APPLICATION OF QUANTITATIVE NDE TECHNIQUES TO HIGH LEVEL WASTE STORAGE TANKS

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ABSTRACT

As various issues make the continued usage of high-level waste storage tanks attractive, there is an increasing need to sharpen the assessment of their structural integrity. One aspect of a structural integrity program, nondestructive evaluation, is the focus of this paper. In September 2000, a program to support the sites was initiated jointly by Tanks Focus Area and Characterization, Monitoring, and Sensor Technologies Crosscutting Program of the Office of Environmental Management, Department of Energy (DOE). The vehicle was the Center for Nondestructive Evaluation, one of the National Science Foundation's Industry/University Cooperative Research Centers that is operated in close collaboration with the Ames Laboratory, USDOE. The support activities that have been provided by the center will be reviewed. Included are the organization of a series of annual workshops to allow the sites to share experiences and develop coordinated approaches to common problems, the development of an electronic source of relevant information, and assistance of the sites on particular technical problems. Directions and early results on some of these technical assistance projects are emphasized. Included are the discussion of theoretical analysis of ultrasonic wave propagation in curved plates to support the interpretation of tandem synthetic aperture focusing data to detect flaws in the knuckle region of double shell tanks; the evaluation of guided ultrasonic waves, excited by couplant free, electromagnetic acoustic transducers, to rapidly screen for inner wall corrosion in tanks; the use of spread spectrum techniques to gain information about the structural integrity of concrete domes; and the use of magnetic techniques to identify the alloys used in the construction of tanks.

INTRODUCTION

There are currently about 250 underground tanks storing high-level waste at DOE facilities at Hanford, Savannah River, Idaho National Energy and Environmental Laboratory (INEEL) and West Valley. Many of these have served for more than 40 years. However, continued storage of the wastes is required since the final disposition of the contents of the tank, as a result of processes such as vitrification, will not be completed until well into this century. There are two alternatives. Construction of new tanks is technically possible. However, the costs are large, particularly in a time of constrained budgets. Hence, there is considerable motivation to continue to use these tanks for an additional 20 years or more. This paper deals with nondestructive evaluation (NDE) issues that are part of a broader aging management program for the continued use of the tanks.

The need for such a program became increasingly clear in the early 1990's, and an important step was the creation of a structural integrity panel, consisting of experts in various relevant disciplines, to provide advice to the DOE regarding structural integrity. The results of their review of the problems are found in a document providing guidelines for the development of a structural integrity program [1]. Contained therein was the outline of such a program, including detailed discussions of aging mechanisms, techniques for monitoring and controlling the associated degradation, nondestructive evaluation techniques to detect and characterize the degradation, evaluation of the results of various monitoring and NDE programs, and management options.

In 2001, the Tanks Focus Area (TFA) identified the development and coordination of new and improved technologies for tank integrity assessment as a high priority development activity. In cooperation with the Characterization, Monitoring, and Sensor Technology (CMST) Crosscutting Program, they put in place a project that involves the collaboration of five U.S. Department of Energy (DOE) main waste storage sites (Savannah River Site, Oak Ridge Reservation, West Valley Demonstration Project, Idaho National Engineering and Environmental Laboratory, and Hanford Site). The Nondestructive Evaluation Program at Ames Laboratory at Iowa State University is coordinating this project under the joint sponsorship of TFA and CMST.

The Nondestructive Evaluation Program of Ames Laboratory benefits from an intimate linkage with the Center for Nondestructive Evaluation (CNDE) at Iowa State University, one of the National Science Foundation's (NSF) Industry/University Cooperative Research Programs. In line with NSF's guidelines for such center's, CNDE is directly funded by industry (typically 20-25 companies serve as sponsors at any one time) and has the goals of performing industrially relevant NDE research, transferring the results to industry, educating the workforce needed to implement them, leading the development of techniques to integrate NDE throughout the component lifecycle, and promoting international cooperation that would lead to more uniform practice of NDE around the world.

Initial activities of this project included visits to the five DOE sites to assess tank integrity needs and subsequent organization of a workshop to identify technology issues, foster inter-site communication, and refine plans of technical activities to support the NDE needs of the sites. This paper provides a summary of those activities, with primary emphasis on the results of the technical support activities.

TANK INTEGRITY WORKSHOPS

The 1st Annual Tank Integrity Workshop was held in Atlanta, Georgia on October 31-November 1, 2000. Its goals were the following.

- To identify any significant impediments that might exist to the safe operation and management of the storage tanks, particularly those common to multiple sites
- To establish groundwork for collaborative efforts aimed at eliminating these impediments, including the development of preliminary actions plans and the improvement of networking among individuals at the various sites.

These goals were addressed through a series of technical presentations that provided an overview of activities at the individual DOE sites and of the DOE Order [2] that governs implementation of a structural integrity program based on the guidelines developed in the Brookhaven report [1]. A series of working sessions followed in which problems were identified. The working sessions sequentially identified the many positive enablers of tank integrity activities that are currently in place, followed by a discussion of remaining challenges that must be overcome. Finally, these were condensed into a series of problem statements, solutions and proposed action plans. Included among the latter were improvements in networking and communications between headquarters and the sites, and across the complex; increasing the uniformity of implementation of needed technologies by making technology experts more broadly available; encouraging the development of necessary technology improvements; and encouraging the implementation of the Order [2] by making the steps needed for its implementation more explicit. More details may be found in the Proceedings of the Workshop [3].

The 2nd Annual Tank Integrity Workshop was held in Las Vegas, New Mexico on November 13-15, 2001. Included were a review of actions that had resulted from the first workshop, updates on activities at the individual sites, a summary of technical advances such as those summarized below, and facilitated discussions designed to identify future actions needed. Included among the outputs were plans for focused meetings of corrosion experts and individuals concerned with making the guidance for implementation of the Order more explicit. In addition, plans were established to share information on a number of technical topics, including operational roadmaps for probe usage, neural network techniques to interpret electrochemical noise measurements, the applicability of probabilistic risk assessment approaches to the tanks, the sensitivity of ultrasonic techniques to various defect conditions. More details will be available in the proceedings of the workshop, under preparation at the time of writing of this manuscript [4].

SUMMARY TECHNICAL ASSISTANCE PROJECTS

In the course of these discussions, a number of technical assistance projects have been undertaken in which CNDE has supported the NDE needs of the sites. An overview of the various projects underway will be presented in this section, followed by a more detailed discussion of one in the next section.

High Speed Guided Wave Corrosion Detection Using Non-contact Ultrasonic Generation

The need to detect corrosion in tank walls presents a formidable challenge in light of the large size of the tanks. Point-by-point measurements based on ultrasonic waves propagating through the thickness of the wall can provide a large amount of detail, especially if the beams are focused. However, the data is acquired at a limited rate because of the need for point-by-point scanning, precluding the scanning of large areas in reasonable time. A technique is being developed that makes use of guided ultrasonic waves propagating along the pipe walls (sometimes knows as Lamb waves) to perform a rapid screening of tank walls for corrosion. The results of such measurements can provide a rational basis for selecting the regions in which more detailed scans are conducted. A more complete discussion of this technique is presented in the next section.

Analytical Support to Assist in the Interpretation of TSAFT Data During Inspection of Knuckles

In assuring the structural integrity of tanks, regions in which inspection is the most important include those where stresses are expected to be highest, since it is in these regions that cracks would be most likely to propagate to failure. Unfortunately, such regions are not always geometrically accessible. A case in point in the double-shell tanks DST) at Hanford is the "knuckle" region, where the sides and bottoms of the steel inner wall of the tanks are joined. It is desired to detect and size defects on the bottom of the tank, but access for ultrasonic transducers is only possible on the sides of the tank. Hence, the ultrasonic waves must propagate around the "knuckle" and information about the location and size of the defects must be extracted from the signals that have been modified by the geometry of the knuckle. A technique knows as the Tandem Synthetic Aperture Focusing Technique (TSAFT) is being used to make such measurements. However, the algorithm used for recovering flaw information depends upon the physics of the wave propagation. Roberts, Pardini and Diaz are cooperating on a study of ultrasonic wave propagation around corners to provide a basis for recovering this information in the knuckle geometry [5].

Spread Spectrum Ultrasonic Techniques to Evaluate the Integrity of Concrete Domes

The steel shells that confine the contents of high-level waste storage tanks are generally surrounded by a concrete structure that plays a major role in providing structural support. The integrity of this structure is of general interest. In the case of the single-shell tanks (SST) at Hanford, in which retrieval of the stored wastes is well underway, this general interest has been heightened by the fact that heavy equipment must sometimes be driven over the buried tanks as a part of the retrieval process. Hence, the ability of the concrete to support the design loads must be assured. Ultrasonic techniques are often used to assess the structural integrity of concrete [6,7]. However, their application to a buried structure with limited access is far from straightforward. Spread spectrum techniques have been shown to be able to detect very small changes in concrete structures in other application areas [8], and the possibility that they can be adapted to characterize the domes of SSTs is being investigated by Wormley and Russell [9].

Characterizing Steel Alloys Based on Their Magnetic Properties

As part of the analysis of the structural integrity of steel shells, it is important to know the fracture toughness of the material, a parameter that is used in determining whether a given crack, in the presence of a specified load, can be expected to fail. For a given set of loading conditions, the greater the fracture toughness, the larger a defect can be before it can be considered to critically compromise structural integrity. The fracture toughness is influenced by the alloy and its microstructure. Due to the age of the tanks, there is not always as good a record of the material from which it was constructed, particularly in light of the priority that was placed upon speed of fabrication in light of military objectives. Correspondingly, there is a need to be able to nondestructively characterize the steels that are present in the tanks. Measurement of various aspects of the hysteresis loop of the material can provide such information [10], and Johnson has demonstrated the ability to differentiate a limited number of selected samples [11].

HIGH SPEED GUIDED WAVE CORROSION DETECTION USING NON-CONTACT ULTRASONIC GENERATION

Current Ultrasonic Inspection Methods

Tank waste at the Hanford site is stored in 149 underground SSTs constructed 1943-1964, and 28 underground DSTs constructed 1968-1986. A NDE program for the DSTs is underway. Through fiscal year (FY) 2001, portions of the primary tank for twelve DSTs have been examined by ultrasonic testing (UT) from within the annulus of each DST. Current plans call for the remaining sixteen DSTs to be examined from FY 2002 through FY 2004, with subsequent reexaminations of DSTs on a five-year cycle through the end of the waste storage mission (2028 or later).

Ultrasonic examination is currently performed using a P-scan™ system (manufactured by Force Institute in Denmark, and distributed in the US through Swain Distribution, Inc., PO Box 99, Searcy, Arkansas.) The P-scan™ system employs a remotely operated magnetic wheeled crawler supported by CCTV cameras. A traveling bridge attached to the crawler is outfitted with ultrasonic sensors. The traveling bridge and crawler move in orthogonal directions, permitting examination of an area circumscribed by the travel path of the crawler and the sweep of the traveling bridge. The crawler is programmed to continuously change positions in small increments along its travel path. At each position, the traveling bridge traverses the tank surface at a constant rate across its range of motion.

Short bursts of high-frequency ultrasonic energy from the transducers carried by the traveling bridge propagate straight or at an angle into the tank wall at increments along the path of the traveling bridge. Reflected beam signals from each incremental X-Y position on the scanned surface of the tank are collected and transmitted back to the data acquisition system. Water couplant is continuously fed to each transducer at a rate needed to maintain an acceptable signal. The data is recorded in electronic memory for post-inspection analysis by qualified inspectors for measurement of wall thickness and determination of presence and geometry of cracks, pits, or other anomalies.

Access to the tank walls for ultrasonic examination is accomplished through one of a pair of 24-inch risers that were constructed opposite each other. The area of the primary tank accessible for ultrasonic examination through a 24-inch riser is limited by vertical pipes in the annulus adjacent to the primary tank wall that deliver ventilation air for cooling. There are eight such pipes per tank, equally spaced around the tank circumference. Thus the area of the vertical cylindrical portion of the primary tank wall accessible through a 24-inch riser is approximately 25 feet in width by 35 feet in height.

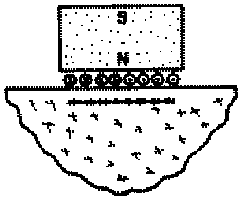
Current practice at Hanford includes examination of a 30 inch wide by approximately 35 foot long area of the primary tank, via two 15 inch wide vertical strips. Presently these vertical strips are aligned, for convenience, with the 24-inch access riser. Together these two vertical strips cover approximately 1% of the area of cylindrical portion of each primary tank, and approximately 10-12% of the area of the primary tank vertical wall accessible between adjacent ventilation supply pipes. Questions have been raised as to whether examination of only 1% of the tank surface provides a sufficient level of confidence to adequately assess tank integrity and support decisions on continued tank use vs. tank replacement.

It typically takes approximately 3 weeks of field work to perform the two vertical scans. Increasing the coverage of the existing P-scan system to examine, for example, the entire area accessible between two adjacent ventilation pipes could take up to 30 weeks, thus significantly increasing per tank examination costs, and significantly reducing the number of tanks that could be examined each year.

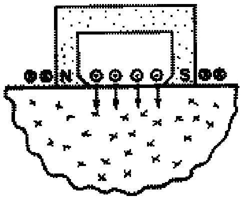
Electromagnetic Acoustic Transducer Principles and Operation

Electromagnetic Acoustic Transducer technology provides an alternate method of generation of the acoustic waves for examination of the tank wall that removes the need for a physical couplant between the transducer and tank wall. The physical principle underlying the generation of an acoustic wave using an EMAT involves the generation of Lorentz forces [12]. When a wire is placed near the surface of an electrically conducting object and is driven by an alternating current, eddy currents will be induced in a near surface region of the object. If a static magnetic field is also present, these eddy currents will experience Lorentz forces. The forces allow for a wave to be generated inside the part to be examined without the need for physical contact between the EMAT and the material to be inspected. In ferromagnetic materials such as the walls of steel plates, there are additional magnetostrictive forces [12]. These augment the Lorentz forces but will not be discussed here because of space limitations.

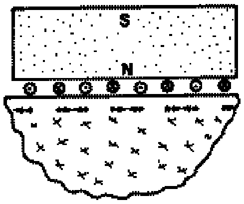
Various configurations of the wire coil and permanent magnet can be used to generate different types of acoustic waves as shown in Figure 1. In each case the coil is driven by a pulsed electrical current of the proper frequency to generate the desired wave. The combination of the electric field forces and the magnetic field force create ultrasonic waves that propagate normal to the surface against which the EMAT is applied as in the top two illustrations or under proper conditions can generate waves that propagate parallel to the surface. Depending on the particular inspection being performed, a single EMAT can serve as both the transmitter and receiver in a pulse-echo configuration or a separate EMAT can be used as the receiver in a configuration known as pitch-catch.



Spiral wound coil creating radially polarized shear waves propagating normal to surface



Tangential field EMAT excites longitudinal waves propagating normal to surface



Meander coil EMAT for exciting obliquely propagating L or SV waves, Rayleigh waves, or guided modes (such as Lamb waves) in plates.

Fig. 1. Coil and magnet configurations generating various types of ultrasonic waves.

When placed on a plate of finite thickness, the configuration shown in the bottom of Figure 1 creates a set of acoustic waves that are known as "Lamb" or "plate" waves.

These waves are generated with two EMAT transducers in a pitch-catch mode to propagate in a plate-like structure. In general, these waves fill the volume of the plate and in the appropriate mode and configuration are sensitive to the thickness of the plate as well as any isolated defects that occur at the surfaces of the plate. Characterization of plate and tube materials using these types of "guided" waves has been well known for a number of years [13]. Variations in the transit time of the propagating wave can be used as a monitor of the thickness of the material for detection of areas of general corrosion on the surfaces of the plate. Changes in the amplitude of the wave similarly can be used as an indicator of obstructions to the wave such as isolated pits or cracks. Commercial systems for detection of these conditions have been developed and are currently in use for pipeline inspections.

A major benefit to be obtained using acoustic waves generated using EMATs is the ability of such transducers to work through a less than optimum surface. In contrast to conventional ultrasonic inspection whereby the ultrasonic energy is created in a vibrating crystal and transmitted through the material surface into the component being inspected, EMATs create the ultrasonic wave inside the component. Detection of the transmitted wave is performed by the combination of electric and magnetic fields at the receiver making transmission of the sound wave through the surface unnecessary. As such then, the condition of the surface of the material becomes much less important. The separation distance between the EMAT and the surface, known as "lift-off", remains an important parameter. Proper design of the EMATs however can minimize any problems due to lift-off changes.

Description of Lamb Waves

Lamb waves (named for their discoverer) are generally produced using conventional piezoelectric transducers. In this case, a compressional wave of suitable angle of incidence and frequency is introduced into a plate specimen. The transmission and mode conversion that occurs as this wave passes into the plate generates a series of waves that combine to fill the volume of the plate and propagate along the length of the plate with a uniform profile of displacements across the plate thickness (in analogy to the electromagnetic modes of a waveguide). These waves generally contain a component of oscillation perpendicular to the surface of the plate and occur in an infinite number of modes. These modes are grouped into two main classes depending on the symmetry of the distribution of particle displacement with respect to the neutral axis of the plate. In symmetric waves, the neutral axis particles have only longitudinal oscillations and the displacement pattern is symmetric about this plane. In the asymmetric waves, the mid-plane particles have transverse oscillations and the displacement pattern is anti-symmetric about this plane.

In both cases the velocity of the wave depends on a number of factors; the plate thickness, the plate material, the frequency of the wave and the mode order. In addition, both the phase velocity (the velocity of a particular wave crest) and the group velocity (the velocity of a short packet of waves) can be measured and are found to be different. In general, the properties of the two modes differ in sensitivity to various defects.

Symmetric waves are generally more sensitive to obstructions to the wave as is the case for pitting and cracking. These flaws can often be best detected using changes in the amplitude of the symmetric wave. Asymmetric waves, however, are generally more sensitive to changes in the thickness of the plate as occurs with generalized corrosion. Measurement of the phase velocity of the asymmetric modes is considered to be the most sensitive Lamb wave property for thickness changes.

Generation of the Lamb waves using EMAT transducers differs somewhat in detail from piezoelectric transducers but is identical in effect [12]. By judicious selection of the frequency in combination with the plate material and thickness, the most appropriate wave mode and mode order can be selected for the desired inspection. Variation of the group velocity between the various Lamb waves is generally the best method to identify the desired mode. Calculation of the group velocity based on the material, thickness and frequency is readily accomplished. Such a calculation is shown in Figure 2. This graph is calculated for an EMAT with a wavelength of 0.320 inches for steel plates and shows the group velocity as a function of the plate thickness for the various Lamb modes and a Rayleigh Wave. The designation of the Lamb modes is S0 for the 0th order symmetric mode up to S2 and A0, 1 and 2 for the asymmetric modes. For a known thickness plate and transducer separation, identification of the wave for the desired mode can be achieved by observation of the transit time for the various echoes.

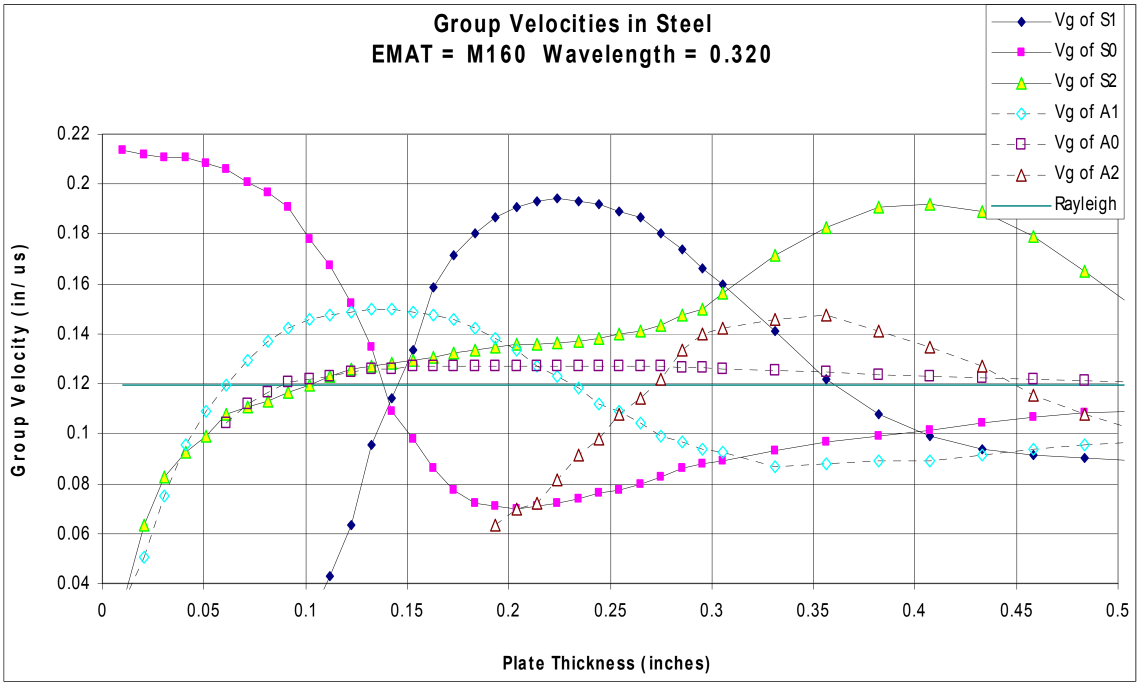


Fig. 2. Example of group velocity versus plate thickness for a given material/EMAT combination.

Demonstration of EMAT/Lamb Wave System

The combination of the increased inspection speed due to the greater volume being examined as compared to the P-scan system as well as the lowered surface finish requirements made EMAT-based, guided-wave inspection attractive for application in the tank farms. Accordingly, a demonstration was conducted at the Hanford site for various personnel on September 25-27, 2001. This demonstration used equipment designed and built by one of the authors (Alers) and was coordinated under the direction of the Ames Laboratory, TFA and CMST. Figure 3 shows a system of the type used for the demonstration. The actual system used for the demonstration is much more compact and portable but functionally is identical to that in the figure. An overall view of the system is shown along with a close-up of one of the transducers.

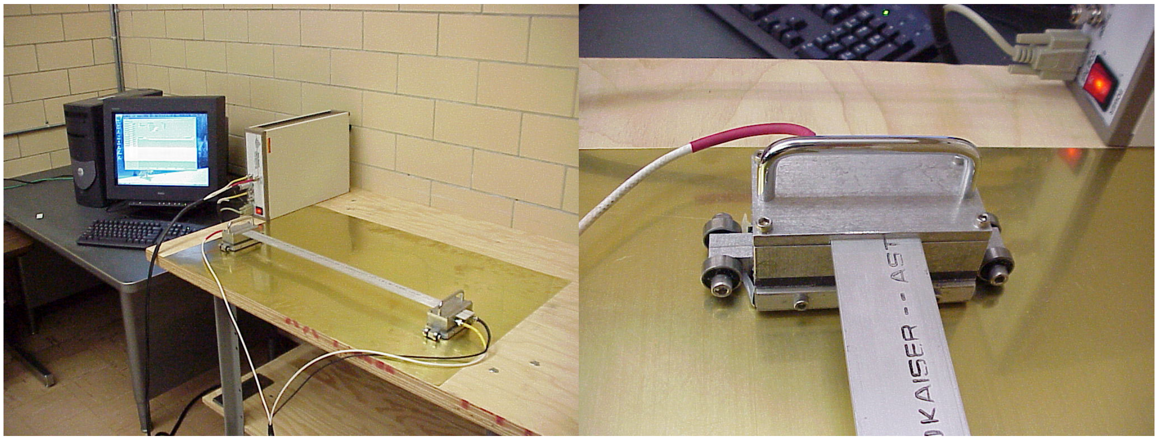


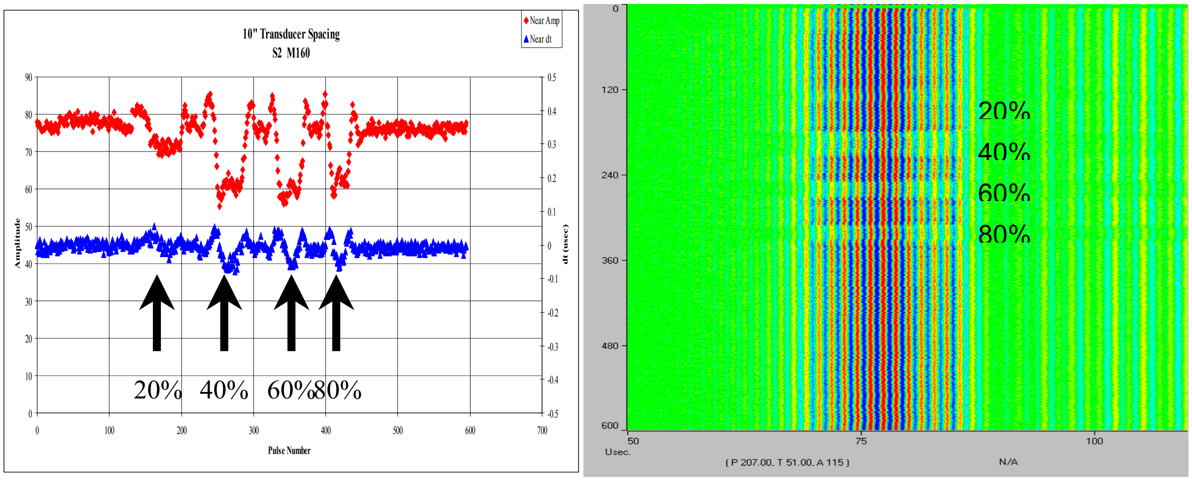
Fig. 3. EMAT inspection system of type used for Hanford demonstration. Close up of EMAT transducer shown at right.

The left view of Figure 3 shows the entire system consisting of a pair of EMAT transducers, the accompanying electronics box and a computer used for control of the electronics and data acquisition and storage. The right view is a close view of the transmitting EMAT transducer. The transducer is mounted on a cart for ease of scanning of the plate being inspected. Careful design of the cart also controls the amount of lift-off that is normally experienced and allows the EMAT to be scanned over rough and/or scaled surfaces as would be encountered in a normal field inspection. The bar between the two transducers is adjustable for varying values of separation of the transducers. This separation is determined by the sensitivity required for detection of the critical flaw. In general, as the transducers are more widely separated, the minimum size of the flaws being detected becomes larger.

A set of plate samples was created for the purposes on demonstrating sensitivity and that simulated the surface conditions found in the tank farm would not be detrimental. These samples contained the defect types being evaluated. One suite of samples were made from 0.375” thick steel plate. One set contained extended regions of thinning created by milling sections 2 inches square to depths of 10%, 20%, 30% and 40% of the plate thickness. A second set contained simulated isolated pits made by creating 0.375” round-bottomed holes at depths of 20%, 40%, 60% and 80% of the thickness. Both sets of plates contained as-received surfaces with no added deterioration by corrosion. In addition, a second suite of samples was obtained from the Pacific Northwest National Laboratory (PNNL) just prior to the demonstration. The surface of these samples had been degraded by rust While not completely characterized, they were considered by knowledgeable Hanford personnel to be “representative” of the surfaces of the actual tanks. One of these latest samples contained a region of thinning produced by milling approximately 30% of the thickness. Thinned regions in the other sample were created by grinding and were estimated to range from 15% of the thickness to less than 5%.

Those samples created at PNNL represented somewhat of a greater challenge than the simulated thinning samples and therefore seemed more appropriate for use in the demonstration. The area dimensions of those samples, however, allowed only a limited separation between the transducers with consequent high sensitivity. These effects combined to make the thinned areas readily detectable by changes in the phase velocity of the chosen Lamb mode.

Results from scanning of the isolated pitting samples are shown in Figure 4. On the left side is shown the observed changes in the echo amplitude and transit time as the transducer pair is scanned over the area containing the pits. The upper line is the change in the maximum echo amplitude as each hole was encountered in the area between the transducers. The lower line is the change in transit time. As was expected and as can be seen from the figure the amplitude change is much more sensitive to the isolate pitting than is the transit time. No attempt was made to discriminate between the various holes on the basis of size. As will be explained in the next section, this demonstration was only to evaluate the potential of this technique as a screening tool for selection of an area for more quantitative examination.



(a) (b)

Fig. 4. Results of scan across simulated isolated pitting sample showing (a) amplitude and transit time changes observed and (b) stacked A-scan showing changes in observed echoes.

The right side of Figure 4 shows a stacked A-scan representation of the scan across the simulated pits. This representation creates a colored 3-dimensional view of a series of acoustic signals. The amplitude of the entire wave train is displayed as a function of color. The horizontal axis represents the arrival time of the wave. Successive acquisitions are displayed adjacent to each other vertically representing the position at which the scan was taken. Changes in the wave train as the wave encountered each pit during the scan are observed as color changes due to changes in the wave amplitude.

Further Work

EMATs have been shown to work successfully through surface roughness and scale conditions representative of those encountered in the actual tanks to be examined. Demonstration of the technology for detection of flaws in sample plates containing generalized thinning and simulated isolated pitting was successful through adherent rust scale on the surface of the plates. While this approach is not necessarily suitable for sizing of defects, its use as a screening tool for selection of an area for subsequent scanning using higher resolution ultrasonic techniques such as the P-scan system yields increased confidence in the integrity of the tank.

The time required to obtain this increased confidence in the integrity of the tank being inspected is relatively minimal. Qualification of the system on known defects to meet the requirements of the inspection will determine the actual distance between the transducers and the scanning speeds obtainable. It is anticipated that these parameters will be such as to allow the entire accessible area of 25 feet by 35 feet to be scanned in 1-2 days rather than the 30 weeks required for the P-scan system. The objective of this screening scan of the accessible area would be to select the most appropriate area for complete evaluation by the P-scan system.

The next step in the development of this technology would be the evaluation in a tank that has been previously scanned with conventional ultrasonic techniques so that the ability to obtain accurate screening information can be confirmed in the field environment. Requirements for the capabilities of the EMAT/Lamb Wave system have been developed. Unless unforeseen problems arise, it is anticipated that the engineering problems inherent in deploying this type of system in an actual tank should be readily solvable. It appears at this time that existing crawler and camera systems already approved for use can be utilized reducing the need for new engineering in those areas.

FUTURE DIRECTIONS

In each of these areas, future work is planned as indicated. In addition, work in other technical areas is being defined. Included is work in the study of electrochemical noise measurements, which can be used to monitor whether the chemical conditions in a tank are conducive to the progression of corrosion, work in the broader area of structural integrity analysis, whereby the results of such measurements are interpreted in terms of the suitability of the tanks for future use, and work in the area of operations analysis, in which specific operational plans are developed based on the measurement results.

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