FEASIBILITY OF HIGH FREQUENCY ACOUSTIC IMAGING
FOR INSPECTION OF CONTAINMENTS: PHASE II

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July 1999

(Milestone C.2.2.B.b)

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ABSTRACT

The nuclear power industry is concerned with corrosive thinning of portions of the metallic pressure boundary, particularly in areas that are not directly accessible for inspection. This study investigated the feasibility of detecting these thickness degradations using ultrasonic imaging. A commercial ultrasonic system was used to carry out several full-scale, controlled, laboratory experiments. Measurements of 0.5 MHz shear wave levels propagated in 25-mm-thick steel plate embedded in concrete showed 1.4-1.6 dB of signal loss for each centimeter of two-way travel in the steel plate (compared to previous numerical predictions of 3-4 dB), and 1.3 dB of signal loss per centimeter of two-way travel in steel plates embedded in concrete prior to setting of the concrete (i.e., plastic). Negligible losses were measured in plates with a decoupling treatment applied between the steel and concrete to simulate the unbonded portions of the pressure boundary. Scattered signals from straight slots of different size and shape were investigated. The return from a 4-mm-deep rectangular slot exhibited levels 23 dB down relative to incidence and 4-6 dB higher than those obtained from both "v" shaped and rounded slots of similar depth. The system displayed an input/output dynamic range of 125 dB and measurement variability less than 1-2 dB. Based on these results, a 4-mm-deep, rounded degradation embedded 30 cm in concrete has expected returns of -73dB relative to the input and should therefore be detectable. Results of this and a prior study indicate that the technique has merit and should be developed more fully and demonstrated in the field.

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EXECUTIVE SUMMARY

The objective of the study is to investigate the feasibility of employing ultrasonic imaging technologies to detect degradation (e.g., wall thinning due to corrosion) of nuclear power plant metallic pressure boundaries, particularly in areas that are inaccessible or have limited accessibility. The work has been sponsored in two phases. The first phase addressed basic feasibility issues using numerical models. Experimental testing was performed in the second phase of the study and is presented in this report. The focus of the experimental work has been to determine if an ultrasonic angle beam inspection system can be used to detect wall thinning in portions of a steel plate embedded in concrete. The three main areas of interest are the physical mechanisms of signal loss, the competing signal environment, and the practical capabilities of a commercially available measurement system. A summary of the significant findings follows:

- The measurement system displayed an input/output dynamic range of 125 dB, which dictates the total amount of loss that can be incurred in a given scenario before a return signal is rendered unmeasurable. The system displayed measurement variations on the order of 1-2 dB, which implies that measured differences greater than 2 dB can be attributed to physical effects.
- The ratio of incident to reflected signal level from variously shaped 4-mm-deep, 10-mm-wide two-dimensional degradations, was shown to be about -23 to -32 dB at 0.5 MHz, depending on the characteristics of the ultrasonic source and receiver. The reflected signals from 12-mm-deep degradations were observed to be about 3 dB higher than those from similarly shaped 8-mm-deep degradations, and 6 dB higher than those from similarly shaped 4-mm-deep degradations.
- When steel plates are embedded in concrete, an additional 1.4 to 1.6 dB of signal loss is incurred for each centimeter of two-way wave travel in the plate, depending on the ultrasonic source. The signal loss induced by the concrete is strongly dependent on the quality of the interface bond between the plate and concrete and the water content in the concrete. For this reason it may be difficult to estimate the character (size and shape) of a detected degradation if the condition of the concrete is unknown.
- The results from the signal loss components experiments can be combined to provide a basis for estimating the total loss induced on an incident signal for many scenarios. For example, a 4-mm-deep rounded degradation, located 30 cm below the air/concrete interface should display reflected signals 73 dB down from the injected signal level. In the absence of competing signals, a degradation of this type should be detectable because roughly 50 dB of signal-to-noise ratio remains (based on the system's input/output dynamic range). However, the competing signal environment, particularly from alternate wave types, may mask the return.
- Rectangular degradations 4 mm or greater in depth located 127 cm below the

air/concrete interface can be clearly detected. The competing signal environment can be accounted for using basic wave propagation analyses. Techniques to either utilize or discriminate against these secondary mechanisms must be implemented for the system to demonstrate success in more challenging scenarios. Alternate designs which inject waves at deeper angles may not require additional discrimination algorithms.

- Dual element transducers adapted for angle beam inspections should be used to eliminate source self-noise which tends to mask returns from actual degradations.
- Waves which are directed directly down the axis of the plate (i.e., without skipping) are much less affected by the presence, and more importantly the condition of the surrounding concrete. For this reason, it will be advantageous to utilize testing equipment which injects waves at extremely shallow angles to maximize penetration and to utilize overall return level as a degradation characterizing tool.

The results from this project can be used to determine, on a preliminary basis, the feasibility of employing ultrasonic imaging in a vast array of degradation scenarios. It appears as though moderately sized corrosive degradations (4 mm and greater depth with fairly abrupt edges) can be detected to distances of around 30 cm below the air-concrete interface using moderate quality commercial off-the-shelf systems. Requirements for utilization of the technique while the plant is shut down and determination of the confidence levels associated with detection of flaws having different geometries requires that the technique be studied in greater detail. Nevertheless, the results from this and the prior study appear to be in general agreement that the technique has merit and should be further developed.

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1.0 INTRODUCTION

Research is being sponsored by the U.S. Nuclear Regulatory Commission at the Oak Ridge National Laboratory to address aging of the metallic pressure boundary in light-water reactor plants. One aspect of this research is related to identification of potential nondestructive evaluation methods that can be used to remotely inspect global regions of the containment metallic pressure boundary that either have limited accessibility or are inaccessible (e.g., portions embedded in concrete).

One potential technique for performing the inspections is ultrasonic imaging which is being developed at the Engineering Technology Center in Mystic, Connecticut. Feasibility studies to evaluate this technique have been conducted in two phases. The first phase addressed basic feasibility issues using numerical models. Experimental testing was performed in the second phase of the study and is presented in this report.

1.1 Statement of Problem and Proposed Solution

Over the life of a nuclear power plant there is a continuing need to ensure that adequate margins are maintained with respect to structural capacity and leaktight integrity. Accurate information on the overall condition of the containment metallic pressure boundary is essential.

Figure 1 presents schematics of two types of nuclear power plant containment cross sections that provide examples of the metallic pressure boundaries of interest in this study. Figure 1a presents a freestanding steel containment in which the 25-mm-thick steel containment vessel represents the metallic pressure boundary. The steel containment is housed within a reinforced concrete shield building. Figure 1b presents a reinforced concrete containment in which a 6-mm-thick steel liner is attached to the concrete to provide leak tightness.

Of particular concern are those regions of the steel plating in either design that are not directly accessible for inspection. It is in these regions that corrosive thinning and pitting of the pressure vessel wall cannot be visually detected (see Fig. 2).

The conventional non-destructive approach to inspecting material thickness degradations is to employ an ultrasonic "pulse-echo" test (see Fig. 3). Here a single ultrasonic transducer injects a beam of compressional waves into a test specimen and receives the reflected echoes from the opposite surface and any discontinuities in the

1a - 25-mm-thick steel containment vessel

1b - Steel-lined concrete containment

Figure 1 – Schematics of containment cross sections.

2.a - Corrosion in free-standing steel containments.

2.b - Corrosion in steel lined containments.

Figure 2 - Potential corrosion areas in free-standing steel and steel-lined concrete containments.

path. The time delay between sending and receiving a pulse-like wave, combined with an assumed knowledge of the test material's compressional sound speed provide means for estimating the material's local thickness and determining the presence of flaws. This technique is used in many industrial applications and has attained a high level of

refinement. Because only one side of the material needs to be accessible, the technique has applications for inspecting steel lined containments. However, it cannot be used when the area to be tested does not have at least one accessible surface (e.g., embedded portions or portions inaccessible due to presence of structures or equipment). Furthermore, the technique cannot perform global inspections.

Figure 3 - Through thickness ultrasonic inspection.

Additional ultrasonic approaches to material inspections which are less conventional but fairly prevalent include the use of Lamb (plate) or surface waves. Although both of these techniques have the capability to propagate inspecting signals from accessible to inaccessible areas, the distance over which they can carry information is limited when constraining boundary conditions are present.

The objective of this research project has been to study the feasibility of using alternate ultrasonic testing technologies for the detection of thickness degradations in fully embedded regions. This, combined with the pessimistic conclusions derived from the previous study regarding inspections of lined containments, places the emphasis on inspecting free-standing steel containments. It is desired to detect degradations that are located on the order of 30 cm or less below the air-concrete interface.

The proposed solution is to propagate ultrasonic waves (either shear or compressional), whose wavelengths are a fraction of the plate thickness, from accessible regions of a free-standing steel containment vessel laterally to detect degradations below the air-concrete interface (see Fig. 4). Ideally, the reflected returns from any material defects would be processed to generate an image of the degradation.

Figure 4 - Proposed solution technique for inspection.

The proposed technique is known as an angle beam inspection, where instead of placing an ultrasonic transducer in direct contact with a test specimen, a plastic wedge is used to couple the transducer to a test structure (see Figure 5). The transducer generates compressional waves in the wedge that are refracted, usually as shear waves, in the test structure (shear waves are used because for a given inspection frequency they have shorter wavelengths than do compressional waves and are therefore capable of resolving smaller defects). These refracted waves then "skip" laterally away from the source through the structure until they encounter discontinuities in the material, which act as acoustic reflectors. The technique is often used to inspect welded joints and to determine the presence of cracks or other structural flaws. The incident waves for this type of test are not typically required to propagate over considerable distances or to propagate in constrained or embedded regions of the test structure, both of which they will be required to do in order to demonstrate success in the proposed test scenarios. Moreover, it is unknown what effect the embedding concrete has on ultrasonic waves propagating in the steel and how well corrosive type degradations act as acoustic reflectors.

Figure 5 - Procedure used in angle beam inspections.

The feasibility of employing the technique under the proposed scenario therefore centers on determining if a measurable and decipherable signal is returned from an area.

exhibiting degradation such as wall thinning due to corrosion. This study addresses the physics side of the problem by investigating the energy lost from the interrogating signals into the surrounding concrete, as well as characterizing acoustic scatter arising from different defect geometries. Also of primary importance is the practical issue of determining the performance limits exhibited by a commercially available angle beam inspection system. The ability to discern and extract the degradation characteristics using acoustic signals that include information about both the corrosive damage and the propagation path is an important but, at this point, secondary concern.

The study will attempt to limit itself to two-dimensional cases, where only degradation variations in the direction of the incident wave are considered and flat plates can be used as propagating media.

1.2 Review of Previous Work

The present work builds on a previous theoretical feasibility study which utilized a widely accepted elastic layered media numerical computer code (OASES) to model the angle beam inspection scenario. Detailed analyses and conclusions can be found in Reference 1. The major conclusions derived from the numerical study include the following:

- The embedding concrete introduces 3-4 dB of signal loss for each centimeter of two-way travel in embedded plates. The “non-spreading” propagation losses in the free-standing steel portions are negligible.
- Notch degradations 4 mm in depth across the plating thickness display reflection coefficients (ratio of reflected to incident wave amplitude including removal of geometric spreading losses) of roughly -23 dB at 0.5 MHz.
- Variation in backscatter is weakly dependent on degradation depth (so long as the interrogating wavelength is greater than twice the degradation depth), frequency, and wedge angle.
- The technique does not appear to be applicable to steel lined, concrete vessels due to an immense loss of energy into the concrete shell. Although conventional ultrasonic pulse-echo testing can be used, it only provides local information and therefore must be carried out over a tightly spaced grid. Angle beam inspection would provide wide-area inspections which would decrease the number of tests required to completely inspect a containment.

The study showed that with sufficient, albeit demanding (80 dB to detect a 4-mm-deep rectangular degradation 20 cm below the air/concrete interface), input/output measurement system dynamic range, the anticipated return levels from a representative degradation located in an embedded region of a steel containment vessel should be detectable.

1.3 Objectives for Present Work

In an effort to not only provide a basis for improving the numerical models, but also to continue the feasibility study in a more practical forum, a series of controlled laboratory experiments were designed and comprise the majority of the efforts contained in this report.

The project's objectives can be broken down into three main areas. The first area concerns characterizing the overall performance limits of a commercially available ultrasonic measurement system, including:

- measurement stability and repeatability,
- the source quality, and
- the system's input/output dynamic range.

The measurement stability and repeatability are important if the overall level of the return signal will be used to identify degradation characteristics. The source quality will ensure that the assumed propagation angle and skip length are used for time-gating and estimating degradation location. The system's dynamic range will dictate the amount of loss that can be incurred in a given scenario.

In an effort to estimate the total loss that will be induced on an incident signal, several building blocks which can be used as components of total loss will be quantified experimentally. The following mechanisms were assumed to play the most prominent roles in contributing to the total signal loss:

- transmission past the degradation -
 - (a) degradation shape effects,
 - (b) degradation depth effects,
- geometric spreading,
- additional propagation losses (e.g. waveguide surface interactions), and
- losses to embedding concrete.

Quantifying these mechanisms comprised the second major series of tests. Empirical relations equating the signal loss dependence on each of the tested parameters will then serve as a basis for estimating the total signal loss encountered for a vast array of scenarios. The ratio of the incident to received signal level must be within the system's dynamic range in order for it to be measurable. Therefore, the first two series of tests provide a rough means for determining what scenarios the technique will physically demonstrate success in for a particular measurement system.

The procedure outlined above for determining operable conditions ignores the significant practical problem of competing signals, which tend to mask the returns from actual degradations. Examples of competing signals include structural or electrical background noise, spurious echoes, transducer ring-down, and acoustic reverberation. The final series of tests will address this issue by simulating a field scenario, and in addition to verifying the general procedure for determining feasibility, estimating the competing signal environment.

2.0 BACKGROUND

2.1 Review of Basic Physics

2.1.1 Directivity of Transducer

Before detailing the experimental test procedures, it is useful to first review the basic physics involved with ultrasonic testing. An ultrasonic transducer is comprised of a metallic external housing which contains a piezo-ceramic disk backed by a high-density material. The piezo element deforms as a voltage is applied across opposite faces. As the piezo element is set into motion, a protective face plate attached to one side of the piezo element is driven and ideally acts as a rigid piston radiator of sound waves into the medium to which it is coupled. The variation of sound wave amplitude as a function of radiating angle is known as the farfield directivity pattern of the source. For a rigid circular piston radiator, the farfield directivity pattern of injected sound waves into a shear free media (the directivity pattern set up in a solid is considerably more complex, but the basic concept holds) is governed by the following equation (Ref. 2):

$$D(\theta) = \frac{J_1[2\pi(a/\lambda)\sin\theta]}{2\pi(a/\lambda)\sin\theta}$$

Here, λ is the acoustic wavelength ($\lambda = c/f$, where c is the speed of propagation and f is frequency), a is the radiator diameter, and $J_1(x)$ is a Bessel Function of the first kind, having order 1 and argument x . Figure 6 shows a plot of the farfield sound wave directivity pattern set up by a 25-mm-diameter radiator vibrating at 0.5 MHz and 1.0 MHz (note that the directivity pattern is axisymmetric due to the symmetry of the radiating surface). Several features of the radiator's directivity patterns are to be noted:

- The directivity pattern takes the form of a main "lobe," centered on the surface normal, and several lower level secondary lobes away from the surface normal direction.
- The half power beam width is defined as the angle at which a radiator's directivity factor is -3 dB relative to the on-axis (0°) value, and is typically used to represent the radiator's spreading angle.
- A radiator of fixed diameter displays a more focused field when vibrating at higher frequencies.

Figure 6 - Directivity factor for a rigid disc radiating in fluid. The black curve represents the relative magnitude radiated as a function of angle (measured from the radiator's surface normal) for a 25-mm disk vibrating at 0.5 MHz, and the gray curve a 25-mm disk vibrating at 1.0 MHz.

Close to the transducer there exists a "nearfield" acoustic response which is considerably more complex than the "farfield" response and cannot be expressed in such compact form. For relatively low frequency ultrasonic transducers (such as the ones used in the following experiments), the nearfield exists within a 25- to 50-mm radius from the transducer. Because the wedges used in the experiments are not sufficiently large to contain the entire nearfield response, the complexity in fully modeling the ultrasonic signals that are injected into a test structure is compounded. For the current study, the farfield approximation of the beam pattern was used.

2.1.2 Transmission and Reflection at an Interface

When waves traveling in one medium encounter an interface with a second medium of different acoustic impedance ($z_{ac} = \rho c$), where ρ is the medium's density, and c is the medium's sound speed, see Figure 7, the wave is partially reflected and partially transmitted. The transmitted wave propagation direction is skewed according to Snell's law:

$$\frac{\sin \theta_1}{c_1} = \frac{\sin \theta_2}{c_2}$$

where θ_1 and θ_2 are noted in Figure 7, and c_1 and c_2 are the wave propagation speed in media 1 and 2, respectively.

In solids, internal waves can be propagated as shear and compressional deformations. Additionally, waves of one type can be converted to another when an impedance discontinuity is encountered. Note that Snell's Law can be rearranged to solve for the refracted transmission angle, θ_2 ,

$$\theta_2 = \sin^{-1}((c_2 / c_1) \sin \theta_1)$$

and that for certain material sound speed combinations and certain incident angles θ_1 , there is no obtainable solution. For example, compressional waves cannot be excited in steel ($c_c=5500\text{m/s}$) when compressional waves travelling in Lucite (a material typically used in ultrasonic (UT) coupling wedges, $c_c=2680\text{m/s}$) are incident at angles greater than 27 degrees. For reference, the shear wave speed in steel is around 3300 m/s.

Figure 7 - Wave reflection and transmission at an acoustic impedance interface.

For normal incidence, the ratio of transmitted to incident wave amplitude is governed by the following equation (Ref. 3):

$$\frac{|T|}{|I|} = \frac{2z_2}{z_2 + z_1}$$

As one would expect, when $z_1 = z_2$ all of the wave energy is transmitted. When $z_1 \gg z_2$, the transmitted amplitude is negligible, so virtually all of the wave energy is reflected. For example, waves travelling in steel that encounter an air interface are virtually totally reflected. Waves propagating in a source wedge (for Lucite, $z_{ac} = 3.16 \times 10^6 \text{ Kg/m}^2\text{s}$) to a steel ($z_{ac} = 45.4 \times 10^6 \text{ Kg/m}^2\text{s}$) test structure are therefore mainly transmitted. Those waves that do get reflected set up a reverberant field inside the wedge. Although this reverberant field dies out relatively fast, it still poses problems in detecting small flaws near the source.

These phenomena are also helpful in describing the structural wave coupling between the steel plate and the embedding concrete. Shear waves propagating in steel have an acoustic impedance only five times that of compressional waves in concrete, implying that a significant transfer of energy from the steel to the concrete will occur. However, the actual ratio of energy that is transferred from the steel to the concrete is strongly dependent on the interfacial coupling conditions, which are not well known. The transmission equations assume continuity of displacement and stress across the discontinuity boundary, a condition that is not necessarily achieved at the concrete-steel interface. Without an adhesive bond, there is minimal interfacial coupling. For this same reason a fluid couplant is used at the wedge-plate interface. Moreover, the water content of the concrete (interfacial characteristics) may also be a significant factor in determining the ratio of transmitted to incident energy.

2.1.3 Wave Propagation and Acoustic Scattering

Wave Propagation - When a wave is injected into a layered media (e.g., a plate in air), and the incident wavelength is significantly smaller than the plate thickness, it can be modeled as a propagating ray (see Figure 8). The ray "skips" laterally down the waveguide, bouncing off the plate's top and bottom surfaces. Locally, where a bounce occurs, the surface displacement is high, giving rise to discrete "hot spots" along the surfaces of the plate. The distance between adjacent hot spots is termed the "skip length" and can be calculated using this simple formula:

$$L_{skip} = 2t \tan \theta$$

where t is the material thickness.

Figure 8 - Basic guided wave propagation in a thick layer.

As was outlined in Section 2.1.1, the injected sound beam takes the shape of a sharp cone. Figure 9 shows a proposed test scenario, where one transducer is used to send and another to receive a sound pulse. The figure shows three hypothetical receiver positions. As the wave moves past each of the receiving locations it spreads. Because the total energy of the wavefront must remain constant, the particle displacement is inversely related to the distance from the source, implying that the measured displacement at receiver position three is less than that measured at receiver position one.

This effect is termed spreading loss. For sources located in a continuous three-dimensional medium, the spreading loss is proportional to $1/r$ and is termed spherical spreading. For sources located in a continuous two-dimensional medium, the spreading loss is proportional to $1/\sqrt{r}$ and is termed cylindrical spreading.

Figure 9 – Proposed test scenario to explain geometric spreading losses.

For angle beam inspections, the spreading loss is actually somewhere between spherical and cylindrical spreading. Figure 10 conceptually shows the injected beam looking from above and from the side of a representative test structure. As the wave propagates, the side to side spreading eventually causes part of the wavefront to leave the measurement area (which is the same width as the source). The vertical spreading, on the other hand, has the effect of elongating the wavefront on the measurement surface. If the measurement occurred at a single point, then spherical spreading would be observed. But because the measurement is actually taken over a finite area, a quasi surface-integrated measurement is made. Therefore, near the source where the vertical and side-to-side spread (d and w in Fig. 10) do not exceed the dimensions of the transducer, there should be virtually no spreading because the entire wave front is captured. As the vertical and side to side spreading approach the measurement area dimensions a mix between spherical and cylindrical spreading should occur, and as the wavefront spread dimensions become significantly greater than the measurement area dimensions, the spreading losses should appear spherical. For a 6 degree half-angle beamwidth, the wave has to propagate about 127 mm (or 89 mm down a 25-mm-thick plate at a 45 degree propagation angle) before spreading doubles the initial area of the cone. Therefore, the measurements made in the following experiments, where waves propagated between 15 cm and 76 cm before being received, should display geometric spreading losses somewhere between spherical and cylindrical spreading.

Figure 10 - Top and side views of spreading cone in a thick layer.

Acoustic Scattering - Impedance discontinuities, or degradations of characteristic dimension less than one half of the interrogating wavelength, are inefficient acoustic scatterers. The criteria for detection is that the structural wavelength be small compared with the characteristic depth of the degradation. However, the inherent damping loss associated with wave propagation in any media is proportional to frequency, as shorter wavelength signals must endure more cycles to interrogate a fixed distance and therefore suffer a greater loss. Thus for maximum wave penetration in an elastic media, the lowest possible frequency should be selected. For this reason, shear waves, which propagate at slower speeds than compressional waves and therefore have shorter wavelengths at a given frequency, are used for angle beam inspections. In selecting the incident frequency, a compromise is required that addresses these two bounding conditions when small degradations are to be detected at considerable distances. Pulse-like incident signals are broadband in nature and therefore have advantages when reflector dimensions are unknown. However, because the incident energy is spread out over a wide frequency range, the incident energy at any particular frequency is small and the maximum value of the frequency dependent system dynamic range is decreased.

2.2 Testing Equipment

The table below lists several manufacturers of ultrasonic transducers and peripheral equipment that were solicited for information on their products.

Company Name	Location
Matec, Inc.	Northborough, Massachusetts
Panametrics, Inc	Waltham, Massachusetts
Inspection Research Technology	Nashua, New Hampshire
Krautkramer	Johnston, Rhode Island

A completely integrated laboratory testing package (pulser-receiver electronics, acquisition software and hardware, transducers and wedges) was obtained from a commercial vendor. The testing equipment is comprised of a pulser/receiver card, a high frequency analog-to-digital acquisition board (both of which are attached to a standard PC ISA bus), controlling software, piezo element contact transducers, coupling wedges and industrial grade ultrasonic gel couplant. The transducers have a 25-mm-diameter circular radiating face producing an estimated half-angle beam width of just over six degrees. The transducers are tuned to 0.5 MHz, which is a relatively low frequency for ultrasonic testing, but will allow for additional penetration. The shear wavelength in steel at 0.5 MHz is about 6 mm.

Wedges are specified by the refracted shear wave angle (measured from the surface normal) introduced into a steel test structure. All of the wedge angles that were used (45°, 60°, and 70°) are past the compressional wave critical angle for steel, meaning that compressional waves will not be excited in the steel plate. It should again be emphasized that the transducer does not generate a planar incident field, so that energy is injected in all directions. Therefore, it is more accurate to say the main lobe of the incident sound field does not excite compressional waves in a steel test structure, but that the side lobes below the main lobe may indeed excite compressional waves.

The equipment can be utilized in either the *through transmission* mode, where separate transducers act as source and receiver, or the *pulse-echo* mode, in which a single transducer injects a wave and then passively listens for a return. These modes of operation are known to the acoustics community as *bistatic* and *monostatic*, respectively. When operated in the through transmission mode, the source and receiver transducers are attached to coupling wedges of the same angle.

The input voltage waveform is a toneburst, with the signal length, level (in percent of maximum) and center frequency specified by the user. The signal length used in all of the experiments was 4 microseconds, and the frequency was 0.5 MHz. The maximum input voltage that the pulser can generate is 300 V. Because the transducers are uncalibrated, the relationship between input voltage and mechanical force is unknown. It is important to note that several more expensive pulser/receiver cards that can generate inputs of 1000 V are commercially available. The acquisition board range is ± 0.5 volts with a precision of 8 bits. The receiver gain ranges from 0-70 dB.

2.3 Test Platforms

The test platforms used were 25 mm by 914 mm by 203 mm (thickness, length, width) mild steel plates. The plate thickness approximates that used for fabrication of steel containment vessels. The width is such that no side interactions will take place when waves are directed down the length of the test platform and the width-centered

source and receiver are not more than 178 mm apart (124 mm for a 45 degree propagation angle, 168 mm for a 70 degree propagation angle). Thus for the following tests, where propagation distances are less than 89 mm, the plate width is rendered effectively infinite.

Artificial "degradations" are actually uniform cross-section slots cut across the plate's width. Because side interactions are intentionally avoided, the degradations are rendered effectively two-dimensional. The effect of a curved degradation edge (i.e., not a straight slot) on reflected returns is an important recommended study for future research.

3.0 EXPERIMENTAL PROCEDURES AND RESULTS

To follow are the descriptions and results from several series of experiments. As outlined in the objectives section, the tests are broken down into three main areas. The first area investigates the measurement system's practical capabilities as well as characterizing the steel plate's behavior as an ultrasonic waveguide. The second area studies the scattering characteristics of several candidate degradations and the effects of concrete on waves propagating in embedded plates. The final area of tests is meant to simulate an actual field scenario and to determine what additional practical problems are associated with applying the technique.

3.1 System Performance and Operability

3.1.1 Performance Check

As a first step in verifying the operability of the equipment, a conventional ultrasonic thickness test was performed. Figure 11 shows a sketch of the experiment and the measured return. A transducer was placed in direct contact (i.e., no coupling wedge) with the longest edge of a 25 mm by 914 mm by 203 mm steel plate, with the idea of injecting compressional waves across the plate's width. When operating in a monostatic configuration, the transducer acts as a receiver while it acts as a source, meaning that the input and free-vibration ringdown of the piezo element are both measured. This is shown as the clipped portion of the signal before 40 microseconds (receiver gain was set to record the reflected signal from the plate's opposite edge, which displayed significantly lower levels than those signals listed above). The first returns after the source has died

Figure 11 - Simulated thickness test, setup and measured return.

down are from the direct path to the opposite edge of the plate and they occur at 75 microseconds. When half of this delay (time of flight for one-way travel) is multiplied by the assumed compressional wavespeed in steel (0.55 cm per microsecond) the 203 mm width is estimated to be 206 mm. Although the transducer used was not designed for this type of test, the results point to a properly operating system.

3.1.2 Dynamic Range

The system's input/output dynamic range was experimentally obtained by measuring the maximum signal that the system can inject and the minimum signal that the system can read. Two transducers (both attached to 45 degree coupling wedges) were placed adjacent to one another on a 25-mm-thick steel plate. With the receiver gain set to the allowed minimum (0 dB) and the input level set to the allowed maximum (100%), the signal transmitted from one transducer to the other was monitored. The receiver position was slowly varied away from the source until the received signal obtained its first maximum (i.e., the receiver fell on the first "hot spot"). This was assumed to be the maximum signal level that could be injected. The maximum measurable signal, coincidentally, just filled the acquisition board range with no receiver gain. Therefore the maximum measurable signal is -6 dB re. 1 volt. The source was then removed from the plate, the receiver gain maximized (70 dB), and one hundred averages of the background signal measured on the plate assembled and averaged (to suppress uncorrelated sensor noise). This averaged signal was assumed to represent the minimum measurable signal.

Figure 12 shows the results. Plotted are the power spectral densities of the maximum and minimum signals. At 0.5 MHz, where the source signal is concentrated, a 125 dB difference can be seen. This difference represents the system's input/output dynamic range.

Figure 12 - Results for system dynamic range.

3.1.3 Measurement Repeatability

In order to attribute differences in measured signals to physical effects, measurement repeatability was quantified. These tests were performed on vertically oriented plates to incorporate the problems associated with fixing the transducers in this orientation. The tests involved measuring the transmitted signal from one transducer to another for several different relative separation distances. Transmitted signals were recorded over a three-day period on 3 plates, for a total ensemble of nine measured signals at each separation distance. Of those nine signals, the ratios of the maximum to minimum received signal levels are plotted in Figure 13 for 5 different source/receiver separation distances. The plot shows a maximum variability of 2 dB, thus allowing measured differences greater than 2 dB to be attributable to effects outside of pure chance.

Figure 13 - Maximum variation in transmitted signal levels for various source-receiver separation distances.

3.2 Source and Waveguide Characterization

In order to accurately image the location and shape of a degradation, the distortion caused by waveguide propagation of unfocused incident waves must be considered. For these purposes, numerical modeling will serve as an invaluable tool. However, the assumptions that must be made by those models will be critical. Therefore, as a basis for refining the numerical modeling assumptions, the waveguide effects on signal propagation were addressed in a series of tests.

Using one transducer as a source and a second as a roving receiver (with both transducers fixed to a 45° coupling wedge), a bistatic array was simulated. By doing so, the incident wave interactions with the plate's edges could effectively be monitored as the wave propagated down the plate. Fig 14 illustrates the experimental setup.

Figure 14 - Test setup for monitoring forward travelling waves in a free plate.

Figure 15 shows a plot of the measured signals for the forward propagating wave. The bottom axis represents time and the left-hand axis represents receiver distance from the source. Image brightness is proportional to the envelope of the received signal level. Note

that the received signal takes longer to reach positions that are located further from the source.

Figure 15 - Combined envelopes of received signals at several locations relative to a fixed source (forward travelling waves).

Several features of this plot can be brought to point:

- "Hot spots", seen as bright features, correspond to structural wave interactions with the measured surface. These features appear with regular spatial periodicity corresponding to the skip length of a 45-degree incident signal.
- The magnitudes of the hot spots diminish as the receiver is moved further from the source. Figure 16 shows the maximum value in each of the signals received between 254 mm and 508 mm from the source along with the estimated decay rate predicted by both spherical and cylindrical spreading. As outlined in Section 2.1.3, the actual decay rate should and does fall between that predicted by spherical and cylindrical spreading. The spreading losses at 254 mm are about 8 dB (this accounts for incident coupling losses as well) and for every additional 254 mm of propagation distance 6 dB of spreading losses occurs (note that these propagation distances are measured along the plate and are based on injection through a 45 degree wedge, for the 70 degree wedge they must be scaled by $\sin 70 / \sin 45 = 1.33$). Because there is no strong evidence of scattering to non-specular waves due to surface interactions, the edge reflections must be

"specular", like a pool ball bouncing off the edge of a pool table. Consequently,

Figure 16 - Geometric spreading predictions fitted to maximum values in received signals at various receiver locations.

the measurement noise floor due to spurious reflections from surface imperfections should be low. Table 1 summarizes the actual spreading loss values.

Distance along plate, 45° wedge (cm)	Distance along plate, 70° wedge (cm)	Loss (dB)
10.5	13.9	11.4
20.6	27.4	13.0
30.8	40.9	15.4
41.0	54.4	17.8
51.1	67.9	19.5

Table 1 – Measured spreading losses.

- A straight line can be fitted through the centers of the slashes, the slope of which corresponds to the global speed at which the energy travels down the plate. This global velocity is given by:

$$v_{\text{global}} = v_{\text{shear}} \cos(\theta_{\text{incident}})$$

This expression provides a convenient verification of the injected incident angle.

Figure 17 shows the results of a similar series of tests measuring the backward propagated signal reflected from the plates opposite edge. The "packets" of signal comprising the reflected returns have now been spread out over time due to geometric spreading and multi-bounce interference. Notice that even in the ideal case of an edge reflector it is difficult to determine the exact position of the reflector in any given time signal, but that the ensemble collection plotted together "points" to the reflector.

Figure 17 - Combined envelopes of received signals at several locations relative to a fixed source (backward travelling reflected waves).

3.3 Assessment of Signal Loss Components

3.3.1 Degradation Shape and Depth Effects

Figure 18 shows a schematic sketch of the test setup used to study the returned signal levels from degradations of various shapes.

Figure 18 - Test setup for degradation shape study.

As noted previously, these degradations are actually straight slots cut across the plate's 203 mm width. All of the degradations in this test were 4 mm deep and 10 mm in width. Monostatic returns were measured at several distances from the slot's leading edges. Figure 19 shows a sample return signal. The reflected signal "level" is defined as the maximum value in the signal packet that is assumed, by simple time gating procedures, to have emanated from the slot.

Figure 19 - Sample reflected return from rectangular slot.

Figure 20 shows the differences in reflected signal level at several source locations relative to the slot. For the 45° wedge, the returns from the rectangular slot are, averaged over source location, around 1 dB higher than those from the rounded slot and 4 dB higher than those from the "v" shaped slot (see Figure 20a). For the 70° wedge, the differences are 5 and 9 dB and are shown in Figure 20b. When an increase in received signal level is obtained at a position located a greater distance from the slot leading edge, this is due to the location's proximity to a hot spot.

These results include the effects of geometric spreading, which are greater for the 45° wedge than for the 70° wedge because the path to and from the slot is longer for the deeper angle. A more thorough analysis of the measured differences would incorporate advanced acoustic scattering theories that are beyond the scope of this study.

It is useful to develop an average "reflection coefficient" for the rectangular slot. The reflection coefficient will be defined here as the ratio of incident to reflected signal level minus geometric spreading. Because the geometric spreading estimates developed in Section 3.2.3 account for incident coupling losses, using that relation to remove the

Figure 20 - Results from degradation shape study.

spreading loss from the measured signal levels presented in Figure 19 will generate a useful result based on the maximum measurable signal. The average reflection coefficient of the rectangular slot using the 45 degree wedge is about -23 dB and for the 70 degree wedge about -23.5 dB. By comparing the reflected returns from slots of various cross-sections to those from the rectangular slot, this result can be used as a basis for estimating reflection coefficients for other slot shapes. Figure 21 shows examples of the time-windowed returns reflected from the three different slots. A comparison of these returns

Figure 21 - Differences in reflected signal character for different degradation shapes.

reveals that the arrival times of the reflected signals are very nearly equal despite the fact that the reflected fields from each degradation are theoretically markedly different. The implication here is that the component of the reflected signal propagating at 45 degrees is

biasly received, and other propagation angles are filtered out to varying degrees. Consequently, the scattered field is measured at very nearly a single angle. Without measuring the entire field it will be difficult to make statements on the character of the reflector. Phased array receivers, as outlined in the Phase I report (Ref. 1), can be used to effectively sample the scattered field over a much wider band of angles. Degradation depth was studied using the same methodology used to study degradation shape. Figure 22 shows a sketch of the slots that were used in this test. All slots were rectangular in shape and 10 mm in width. The slot depths were either 4, 8 or 12 mm. Reflected signal levels were determined in the same manner used in the shape study.

Figure 22 - Test setup for degradation depth study.

Figure 23 shows the differences in reflected signal at several source locations relative to the slot for both a 45° and 70° wedge pair. For the 45° pair (Fig. 23a), the returns from the 4-mm-deep slot are, averaged over source location, around 3 dB lower than those from the 8-mm-deep slot and about 6 dB lower than those from the 12-mm-deep slot. This trend is as expected, as deeper slots project a greater area of acoustic impedance.

Figure 23 - Results from degradation depth study.

Figure 23b shows the reflected signal levels from the three different slots using a 70-degree wedge set. The resultant trend for this case is not as expected. For some source -receiver separation distances the reflected returns from the shallowest slot are actually greater than those from the deepest slot. The odd trend was qualitatively observed over a broad range of separation distances, eliminating skipping effects as a possible explanation. The explanation for these results may, again, only be realized after incorporating advanced scattering theories.

3.3.2 Concrete Effects

The final series of tests to assess the individual components of signal loss involved measuring the effects that concrete has on waves travelling in an embedded plate. Figure 24 shows a photograph of the wooden molds that were built to allow the midsection of three plates to be embedded in concrete. The signal transmitted from one end of the plate to the other was measured before and after filling the molds with concrete. To determine the effect that bond quality has on induced losses, one of the plates was wrapped with a single layer of 4-mil-thick plastic sheet. The other two plates were tested under identical untreated conditions in order to quantify, albeit sparsely, the concrete effect's repeatability. These plates are referred to either as "coated or treated", (i.e., wrapped with a plastic sheet), or untreated, (i.e., no plastic sheet).

Figure 24 - Test base for concrete effects test.

Figure 25 shows a simplified schematic of the test setup for a single plate. The source transducer location, s , was varied from 6.3 cm to 11.4 cm in 1.27 cm steps in order to sufficiently sample one half of a skip length for the 70 degree wedge. The wave propagating through the embedding region was monitored by a fixed position receiving transducer. The received signal level is, as before, defined as the maximum value in the incident signal packet reached by the receiver.

Figure 25 - Test setup for concrete effects test. All units are in millimeters.

Figure 26a shows the signal level received for three free standing (i.e., no embedding concrete) plates, for several source locations. As expected, there is only minimal variation from plate to plate and the plastic wrap has no noticeable effect. Figure 26b shows the received levels after embedding the midsections of the plates in concrete. The two uncoated plates display a significant loss in signal level (30 dB, or 1.6 dB per centimeter of two-way travel) while the coated plate level remains relatively high, incurring virtually no losses. Note that the results for the untreated plates are very similar, with the differences being attributable to a combination of measurement variation and concrete bond variation. Upon removing the plates from the test base, the frictional effects between the concrete and the wrapped plate were sufficient to support the weight of the concrete. The interface, or bond, between the concrete and steel plays a critical role in determining the proportion of energy lost from waves travelling in the steel.

Figure 26 - Transmitted signal level for three plates (one coated, two uncoated) either free-standing (26a) or partially embedded in concrete (26b)

Figure 27 shows the results for the transmitted signal levels through the coated plate either partially embedded in plastic or hardened concrete. Note that the transmitted levels are 5-7 dB lower for the plastic concrete case. These results highlight the importance of the boundary condition between the embedding medium and the plate. The ideal assumption of displacement continuity across the interface holds much better when

the embedding medium is a fluid, and is highly dependent on the interface bond when the embedding medium is a solid.

Figure 27 - Transmitted signal levels for the treated plate partially embedded in either plastic or hardened concrete.

Figure 28 shows the received signal levels using different wedges tested on a single untreated plate after it was embedded in concrete. The 70-degree wedge shows transmitted signal levels that are roughly 4-5 dB higher than those received using the 45-degree wedge. Assuming that both wedges couple equally well to the test structure, this result is to be expected because the incident wave injected by the 70-degree wedge experiences fewer interactions with the concrete-steel interface due to the longer skip distances.

Figure 28 - Transmitted signal levels for embedded plate using different wedge angles.

The results from this series of tests show that characterizing a degradation based on reflected returns may be difficult even if its position can be determined. Because the propagation path plays such a prominent role in determining the level of the returned signal, and because the conditions of the path cannot be well known without destructive testing, the overall level of the reflected returns cannot be used (for the system and procedure employed here) to confidently characterize degradation located below the air/concrete interface.

3.4 Implications of Masking Signals

To this point, the objectives of the experiments have been to determine the system loss components in order to provide a total loss estimate and verify that the total loss does not exceed the system's dynamic range. However, these procedures do not address the problem of competing signals. To determine the role that competing signals may play in dictating the technique's feasibility a simulated field condition was tested. Figure 29 shows the test setup. The signals reflected from a rectangular slot (4-mm-deep) located 127 mm below the air-concrete interface were measured and compared to those obtained with no concrete present.

Figure 29 - Test setup for simulated field scenario (dimensions in mm).

It was noticed in previous tests that the source “self-noise” tended to mask low level returns. Figure 30 shows a schematic sketch highlighting the mechanisms of source “self-noise.” In addition to coupling to an injected shear wave the incident signal also:

- reverberates inside the wedge due to the surface reflection from the wedge-test structure interface and the side lobes "spraying" the sides of the wedge,
- bounces repeatedly across the thickness of the test structure directly under the wedge, and
- couples to other wave types, such as surface and compressional waves.

Figure 30 - Mechanisms for source self-noise.

By altering the test setup to that shown in Figure 31, where a second transducer is used to bistatically receive the reflected returns, the inner wedge reverberant field and the through thickness standing echoes are eliminated.

Figure 31 - Bistatic measurements taken to eliminate source self noise.

Figure 32 shows the reflected time signals received for the 70-degree wedge located 203 mm from the slot's leading edge for three cases: monostatic measurements with no concrete; monostatic measurements with concrete; bistatic measurements with concrete. As is shown in the middle plot, the additional receiver gain needed to monostatically measure the return reflected from the slot embedded in concrete causes the previously low-level source self-noise to now completely mask the return. When the returns are measured bistatically (as is shown in Figure 32's bottom plot), the source self-noise is suppressed and the returns from the slot are illuminated. Without this simple procedural alteration, the inspection technique would not show success even in this idealized example. Based on the results from the signal loss component experiments, the reflected signal in the embedded case should be about -51 dB (9.4 dB of spreading loss, -23.5 dB reflection coefficient, 18 dB of loss to concrete) down from the maximum measurable signal (-6 dB). It was measured at 50.5 dB, thus supporting the signal loss estimation technique.

Figure 32 - Time histories of reflected signals from rectangular slot for three different cases.

Figure 33 shows in greater detail the bistatically measured return from the plate embedded in concrete. Although the return from the slot is evident, there are still competing return signals (occurring between 50 and 130 microseconds) that have not been eliminated by using a bistatic approach. These returns would normally be considered secondary, but because the peak in the reflected packet emanating from the slot is suppressed by the effect of the concrete, they are now only 6-10 dB down (linear factor of about 2-3).

It is interesting to note that the reflected signal builds somewhat sharply at around 60 microseconds. This time delay corresponds very nearly to the time it would theoretically take a compressional wave propagating directly down the plate's axis to and from the slot's leading edge. Thus, it appears as though an incident side lobe has coupled to a compressional wave in the steel. Moreover, these signals could be considered a localizing aid as opposed to competing signals. Here, the compressional returns are down by a linear factor of 3 (or 9.5 dB) relative to the reflected shear wave field. An important point is that if a competing signal can be identified, then it can in all likelihood be removed from the return signal during post-processing. Implementing advanced signal processing

Figure 33 - Reflected signal from an embedded rectangular slot.

algorithms to exploit and/or discriminate phenomena of this type is an important recommendation for future work.

In light of this observation, the through transmission tests to determine the effect of the embedding concrete were re-scrutinized. Figure 34 shows (from top to bottom): the transmitted signal through a free plate; a treated plate embedded in cured concrete; an untreated plate embedded in cured concrete. As was shown in Section 3.3.2, the effect of

Figure 34 - Time histories of signals transmitted through free, lined and partially embedded, and unlined partially embedded plates.

the plastic wrap was to virtually eliminate the additional losses imposed by the embedding concrete. Comparison of Figure 34's top and middle plots bears this out. Also notice that the character of the transmitted signal is not altered significantly. However, the character, in addition to the overall level, of the transmitted signal through an untreated partially embedded plate, does change. In fact, the signal again builds sharply just as a compressional wave directed down the axis of the plate would theoretically reach the receiver (see Fig. 35). Thus it appears as though the transmitted shear wave, which skips down the plate and therefore interacts repeatedly with the concrete interface, is affected by the concrete to a much greater degree than are those waves which propagate directly down the axis of the plate.

Figure 35 - Breakdown of time of travel for a compressional wave travelling down the axis of the plate.

Figure 36 highlights the time period in question for all three cases. Shown, for clarity, are the envelopes of the transmitted signals. The earliest arrivals, which are necessarily from those waves travelling directly down the plate's axis, are least affected by the concrete (10-16 dB as opposed to 30 dB of loss for shear waves).

Figure 36 - Early arrivals in the transmitted signals through free, lined and partially embedded, and unlined partially embedded plates.

Figure 37 shows the early returns for the case of plastic concrete. Again, the early arrivals are least affected by the concrete.

Figure 37 - Early arrivals in the transmitted signals through free, lined and partially embedded in plastic concrete, and unlined partially embedded in wet concrete plates.

It can therefore be concluded that as the degradation distance below the air/concrete interface increases, the effects of concrete will act to suppress the returned shear wave field, which propagates at an angle to the plate surface, to levels below the returned compressional wave field, which propagates parallel to the plate surface. In the case of the test results shown in Figure 28, only 9 dB of additional loss could be incurred before the compressional wave returns would completely mask the shear wave returns, opening the possibility for misinterpretation of the location of a degradation because the wrong wavespeed is used.

These results show that by using signals that are directed down the axis of the plate at angles deeper than 70 degrees, the return level's strong dependence on path conditions may be suppressed.

4.0 CONCLUSIONS

Inspection of inaccessible portions of the metallic pressure boundary components of nuclear power plants requires special attention. At these locations the pressure boundary components may be subjected to corrosion that may challenge the structural integrity of the containment and, if through-wall, can provide a leak path to the outside environment. Techniques currently utilized to determine the condition of the metallic pressure boundary are time consuming and require access to one or both surfaces for application. With the exception of removal of material to make the pressure boundary accessible, no suitable procedures currently exist. One approach, however, that may provide the needed inspection procedure is the use of high frequency acoustic imaging.

A numerical study has already been carried out to address preliminary feasibility issues. As a basis for improving these numerical models, and also to continue the study in a more practical setting, a series of controlled laboratory experiments were executed. The experiments were designed to assess the performance of a commercially available fully integrated angle beam inspection system, and to further investigate the underlying physics that govern the use of angle beam inspections.

The experimental results are as follows:

- The measurement system displayed an input/output dynamic range of 125 dB. Therefore, in the absence of competing signals, 105 dB of losses can be incurred while still maintaining a 20 dB signal-to-noise ratio. The system tested is of moderate quality, and the dynamic range could in theory be increased by as much as 35 dB by selecting a more powerful pulser and a higher precision acquisition board. The system displayed measurement variations on the order of 1-2 dB, which implies that characterization of degradation dimensions will be subject to a 25% margin of error and that measured differences greater than 2 dB can be attributed to physical effects. The source was verified to inject waves at refracted angles very near those specified by the manufacturer.
- The mild steel plates used in the experiments propagated signals as if they were effectively free of surface imperfections, which would otherwise act as random scatterers. Under similar conditions, the surface generated noise floor due to surface flaws should be minimal.
- The reflection coefficient from a 4-mm-deep by 10-mm-wide effectively two-dimensional degradation (i.e., infinite straight slots), measured using a 45-degree wedge, was shown to be about -23 dB at 0.5 MHz. With the same wedge, rounded and "v" shaped degradations of similar depth and width showed returns on average 1 dB and 4 dB, respectively, lower than those returned from the 4-mm-deep

rectangular degradation. For the same wedge, returns from a 8-mm-deep rectangular degradation showed returns 3 dB higher than those from the 4-mm-deep degradation and a 12-mm-deep slot showed returns 6 dB higher. Using a 70-degree wedge, rounded and “v” shaped degradations of similar depth and width showed returns on average 5 dB and 9 dB, respectively, lower than those returned from the rectangular degradation. The measured data does not show a strong correlation between reflected signal level and degradation depth using the 70-degree wedge. These results provide a preliminary basis for estimating reflected signal levels from a vast array of two-dimensional degradations.

- When plates are embedded in concrete, an additional 1.6 dB and 1.4 dB of signal loss is incurred for each centimeter of two-way travel using 45-degree wedges and 70-degree wedges, respectively. (Phase I numerical results also predict the relation between signal loss and travel distance to be exponential in nature). Plates that have a plastic wrap between themselves and the embedding concrete show virtually no additional losses compared with free plate signal losses. Therefore, in regions where corrosion is suspected, it is likely that the concrete-to-steel bond is compromised, and the effect of the concrete may be minimal. However, the presence of water in the concrete may significantly increase the signal loss that is induced.
- The results from the signal loss components experiments can be combined to provide a basis for estimating the total loss induced on an incident signal for many scenarios. For example, a 4-mm-deep rounded degradation located 30 cm below the air/concrete interface should display reflected signals 73 dB down from the incident signals using a 70 degree wedge. In the absence of competing signals, a degradation of this type should be detectable because roughly 50 dB of signal-to-noise ratio remains (based on the system's input/output dynamic range). However, the competing signal environment, particularly that from the compressional wave field, may mask the return.
- Rectangular degradations 4 mm in depth located 127 mm below the air/concrete interface can be detected using a bistatic measurement arrangement. The competing signal environment, which tends to mask returns from actual degradations, can be accounted for using basic wave propagation analyses. Techniques to either utilize or discriminate against these secondary mechanisms must be implemented for the technique to demonstrate success in more challenging scenarios.
- The losses induced by concrete are strongly dependent on the coupling conditions at the steel interface. For this reason, it may not be possible to use the valuable tool of overall return signal level to characterize degradations. Waves directed at shallow angles are least affected by the concrete, regardless of coupling condition, and may be of more value.

5.0 RECOMMENDATIONS

Several procedural recommendations can be made based on the practical knowledge gained in this study:

- The system used in these experiments can only be applied to more challenging scenarios with the aid of algorithms which can discriminate the compressional and shear wave fields. This can be done by measuring the reflected signal at several locations and employing a Radon Transform, which discriminates waves travelling at different velocities (Ref. 4).
- The transducers used in these experiments act as relatively narrowband mechanical filters (in relation to conventional, highly damped transducers) and are tuned to 0.5 MHz nominally. Frequency concentrated tone burst waveforms were used to minimize the energy lost outside of the effective transducer filter and therefore to maximize the injected power. In retrospect, the added problems of a relatively lightly damped piezo crystal (which had a significant ringdown period) and a relatively long (in time) input signal (required for frequency focusing) do not justify their selection over a highly damped crystal excited with short pulses, which would return more temporally focused reflections.
- Because the source self-noise is sufficiently high to mask returns from moderately sized degradations near the source, or small, distant degradations, a bistatic arrangement is recommended. Dual element transducers, which incorporate this idea into a single device, are presently used for through thickness testing and would be advantageous for the present application as well.
- Waves that are directed directly down the axis of the plate are much less affected by the presence, and more importantly the condition of the surrounding concrete. For this reason, it will be advantageous to inject waves at extremely deep angles to maximize penetration and to utilize overall return level as a degradation characterizing tool.
- It is imperative that gel couplant completely fills the space between the transducer-wedge interface and the wedge-test structure interface. This becomes increasingly difficult when wedges are coupled to vertical structures. If proper measures are not taken, the measurement repeatability suffers greatly.

The following is a list of practical issues which should be addressed before attempting to employ the technique :

- Three-dimensional effects, such as plate curvature, degradation curvature and the

mixing of return signals from several closely spaced degradations.

- Effects of structural discontinuities in the metallic pressure boundary, such as presence of welds, and anchors or studs.
- Effect of form that corrosion takes (e.g., pitting or general) on results.
- Effect of quality of bond between concrete and steel on results, particularly the significance of corrosion occurrence.

As noted previously, the spatial filtering inherent to the transducers used here effectively limits the measured reflected field to a narrow propagation angle band. Reflector characterization schemes would ideally be based on the full field. This can be accomplished using a phased array of sensors. Unfortunately, waves returning at different angles are affected to various degrees by the condition of the surrounding concrete. This is considered to be the single biggest obstacle to applying the technique, because return levels are not solely dependent on the overall size of the defect from which they emanate. It may be necessary to develop nondestructive techniques to determine the condition of the steel/concrete bond.

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