Recent Advances in the Application of Acoustic Leak Detection to Process Recovery Boilers

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Abstract

For over two decades, acoustic signal processing methods have been used to detect leaks in pressurized systems of utility and industrial power plants. These methods have been proven to be sensitive to the sound waves resulting from the turbulence produced at the source of the leak by the escaping fluid or gas. Through ongoing research and operational experience, effective and reliable methods of applying acoustic leak detection have been developed.

In theory, leak detection using the acoustic method is simple and straightforward. Sound waves are detected by transducers (sensors) that convert the mechanical waves to electrical signals. These signals are then processed and the resulting root-mean-square (RMS) voltages are tracked. An increase in these voltage levels is relied upon to indicate the onset and growth of a leak.

In practice, however, the application almost always involves several considerations, including significant amounts of interfering background noises, unacceptable sound wave attenuations, and inaccessibility of desired sensor locations. For these and other reasons it is imperative that proper specialized techniques, generally unique to a given application, be employed to ensure optimum sensitivity.

This paper describes the basic principles of applying acoustic leak detection to the various components of utility and industrial power plants. It explains the differences between airborne and structure-borne monitoring techniques and how to choose the proper method for the application. It describes the various techniques of frequency discrimination and proper sensor selection for optimizing signal-to-noise ratios, thus maximizing sensitivity to leak noise. It shows how the presence of corrosion and/or insulation adhesion adversely affects sensitivity by severely attenuating structure-borne sound waves. Finally, it describes the importance of acoustically isolating sensors from the extraneous and non-leak-related noises usually present at sensor locations.

Introduction

The availability of utility and industrial power plants is of major importance and, during the last 20 years, substantial efforts have been made to reduce down-time. Much of the focus has been concentrated on improved techniques for the inspection and evaluation of critical plant components prior to failure.

A significant part of this evaluation capability deals with early detection of leaks in pressurized systems, especially boiler tubes. In utility boilers, early detection of leaks is primarily a financial issue. High velocity steam escaping from a tube leak can quickly cause extensive damage to the adjacent tubes, which increases repair costs and down-time. High cost replacement power may also be needed if a forced outage occurs during peak demand.

When a leak occurs in the furnace of a process recovery (PR) boiler, the potential for an explosive smelt/water reaction exists, and the need for reliable leak detection capability becomes a safety issue. Property damage and personal injury are the primary concerns.

Detection of tube leaks using fluid-borne acoustic sensors was first developed during the early 1970s in Europe for feedwater heaters and later applied in an airborne form to large power generation boilers. This technology was subsequently introduced into the U.S. market by The Babcock & Wilcox Company (B&W) in the early 1980s.

While being successful in utility boiler applications, the airborne approach to leak detection has limitations in the application to PR boiler furnaces. These limitations arise from several factors, including:

- The attenuation of airborne acoustic signals is greater because of particulate loading and flue gas water vapor content.
- Black liquor and smelt coat the furnace walls, making it extremely difficult to maintain an open acoustic path from the furnace enclosure to an airborne sensor.
- The airborne technique does not work when sootblowers are running, and the new high solids fired units have been reported to require continuous sootblowing with as many as three lances active at any given time.

To overcome these limitations, alternative approaches had to be evaluated. During the past few years, B&W has invested in a major effort to develop a technique that relies upon the monitoring of structure-borne sound waves which propagate within the furnace membrane tube walls of PR boilers. This paper summarizes this experience with the development and application of both airborne and structure-borne acoustic leak detection methods in power plants.

Technical Discussion

Overview

As a leak develops in a pressurized system, turbulence created by escaping fluid generates pressure waves within the contained fluid itself, throughout the low pressure medium (usually a gas) into which the fluid is escaping, and within the container structure. These are commonly referred to as fluid-borne, airborne, and structure-borne acoustic waves, respectively.

To detect leaks, the energy associated with these mechanical waves can be converted into electrical signals with a variety of dynamic pressure transducers (sensors) that are in contact with the medium of interest. Several methods of signal processing are available that allow the voltages generated by these sensors to be evaluated for the presence of a leak.

As mentioned above, leaks in a pressurized system generate sound waves in three media. The decision regarding which types of acoustic waves are most reliably detected is important from both functional and economical considerations. This decision, in some cases, is not simple. Factors such as background noise level, sound attenuation within the medium, signal processing strategy, and installation costs play a role.

Fluid-Borne Leak Detection

The most well known use of fluid-borne leak detection is in the earlier work on feedwater heater applications. It was ultimately found, however, to be inadequate due to widely fluctuating background noise levels during load changes. In other applications, this method is rarely used because the sensor must be in contact with the contained fluid, which requires mounting it through the wall of the pressurized container.

Airborne Leak Detection

Since 1974, airborne leak detection has been predominantly used in large commercial boilers. Airborne methods are well established and have detected leaks as much as a week before any other means available.

In airborne applications, microphones or low frequency resonant piezoelectric transducers are coupled by hollow waveguides to the gaseous furnace medium. The waveguides are usually attached through penetrations in inspection doors, unused sootblower ports, or the casing.

The airborne waveguide, shown in Figure 1, serves three purposes. It couples the sound waves from the furnace interior to the transducer face, protects the transducer from excessive heat, and allows easy access to the transducer for inspection or replacement.

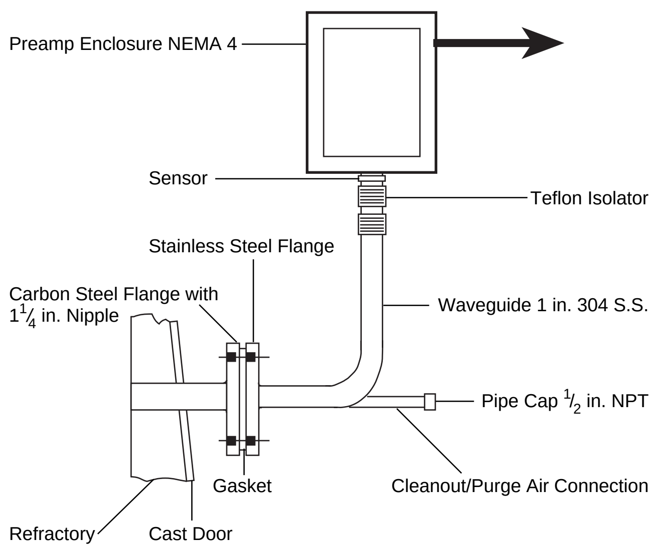

Figure 1 Standard installation of preamp, sensor and waveguide.

Structure-Borne Leak Detection

The structure-borne method of leak detection has found applications in valves and pressurized pipelines. Under a recent Electric Power Research Institute (EPRI) sponsored project, a high frequency structure-borne approach was found to be the best method for detecting leaks in feedwater heaters. The structure-borne technique uses piezoelectric transducers coupled to acoustic emission type waveguides which are weld-attached as shown in Figure 2.

In this application, a single structure-borne sensor mounted to the outlet side of the tube sheet will fully cover a high pressure feedwater heater. Low pressure feedwater heaters require an additional structure-borne sensor mounted to the inlet side of the tube sheet.

An alternative structure-borne technique uses accelerometers, rather than piezoelectric transducers, mounted to the ends of the waveguides. While similar performance can be obtained in some cases, the inherent nature of accelerometer function can produce misleading results in others. This will be discussed further in a later section of this paper.

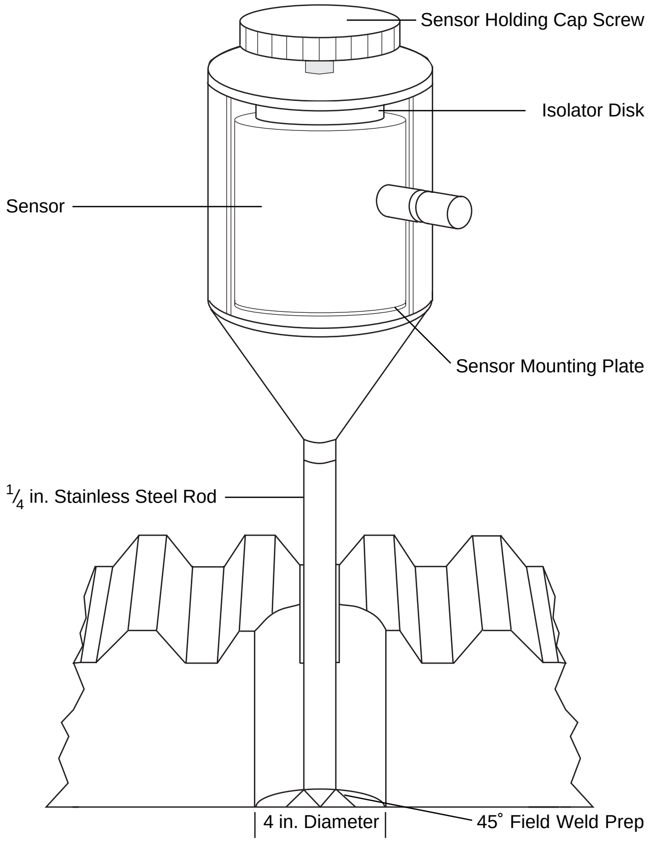

Figure 2 Structure-borne waveguide.

Background Noise

In leak detection applications, the most important factor to consider is background noise within the propagation medium of interest. Almost all background noise can be characterized as white noise combined with discrete frequency noise.

White noise can be defined as containing components at all frequencies within a range or band of interest. Both normal boiler noise and leak noise are considered to be white noise. Boiler noise is best described as low frequency white noise (rumbling) while leak noise is best described as higher frequency white noise (hissing).

Discrete frequency noise is usually composed of a fundamental single frequency (tone) and several associated harmonic frequencies. These sounds are best described as whistling or humming noises.

Sound Wave Attenuation

In any medium, low frequency sound waves will be attenuated less, and therefore travel farther, than high frequency sound waves. Also, in most cases, sound will travel farther in solids and liquids than in gases. These are primary considerations when determining how far away from the sensor a leak can be detected.

Acoustic attenuation characteristics of the various media also play a role in influencing which leak detection method to employ. For instance, the gaseous medium present in PR boilers imposes significantly more airborne signal attenuation because of high concentrations of water vapor, saltcake, and suspended char that are not present in utility boilers. In fluid-borne applications involving pipes or tubes, the presence of gas bubbles will severely attenuate the fluid-borne signal. In structure-borne applications, the presence of corrosion, surface adhesion of insulation, and/or welded attachments will severely attenuate structure-borne acoustic waves.

Signal Processing Strategies

In all methods of acoustic leak detection, the objective is to be able to tell the white noise generated by a leak apart from the background noise at a reasonable distance. Since high frequency sound waves are more severely attenuated than low frequency waves as they propagate through a medium, a general rule of thumb is to use the lowest frequency range possible where the leak noise stands out from the background noise. This will ensure the greatest amount of coverage by the fewest number of sensors.

The lowest useable frequency range is determined by testing. With most sensors, a high pass filter is used to eliminate the lowest of the detectable frequencies which can overload the inputs to the signal processor. This filter is usually located near the sensor in the preamplifier, which is used to boost the signal level to a point where it can be sent over a long distance to the signal processor.

One method of signal processing involves bandpass filtering of the input signal at the optimum frequency range and then applying an RMS conversion to establish an average direct current (DC) voltage level of the signal. This voltage level is then compared to a fixed threshold level that represents the maximum normal background noise level in the optimum frequency range. When the measured signal level exceeds the threshold level for a preset amount of time, a leak is indicated. Within a filtered band, the RMS conversion method can easily detect leaks with as little as a 3dB (1.4 to 1) leak signal-to-background noise ratio.

Another signal processing scheme is to take the entire signal and filter it into several frequency bands. The noise levels in these bands are then monitored and assigned a weighted value based on their likelihood to be leak related. As in the first method, when the appropriate threshold levels have been exceeded long enough, a leak is indicated. In some cases, an alarm is not generated until one of the higher frequency bands confirms a suspected leak, which may not be until it has grown substantially.

A third signal processing scheme is to immediately digitize the incoming signal and perform a Fast Fourier Transform (FFT) on it to produce the frequency spectrum. This spectrum is then stored in memory and compared either visually or by software to a previous spectrum that is characteristic of normal background noise. If a sufficient difference exists between these spectra and the normal spectrum for a long enough time, a leak is indicated.

Installation Costs

Economics play a decisive role in selecting one leak detection method over the other. For an application where no boiler wall penetrations are available, the structure-borne method would be an obvious candidate. No openings are needed, no pressure part cutting and welding are required, and all installation work can be completed from the outside of the boiler.

On the other hand, if several structure-borne sensors are required to cover the same amount of area as one airborne sensor, then the costs of the additional sensors, signal processing hardware, and cable installation need to be considered.

Development of the Application of Structure-Borne Leak Detection to the Furnace Membrane Tube Walls of Process Recovery Boilers

Over the past three years, a significant development project was undertaken to determine the optimum method for using structure-borne acoustic leak detection to cover the furnace walls of PR boilers. This method would also be extended to utility boilers, where openings for airborne waveguides are sometimes scarce and removal of flyash from the waveguides must be dealt with. The program began in 1990 and was completed late in 1993. The basic outline for this developmental effort was as follows:

I. Develop and characterize a "leak source" simulator
II. Perform preliminary laboratory testing on a section of PR boiler wall panel
III. Locate an Alpha test site and perform field tests
IV. Locate a Beta test site and perform wide scale testing

Leak Source Simulator Development

To successfully develop a structure-borne leak detection system, the first need was to be able to simulate a leak and quantify it. To meet these objectives, a two part study was undertaken. The first goal was to develop a device to simulate a leak signal using compressed air as the energy source. The second objective was to develop a data base to correlate leak signals with respect to fluid, pressure, and orifice diameter.

Cold water, hot water, saturated steam, and air leak signals were studied at pressures ranging from 30 psig to 2,000 psig and orifice diameters ranging from 1/32 inch to 1/2 inch. Information gained from these studies provided a mathematical model that relates signal levels generated by high pressure leaks through small holes with low pressure leaks through large holes.

This recently patented leak source simulator, shown in Figure 3, uses 90 psi plant air escaping through a 1/4 inch diameter orifice to simulate a 1300 psi steam leak through a 1/16 inch diameter hole.

Laboratory Testing

Once the leak source simulator development was complete, the device was used to investigate the attenuation characteristics of a PR boiler furnace wall panel. This was accomplished by strategically locating a few fixed sensors and then moving a portable leak source simulator from point to point in a grid.

It was found that structure-borne sound waves travel much further along a tube than across the membranes from tube to tube. Welded obstructions, such as windbox attachments, were found to severely attenuate structure-borne signals that cross them. It was further found that the injected signals could not be detected with a sensor mounted to the header, even with the source mounted a short distance away.

A rake assembly was then attached across the tubes to determine if the directivity ratio could be improved. The rake was composed of 1/4 inch diameter pins welded to each tube and all welded to a common 1-1/2 inch by 3/16 inch bar that spanned the tubes. It was found that by doing this, the source was detectable as well across the tubes as along them.

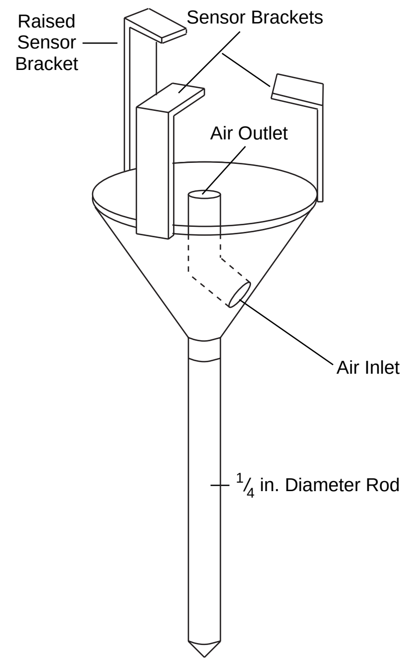

Figure 3 Structure-borne leak source simulator.

Initial Field Testing

Following the laboratory tests, several sets of field testing were conducted at a southern paper mill to confirm and broaden the understanding of structure-borne leak detection in the furnace walls of a recovery boiler.

One tube of this 900 ton/day PR boiler was instrumented from lower header to upper header with leak source simulator waveguides spaced an average of about thirteen feet apart. At the liquor gun level, a four foot wide rake assembly was installed centered on the selected tube. A single floor tube was then instrumented with two of the simulator waveguides spaced fourteen feet apart. The test layout is shown in Figure 4.

The first objective was to determine leak signal attenuation rates with the boiler off-line and empty, off-line and water filled, and on-line. The second objective was to characterize background noise levels with the boiler on-line at full load. A third objective was to establish the best combination of sensor type and filtering strategy to maximize the simulated leak signal-to-background noise ratio.

A wide variety of commercially available sensor types, including accelerometers, were tested. Overall, a frequency span from 5 kHz to 200 kHz was investigated. The sensors were tested both with and without being covered by an acoustic enclosure used for shielding out external background noise. Results from this field testing included the following:

- With the boiler off-line and empty, simulated leak like signals could be detected at high frequencies as far as 90 feet along a tube. The signals could not be detected, even at short distances, in the upper or lower headers.
- Substantial attenuation was found, as expected, when the signal crosses a windbox attachment weld.
- Background noise levels were found to be relatively low during full load operation. The floor tube background noise level was considerably lower than that of the wall tube.
- The best performance was achieved using a 150 kHz resonant sensor. This sensor could detect the simulated leak signal in excess of 30 feet along the tube. It was also found that this sensor was virtually immune to sootblower noise, even without the acoustic enclosure.
- External air coupling tests accomplished by opening 90 psi air valves near the sensors showed the 150 kHz sensors to be affected if the valve was less than 10 feet away. We concluded that the acoustic enclosures would be a necessary part of a structure-borne leak detection system for this application.
- The accelerometers were found to be extremely susceptible to externally coupled airborne noise, even with the acoustic enclosure in place.

It was immediately determined that so far, only one tube in one boiler had been investigated. The existing four foot long rake had provided no useful information. A plan was then devised to install two levels of rakes covering a span of half the width of each of two adjacent furnace walls. The lower level would be installed just above the liquor gun ports and the upper level would be installed just under the nose level.

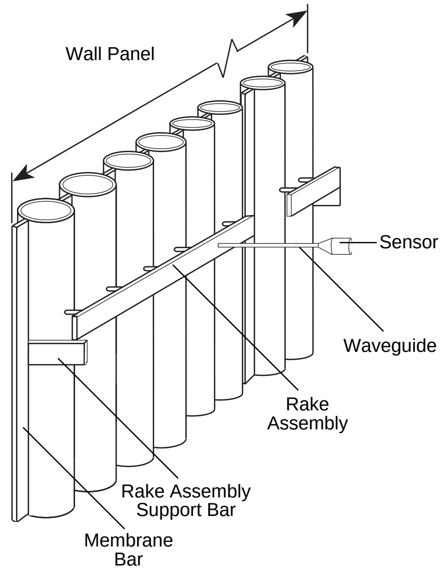

Figure 5 Rake installation.

Beta Testing

During the Spring 1993 outage, the East and South walls of the PR boiler at the southern mill were outfitted with rake assemblies. The rakes were then instrumented with standard structure-borne waveguides, 150kHz sensors, and acoustic enclosures. Nine leak source simulator waveguides were attached to tubes in a rectangular grid between the rake levels on the East wall. The rake attachment details are shown in Figure 5 and the test layout is shown in Figure 6.

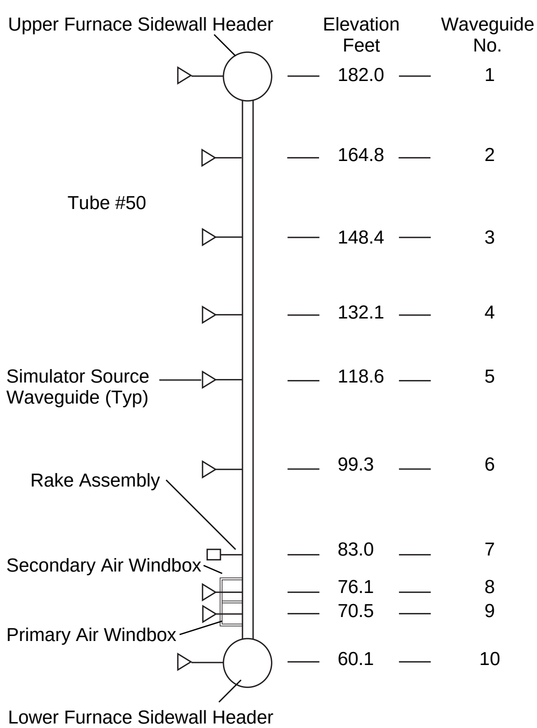

Figure 4 Field test layout.

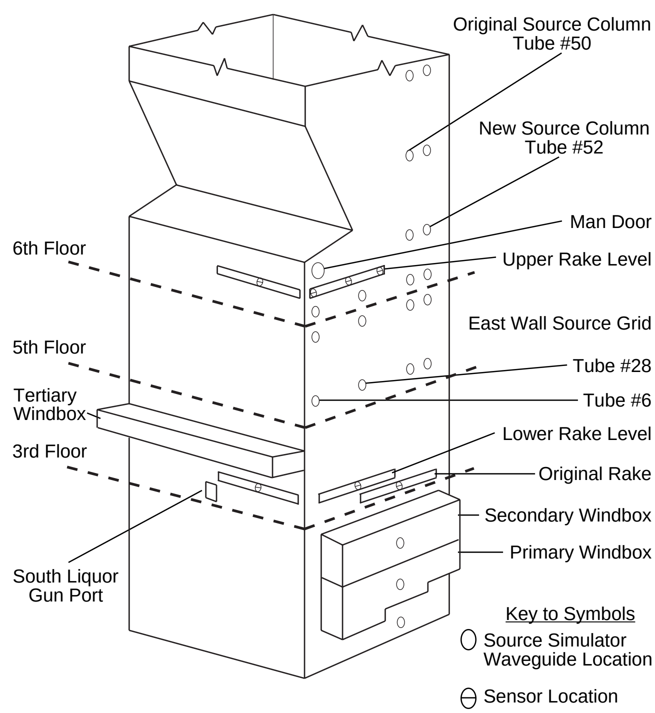

Figure 6 Beta test rake layout.

Several rounds of testing were performed, each based on the results from the previous round. During the latter stages, a task force was formed from various disciplines to evaluate the test results and make recommendations for the following round.

The goal of the initial testing was to simulate leaks at the various points in the grid and determine the responses in and effectiveness of the rake assemblies. The results were as follows:

- Due to geometric spreading, severe signal attenuation occurred in the first few feet of rake. It was found that the current rake design was unacceptable for this particular application.
- The testing sequence involving the sources in the grid provided unexpected results. While the sources on the right side of the rake near the initial vertical row of waveguides produced signals that could be detected in the rake, the grid sources in the middle and left sides of the rake could not be detected at all.

  Detailed investigation showed that the wall panels on the right side of the rake had been recently replaced. They were found to be painted and the insulation had also been replaced. The remainder of the furnace wall was composed of older unpainted panels that were corroded to the point where the fibers of the insulation were actually intermeshed with the tube surface. It was concluded that the leak source signal was completely attenuated in these areas before it had travelled as much as ten feet.
- A query directed to field service personnel produced an answer that corrosion-adhesion of insulation to the tube walls is a common occurrence in boilers of all types.

With the effectiveness of the high frequency structure-borne approach in question, it was decided to strengthen the simulated leak signal. This was accomplished by mounting 1/4 inch pipe nipples to the membrane between tubes and injecting air directly through the wall. We found that the 50% loss in signal strength due to the welded simulator source waveguide was eliminated, as was the external airborne noise due to the simulator itself.

Lower frequency approaches were reinvestigated by performing side by side comparisons of the airborne method, a low frequency AE type structure-borne sensor, and an accelerometer. The side by side tests included leak source simulations, sootblower operation, and generation of external ambient noise.

Conclusions and Recommendations

Final Conclusions

- In units where corrosion-adhesion of insulation exists, the high frequency structure-borne approach will not work. The low frequency structure-borne approach, although affected by the attenuation of the insulation, will work at a reasonable range.
- The low frequency (2-20kHz) structure-borne approach detects simulated leaks in the same wall much better than the airborne approach. From a single weld attached waveguide, a simulated leak can be detected about four times further along a tube than across the tubes.The airborne approach, however, detects simulated leaks in adjacent and opposite walls much better than the low frequency structure-borne approach.
- The rake improves the lateral distance that a simulated leak can be detected, but not by a wide enough margin to justify the cost.
- A low frequency AE type sensor responds better than an accelerometer, but not by a wide margin. The acoustic isolation enclosure reduces the sensitivity of the AE type sensor, but not the accelerometer, to external noise. This means that accelerometers should not be used if the primary purpose is the detection of boiler tube leaks.
- In corroded regions, membrane attachment of waveguides shows better performance than tube attachment.
- The airborne approach is more sensitive to near sootblowers as the low frequency structure-borne approach. The low frequency structure-borne approach is more sensitive to far sootblowers as the airborne approach. This occurs because the higher frequencies are reflected and/or absorbed by the furnace wall.

If a small leak occurs in a tube internal to the boiler, such as in the convection pass area, the walls block most of the noise from a structure-borne sensor. On the other hand, the noise will pass through an open waveguide and reach an airborne sensor. As an analogy, you can overhear the conversation in the neighbor's yard a lot better if you open the window instead of listening through a drinking glass pressed against the window. The result is that while the structure-borne method is best for detecting leaks that occur in or near the wall, the airborne method is the best for detecting leaks that occur internally.

Strategy for Implementation

When devising a scheme for implementation of these findings, several factors were considered, including geometry. The first general guideline is the intent to be able to detect a 1/16 inch diameter (what is considered to be a pinhole) leak at 1300 psi in a furnace wall tube.

A minimum of a 3dB (1.4 to 1) signal-to-noise ratio is required for a leak to be easily detectable. Generally, sound losses are expressed in dB per foot. In reviewing the data and extrapolating, it was found that the simulated source produces a signal-to-noise ratio of about 20dB (10 to 1) at the source. It was also found that the attenuation coefficients are about 1/2 dB/ft along a tube and 2 dB/ft across the tubes. If this is plotted out to the 3dB edge, a diamond shaped area of coverage results. The vertical points are 60 feet apart and the horizontal points are 16 feet apart.

If the boiler tested is considered to represent a typical PR boiler with about a 1000 ton/day capacity, then the typical PR furnace is a box that is about 35 feet wide, 30 feet deep, and 120 feet tall. In order to get complete coverage, the first level of sensors would be placed just above the lower headers at a spacing of 16 feet apart. This level would contain eight sensors. The next level of 8 sensors would be placed 30 feet above the first level and staggered 8 feet sideways.

This pattern would then be repeated for the four levels required to provide complete coverage of the lower furnace. If full furnace wall coverage is desired, six additional sensors would be located just below the upper wall panel

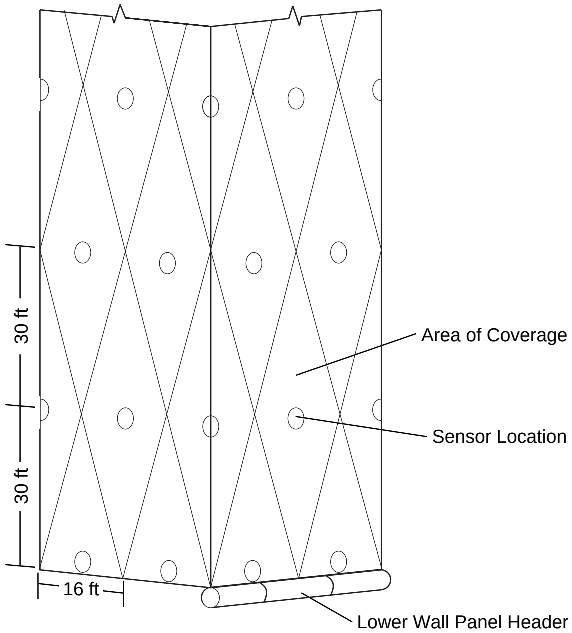

Figure 7 Structure-borne furnace wall leak detection implementation strategy.

headers. A diagram showing sensor locations and coverage for two adjacent walls is given in Figure 7.

Recommendations for Implementing Acoustic Leak Detection in Process Recovery Boilers

Upper furnace and convection pass.

- Airborne leak detection techniques provide the best performance in the upper furnace and convection pass areas.
- The optimum airborne monitoring frequency range is 2-15 kHz.
- Eight to twelve airborne sensors are typically needed to cover the convection pass area and upper furnace.
- Two to four airborne sensors will cover the penthouse.
- An automatic purge system should be installed to keep the waveguides clear of saltcake.

Lower furnace walls.

- Low frequency structure-borne leak detection techniques provide the best performance for furnace wall tubes.
- The optimum structure-borne monitoring frequency range is 2-20 kHz.
- It is recommended that structure-borne acoustic waveguides be attached to tube membranes.
- The area of coverage by a structure-borne sensor is diamond shaped. Each level of sensors should be center staggered with respect to the level beneath it.
- Structure-borne sensors should be equipped with acoustic enclosures for isolation from external airborne noise.
- Either piezoelectric transducers or accelerometers are acceptable for structure-borne furnace wall applications, but one should be aware that accelerometers may not be isolatable from external airborne noise.
- Both airborne and low frequency structure-borne leak detection methods suffer from interference during sootblower operation. A minimum of a five second gap of quiet time between lance pairs is required for these methods to function.

Furnace floor tubes.

- Although the low frequency structure-borne approach is recommended, it is not believed that current signal processing methods are fully adequate for PR boiler floor tube leak detection. It is thought that floor tube leaks under the char bed will produce burst type acoustic emissions “popping” rather than the continuous type “hissing.” Feasibility studies have been initiated into using structure-borne sensors and pattern recognition acoustic emission technology to detect leaks in floor tubes and smelt spouts. This technology is also expected to be useful in detecting the occurrence of composite tube cladding cracks through the same sensors used for furnace wall tube leak detection.