (times half of the velocity of sound), the X coordinate. The resulting map gives the appearance of a C-scan and, actually, contains the same ultrasonic information. Because the X coordinate is effectively scanned at the speed of sound (approximately 10,000 ft/sec) and the other coordinate is the mechanical speed of the transducer which can be as high as 30 mph (approximately 50 ft/sec), a very large area can be inspected in a short time. We have chosen to call this type of ultrasonic inspection scan an **E-scan** ™, because it utilizes EMATs and derives its speed and reliability of display on the fact that EMATs are used as the transducers.

Figure 2 shows an example of an E-scan produced by scanning a transmitter/receiver pair of EMATs in a circumferential direction past a row of four simulated corrosion pits in a 14” dia. x 0.25” wall pipe. The simulated pits were hemisphere shaped depressions 1” in diameter with depths of 20, 40, 60 and 80 percent. The pits were arranged along a circumferential path around the pipe as shown in the photograph.

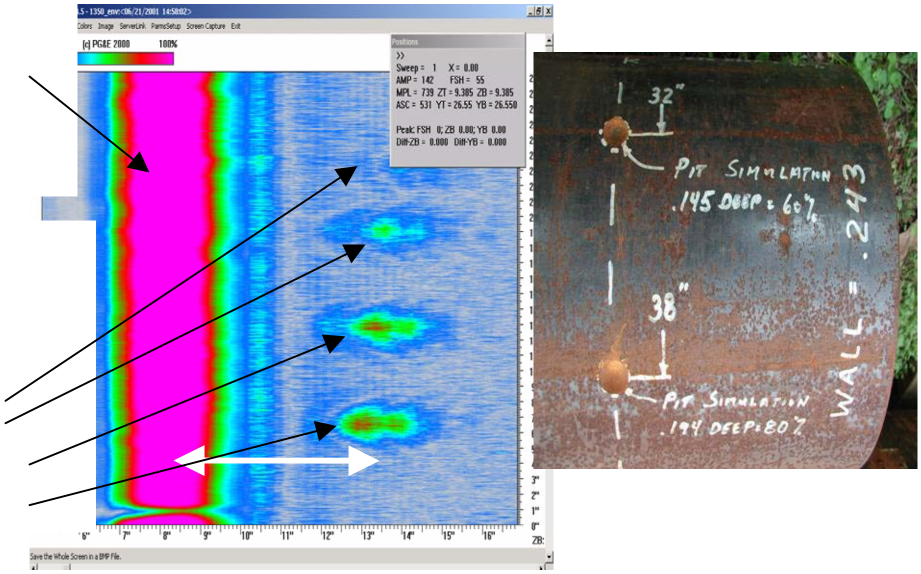

Figure 2. Example of an **E-scan** of a 14" diameter x 0.25" wall pipe containing simulated corrosion pits in the form of 1" diameter. hemispherical depressions with depths of 0.050" (20%), 0.102" (40%), 0.145" (60%) and 0.194" (80 %).

The simulated flaws were 10" from the circumferential scan path of the EMAT receiver. Besides the speed of inspection and the C-scan appearance of the **E-scan** method, this technique has several additional features that make it particularly useful for field inspections: These are: (1) The Direct Transmission signal measures the amount of energy in the ultrasonic wave incident on a flaw so that the ratio of the echo signal to the direct transmission signal measures the absolute reflectivity of the flaw, which is a more reliable measure of the severity of the flaw than a simple echo amplitude; (2) If the flaw is located between the transmitter and receiver, the attenuation of the signal when it passes the flaw can be used to detect, as well as characterize, the flaw *independent of the flaw's orientation* and its ability to form a detectable back-reflection echo; (3) The shift in arrival time of the signal transmitted past the flaw is a measure of the phase shift caused by the flaw and is an additional signal feature available for characterizing the severity of the flaw. (4) Different Lamb wave modes can be excited and detected with the same mechanical set-up by simply changing the transmitter drive frequency or switching between different coils mounted under each EMAT magnet:

Results: The following paragraphs present examples of how the E-Scan inspection mode has been used to detect and measure various flaws that are commonly found in the inspection of tubular products.

1.*Detection of misoriented flaws.* A serious drawback of the ultrasonic pulse-echo technique is that it is insensitive to flaws that reflect energy at an angle to the incident beam. Thus, a crack can be missed if its reflected energy goes to the side and misses the receiver. Figure 3 shows an E-scan of a similar pipe with simulated corrosion thinning as shown in Fig. 2 except the horizontal coordinate (the transit-time axis) has been expanded to show the echo reflection from the end of the pipe, beyond the flaws at the far right of the display.

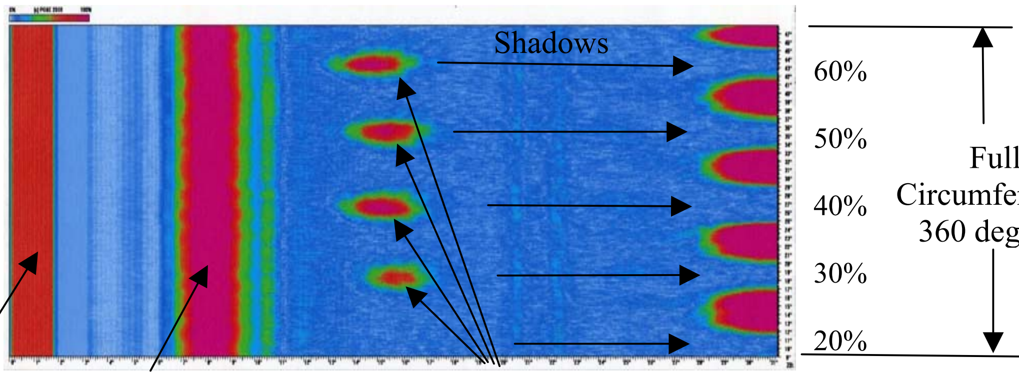

Figure 3. Complete E-scan of five simulated hemispherical thin areas in a pipe. The horizontal or time-of-arrival axis has been expanded to show the "Main Bang" at time=zero, the Direct Transmission signal at a time determined by the transmitter-receiver separation distance, the flaw echo signals whose times-of-arrival are determined by the distance between the EMATs, and the shadow of the flaw cast in the echo from the end of the pipe.

If no flaws were present in the pipe, the echo from the pipe end would have been a solid vertical line replicating the direct transmission seen on the left hand side of the figure. When the five simulated flaws were present, they would produce two features in the E-Scan. Echo signals would occur which reduce the transmitted energy beyond the flaws and, therefore, cause a local reduction in the energy that reached the end of the pipe, casting a shadow in the pipe end reflection. The right hand blobs in Fig. 3 show the end wall reflections between the shadows cast by the thinning. The Fig. 3 specimen had dish shaped thinning flaws which can reflect Guided Wave modes if the mode is properly chosen. It is important to note the reflections were *not* from a properly oriented crack, but from a dish shaped thinning which *can be* reflected, and can also casts shadows in a guided wave. Both of these effects are practical NDE affects. The guided wave mode chosen in this scan selectively reflects from thinning greater than 30% deep and thus ignored the 20% thin spot. The presence of the 20% thinning was evident by the corresponding shadow cast in the end of pipe echo. We have named this technique the Acoustic Feeler Gauge, AFG ™, which offers some quantitative information of the corrosion damage.

The shadows shown in Fig.3 show exceptional contrast because the back wall echo had to pass through the thin areas twice. If the scan was performed in through transmission fashion with the thinning in between the transducers the shadows would still be apparent as in Fig.3 but the echoes would not. If the flaws were cracks or slots inclined to the pipe axis, which would not reflect energy back to the transmitter-receiver pair, the echo would not appear on the E-Scan, but the shadow would still be present to evaluate the feature. The character of the shadow would measure the circumferential extent of the cracking, or thinning and provide some information on depth and shape. Additional information can be gleaned by analysis of the interference patterns caused by the wave packet passing the feature. These interference patterns have been an important aspect in the interpretation of damage features. The E-Scan has proved instrumental for advanced interpretations of guided wave interactions with material degradation.

2.*Quantitative display modes.* The information used to form the E-scan are stored in the computer memory as a three dimensional array of time, position, and amplitude. This data can be manipulated in several ways for quantitative analysis. Figure 4 shows an example of a quantitative enhancement to the E-Scan. The arrival time versus position line graph is useful for measuring the change in sound velocity that results from passing through a flaw. For guided waves whose velocity depends on the thickness, these time shifts can be used to estimate the remaining wall thickness in the corroded region. The amplitude versus position line graph is useful for measuring the details of the “shadow” cast by a flaw and, therefore, the total amount of energy scattered out of the ultrasonic beam by the flaw. This energy loss can be correlated with the volume of material lost to corrosion and the shape of the flaw area. If the X coordinate (time-of-arrival) and Y coordinate (the scanning steps) of the E-scan are expanded to show the individual pixels that make up the display, a very detailed picture of the inner structure of the RF signal can be displayed. This is shown in the left portion of Fig. 4. For guided waves that are dispersive, this expanded view gives information on the group velocity, the total energy in the signal, and the phase velocity along paths that cross the flaw at different circumferential locations. An analysis of the relationship between these velocity variations and the detailed dimensions of the flaw go beyond the scope of this paper and will be discussed in future publications.

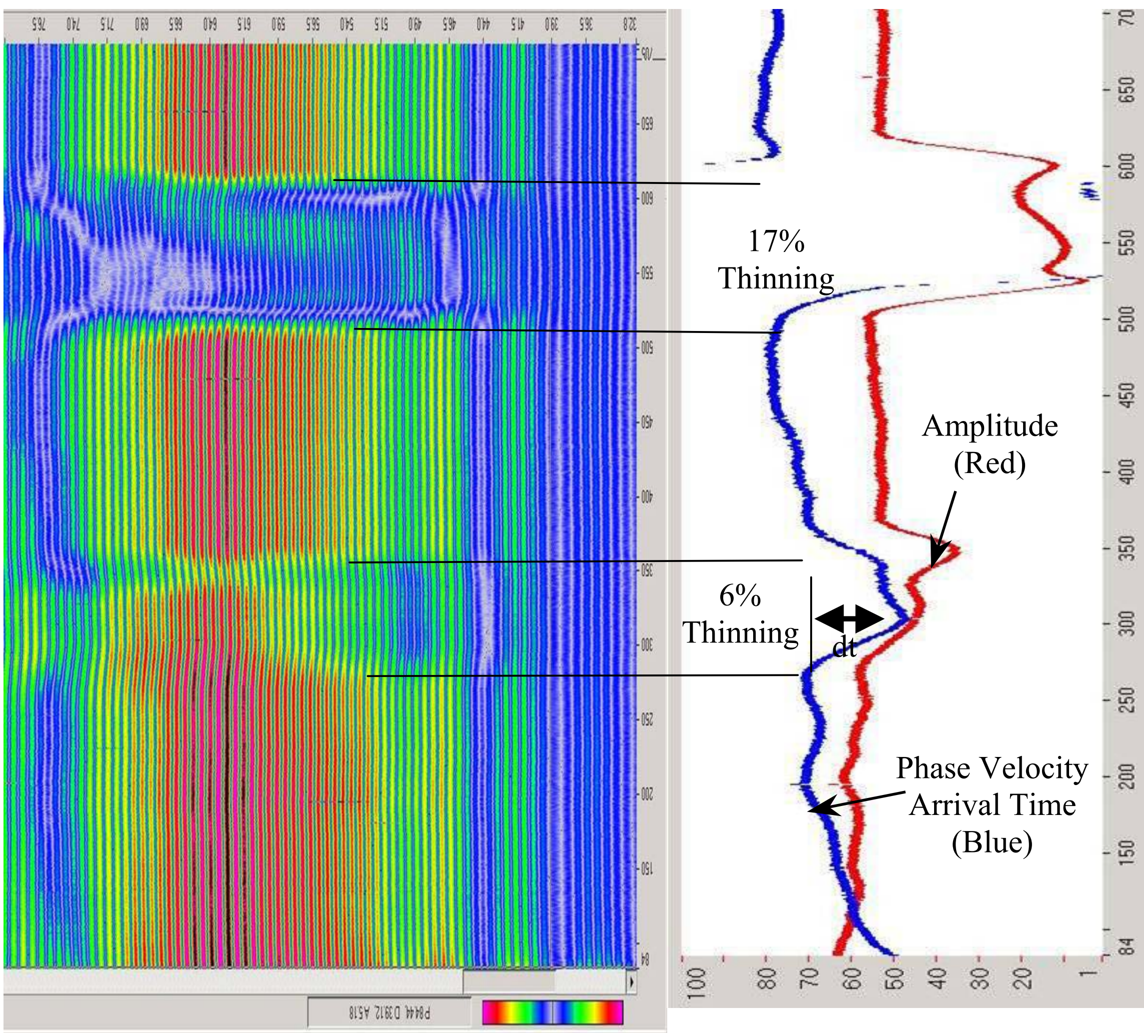

Figure 4. Line Graph Enhanced display of an E-scan. (Left) E-Scan of Lamb wave through two localized thin areas. The change in amplitude was clear but the change in arrival time through the 6% thinning was less obvious. (Right) Line graphs of the amplitude and phase velocity enhance the change in velocity through the 6% thin area.

3.*Quantitative Measurements of Flaw Size.* When a Guided Wave passes into a corroded region of pipe, it encounters a pipe wall whose thickness varies with position. All guided waves have propagation velocities that depend on the thickness of the plate supporting them so as the thickness of the pipe wall changes, the wave will slow down or speed up depending on the local

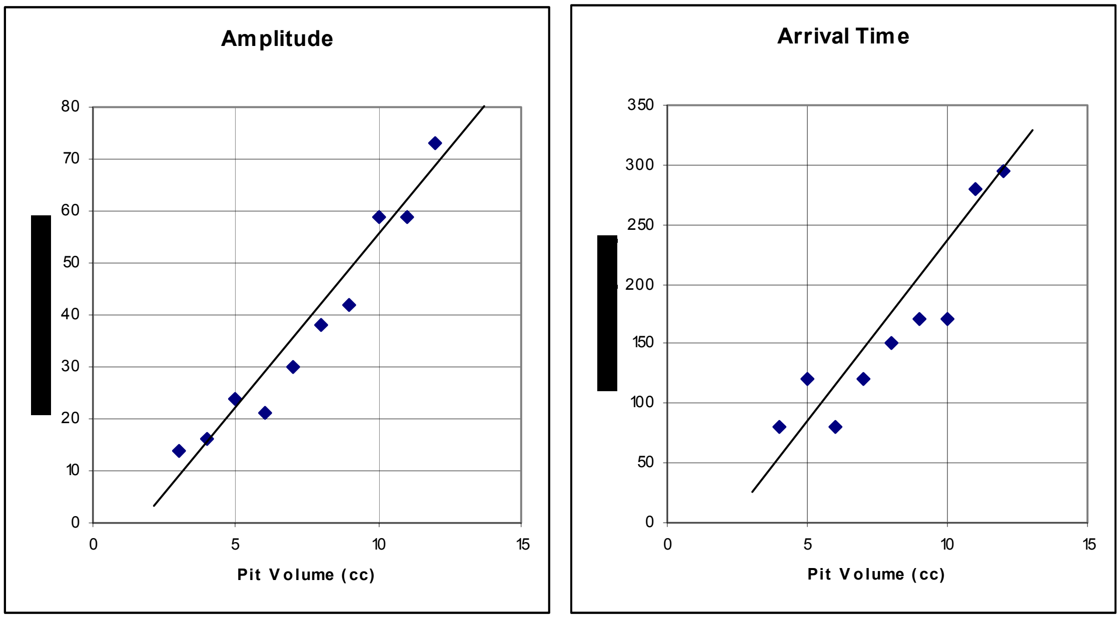

Figure 5. Correlation observed between the amplitude drop and the shift in transit-time of a guided wave passing through real corrosion and the volume of that corrosion.

thickness it encounters. Therefore, the wave that has passed through a corroded region will exhibit an arrival time that depends on the length of time it spent at each thickness level. To a first approximation, the change in arrival time of a guided wave that has passed through a corroded region should be proportional to the average thickness, times the average length, of the corroded region. This, in turn, is proportional to the volume of material missing from the corroded region. A similar argument can be made for the change in amplitude of a sound wave that has passed through corrosion. Here, the energy scattered out of the sound beam should be proportional to the depth of the individual pits times the number of pits in the length of the region – again, a quantity proportional to the volume of material missing from the corroded region. Figure 5 shows two graphs that expose a linear correlation between the measured arrival-time shift and the percentage change in signal amplitude as a function of the volume of material removed from the pipe This data shows the EMAT Guided Wave results from real corrosion in boiler tubes which was quantified by TOFD and metallography.

4. *Mapping of Corrosion Damage.* A very useful application of the E-scan technique is the mapping of corrosion damage in areas of a pipe that are inaccessible. Such areas occur under pipe supports, at the entrance to concrete vaults or when the pipe enters the ground. Corrosion is very likely to occur in the first 5 or 10 feet from where visual inspection becomes impossible. By placing the EMAT transmitter/receiver pair on the pipe adjacent to the inaccessible region and scanning them around the circumference, an E-scan presentation of the echoes from the first 5 or 10 feet of hidden pipe can be produced. Figure 6 shows an example of such a scan made on a corroded, 30” diameter pipe that had been unearthed in order to expose the true nature of the corrosion. Here, circumferential scans were made with three EMAT pairs operating at three different guided modes. Each wave mode responded to the corrosion with a different sensitivity to pits of different depth. A photograph of the pipe is shown on the left with three E-scan presentations on the right. In this example, the EMAT pair was located upstream from the

severely corroded region and the mechanical scan coordinate was circumferential, and shown horizontal in the figure. The time-of-arrival coordinate is in the axial direction and vertical in the figure. The large signal (or pair of signals) extending across the top of the figure at the top of the E-scan is the direct transmission signal, which appears irregular because pitting corrosion under the EMATs reduced their efficiency along the scan path. Two Direct Transmission signals appear in the high resolution scan because two guided wave modes with differing group velocities were generated by the EMATs.

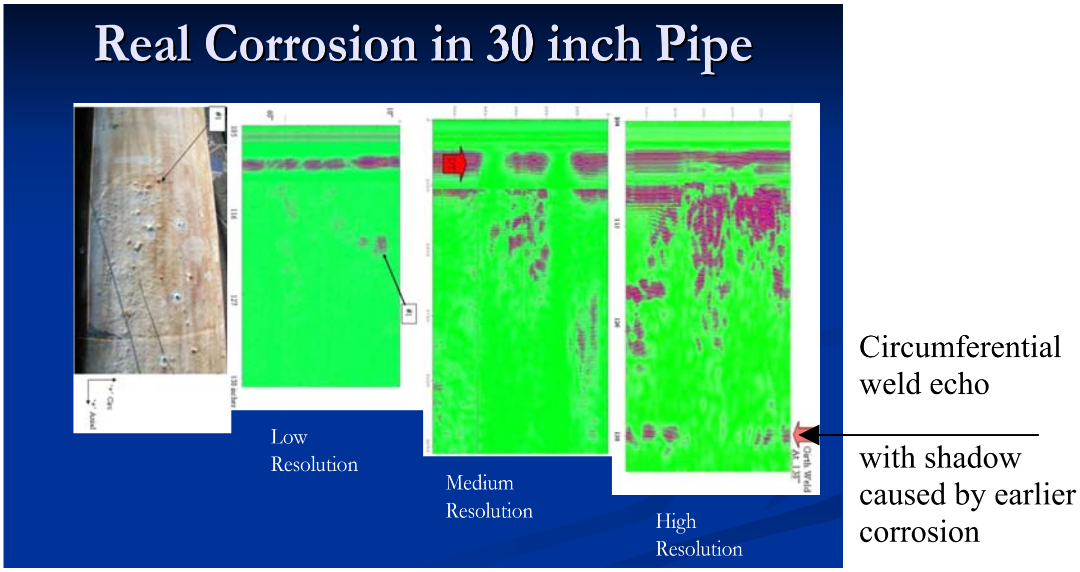

Figure 6. Three E-scan presentations of a field of general corrosion and pits near a circumferential weld in a 30” diameter pipe.

The individual echo signals displayed in the lower parts of the three E-scans were reflections from individual pits at differing axial and circumferential locations. Differing reflection amplitudes are a result of differing reflection coefficients of the pits for differing wave modes. By careful selection of the wave mode, the reflection coefficient can be designed for a desired depth of corrosion. The use of multiple wave modes can quantify corrosion depth by bracketing into different groups as shown in Fig.6. For example low resolution detects corrosion greater than 70%, medium resolution detects corrosion greater than 50% and the high resolution could detect corrosion greater than 30%. The tool works like a mechanical feeler gauge detecting remaining wall, less than a fixed value, except it works acoustically. We have called this technique the Acoustic Feeler Gauge, AFG ™. Clearly, the ability to collect pulse-echo data with different sensitivities to depth is a very useful tool in making quantitative measurements of the severity of the corrosion.

Conclusions: Because EMATs excite and detect ultrasonic waves at the surface of the part without a coupling layer of liquid or grease, they are able to deliver very reliable coupling to metal parts, and therefore, are able to operate under adverse environmental conditions. In particular, they can be scanned over large areas with simple scanning mechanisms and have the potential of interrogating flaws at large distances with guided waves having different characteristics. This latter property is destined to make possible new improvements in the ability to size and characterize a flaw found by conventional pulse-echo techniques. By designing the scanning system to deduce one coordinate from time-of-flight measurements and the other from a distance encoder, a large ultrasonic map similar to a C-scan can be produced easily and quickly. Several examples of the maps, called E-scans, have been presented in the text.