Design and implementation of a commercial acoustic leak-detection system for black liquor recovery boilers

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A commercial leak-detection system developed for black liquor recovery boilers uses acoustic transducers to provide continuous surveillance during all normal boiler operations, including the use of auxiliary fuel burners.

The economics of kraft pulping depend heavily on the safe, continuous operation of black liquor recovery boilers. In addition to their role in the regeneration of pulping chemicals, recovery boilers generate a large proportion of the steam required for millwide operations. Despite the efforts of paper mills, insurance companies, and boiler manufacturers, smelt-water explosions caused by boiler-tube leaks continue to pose a threat to normal boiler operations.

Methods to detect steam leaks in power boilers have been proposed and tested by researchers for nearly 20 years. Most leak-detection schemes monitor the total airborne or structural acoustic energy levels within the boiler to determine if a leak is present. Many limitations of such acoustic leak-detection strategies have been documented. These limitations include:

- High background noise levels associated with combustion
- Severe attenuation of acoustic energy within the boiler
- Limited durability of acoustic sensors in the harsh environment of the boiler.

Although various leak-detection concepts have been proposed, no commercially viable leak-detection system for black liquor recovery boilers has been available.

An acoustic leak-detection system for recovery boilers has been developed by researchers at Westvaco. This system incorporates many of the concepts proposed by Marziale *et al.** but utilizes spectral analysis techniques to overcome most of the inherent limitations of other leak-detection schemes. This acoustic leak-detection system has been installed on all Westvaco recovery boilers. Subsequent testing has confirmed that the system is effective in detecting simulated leaks.

System operation provided early detection of an actual leak, which resulted in the use of emergency shutdown procedures before damage could occur, as reported at the Fall 1988 Conference of the Black Liquor Recovery Boiler Advisory Committee (BLRBAC). The system technology has been licensed to NDT International, Inc., for manufacture and supply to the entire paper industry.

Background

A promising approach toward an automated leak-detection system has been to monitor the difference between the characteristic roar of combustion and the airborne acoustic noise generated by a steam-tube leak. The noise created by a steam leak can be explained in terms of turbulent eddies that generate broad-band acoustic noise. After demonstrating that the combustion roar exhibits a characteristic acoustic power spectrum, Marziale *et al.* concluded that leaks on the order of 1/16- to 1/8-in. diameter could be distinguished from the background noise levels if (a) the soot blowers were not blowing steam, (b) the electronic signals were filtered appropriately to accentuate the distinction between normal background noise and leak noise, and (c) auxiliary fuel burners were not operating in the boiler.

A first attempt at developing a commercial leak-detection system specifically for a black liquor recovery boiler was undertaken in a joint venture between Westvaco Corp. and Babcock & Wilcox Co. A prototype 8-channel system was installed in a 1350-ton/day Combustion Engineering boiler. This prototype system was subsequently abandoned due to a number of significant design limitations:

1. The system architecture relied heavily on custom hardware. This approach did not provide the flexibility of a software-based architecture to adapt the data

*Marziale, M. L., Guy, C. D., Nuspl, S. P., and Whitten, P. G., Tappi J. 72(7): 67(1989).

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sampling methods and the signal analysis techniques to the following: (a) changing boiler-operating procedures, (b) feedback from operations personnel, and (c) anticipated developments in the field of acoustic leak detection.

2. The circuitry for real-time analog signal processing was not quick enough to capture a full 8-channel data set in the brief intervals between the operation of successive soot blowers.
3. Boiler operators became frustrated with the slow and tedious access to the system information. As a result, operator interaction with the system dropped almost to the point of neglect.

Because of these limitations, Westvaco development efforts were initiated to produce a commercially viable acoustic leak-detection system specifically designed for black liquor recovery boilers. From the outset of these efforts, the goal was a system that would be used effectively by boiler operators to improve the safety of their work environment. To this end, input from the operators was solicited and incorporated extensively into the design of the display formats and the user interface.

A number of concerns generated by Marziale *et al.* had to be addressed before a viable system could be realized. These included:

- Determination of appropriate sensor distribution to provide full coverage for the entire furnace section of the boiler
- Ability to detect steam-tube leaks while auxiliary fuel burners are operating.

The final system design was influenced by results of boiler tests to study these points.

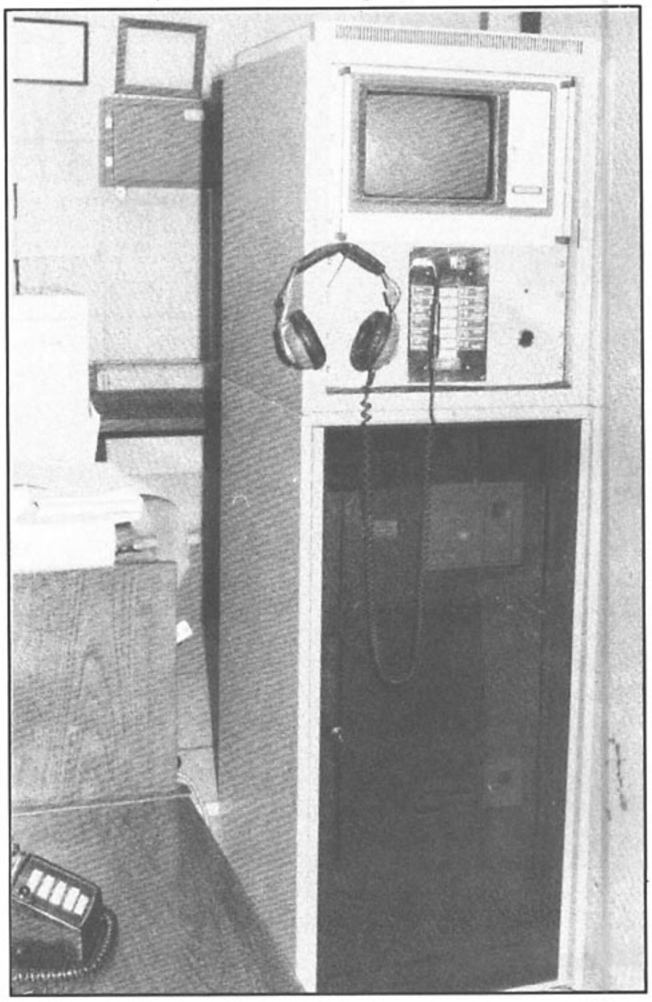
Current acoustic leak-detection system development

A 12-channel automated acoustic leak-detection system has been designed for use on black liquor recovery boilers. By refining many of the design specifications of an earlier prototype system and incorporating them with an additional set of functional specifications suggested by boiler operators, a unique system with a viable operator interface has been developed **(Fig. 1)**. **Figure 2** is a descriptive schematic of the system.

The system consists of three major components. Waveguide and sensor units convert the interior acoustic noise to electronic signals. The signals are transmitted by electrical cable to the processing unit, which performs the signal conditioning and analysis, system control, and data storage. The operator interface consists of a 24-function keypad and a color video monitor.

The boiler sensors are piezoelectric transducers for sound pressure measurements. These transducers exhibit sensitivity to sound pressure in the frequency range of interest and are capable of withstanding the dust, vibration, and sustained high temperatures (up to 250°F) typical of the environment outside a recovery boiler. The piezoelectric elements are either quartz or ceramic crystalline structures, hermetically sealed in stainless steel enclosures.

1. Console for operator interface and signal processing

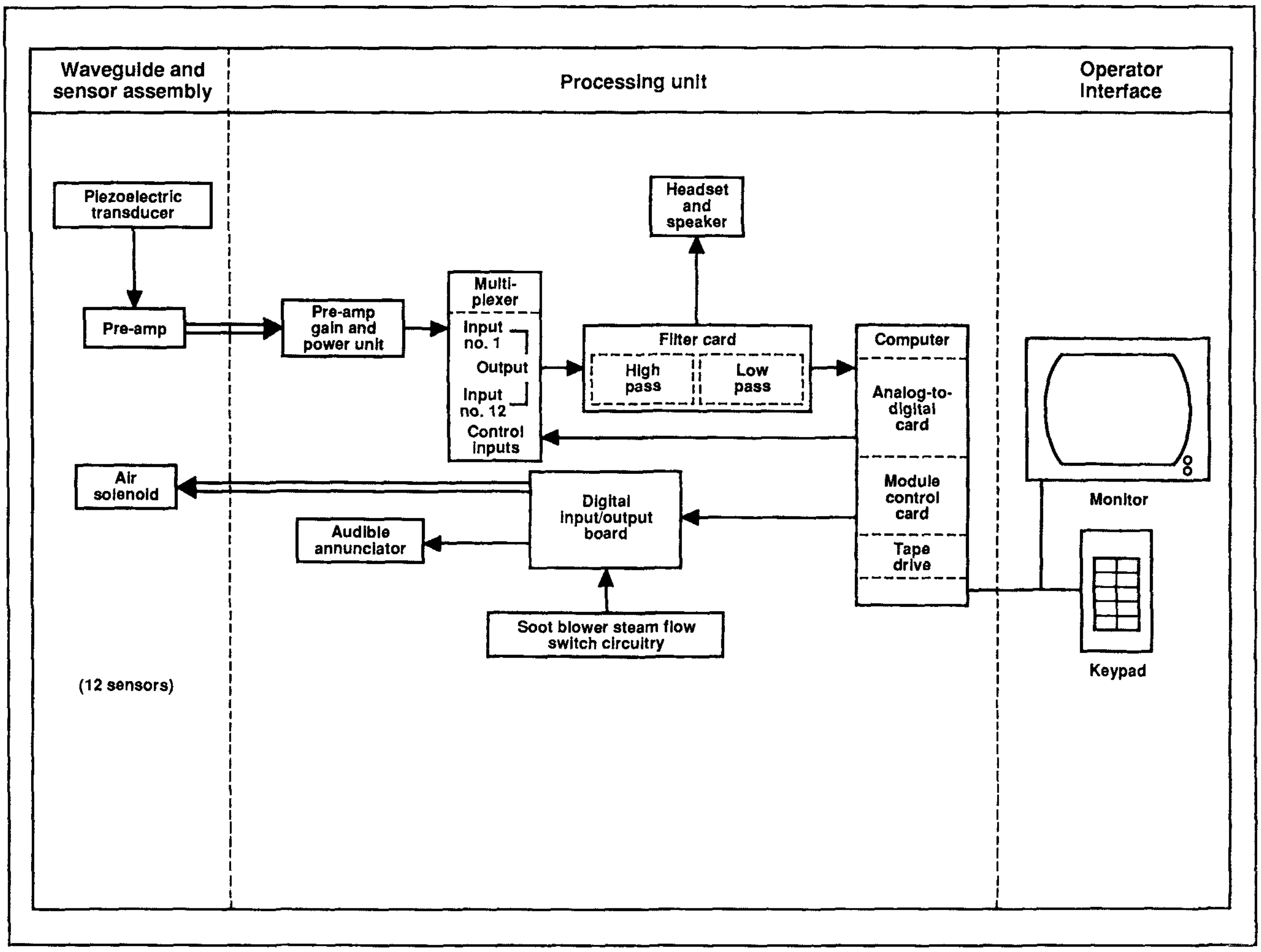


A typical waveguide and sensor assembly is shown in **Fig. 3**. The transducer and associated electronics are mounted outside the boiler at the end of a stainless steel waveguide, which is fixed through the wall of the boiler. The waveguide provides a path through which boiler noise is transmitted to the transducer. The waveguide is purged with air automatically at periodic intervals to clear any accumulated loose debris. Automated equipment for mechanical rodding is used in locations where the air purge is not effective.

The process and control software runs on a single processing unit. This unit analyzes the signals, generates leak classifications, stores the data, and drives the video display. The system was designed to operate both on personal computers that use the Intel 80286 chip and are compatible with the IBM PC AT and on many current computers with the Intel 80386 chip.

In addition to the main processor, the computer has the following components installed: fixed hard disk, removable mass-storage device for backing up system and data files, high-speed 12-bit analog-to-digital conversion card, and digital input/output controller. The digital input/output controller is connected to an external solid-state driver board. It activates air-purge solenoids and mechanical-rodding equipment designed to clear the waveguide of debris periodically. In the event that an

2. Schematic of acoustic leak-detection system



abnormal condition is detected by the system, an external audible annunciator is tripped.

The system collects data at periodic intervals when there is no steam flowing through the soot blowers. To minimize the time required to collect a full set of data, the system converts an entire 12-channel data set from analog signals to digital signals and stores them in the computer's memory before performing any data analysis. The analysis, which takes a relatively longer time to complete (approximately 25 s), is performed after the data have been collected and the soot blower steam resumes flow.

Once collected, the data are processed digitally using fast Fourier transform (FFT) techniques. Although similar results may be obtained using analog circuits, digital techniques offer advantages over the prototype system in terms of data collection rates. The analog raw data can be converted to digital values and stored rapidly (at rates up to 200,000 points/s) during the short sampling window, before any analysis is performed.

The software package developed specifically for this application has enabled the system to be adapted quickly and effectively to new technology, boiler operating procedures, and operator feedback. Because all the analysis is performed with software, upgrades can be incorporated without difficulty.

The leak-classification algorithm contained in the software considers both the magnitude and the duration of the boiler noise levels. The basic premise assumes that a steam leak will increase in volume as the leak size grows. Therefore, noise that returns to normal levels after a short duration at an elevated level is not classified as a tube leak. Abnormally high noise levels that persist or increase with time are classified with increasing severity until a "red alarm" state is reached. Extremely high noise levels, which may indicate a tube rupture, generate an immediate leak report. The classification scheme successfully reduces false alarms caused by sources other than tube leaks, while maintaining adequate response time to potential leak conditions.

The system provides the operator with an audible monitoring channel. By selecting any one of the 12 sensors, the operator can listen to the conditioned boiler noise on a speaker or a set of headphones. This allows operators to scan the boiler rapidly for abnormal noise before entering a potentially dangerous area.

System confirmation tests

A viable leak-detection system must utilize an adequate number of sensors strategically located along the boiler perimeter to detect leaks, which may occur anywhere within the boiler. Many factors influence the ability of a sensor to detect leaks in the hostile environment of a recovery boiler. These factors include (a) high background noise levels associated with combustion, (b) turbulence and drafting effects within the furnace, (c) attenuation of acoustic energy due to soot and other particulates, and (d) path obstacles such as tube banks between the leak and the sensor. These adverse influences prevent the establishment of an "effective radius" for acoustic sensors. The number and distribution of acoustic sensors must adequately account for all such influences and ensure detection of any leak that may occur.

The installed leak-detection systems use 12 piezoelectric transducers to monitor noise levels within each recovery boiler. In the first two system installations, sensors were positioned intuitively by considering the adverse influences of boiler drafts and path obstacles. Because flue gases tend to draft upwards and because of the higher concentration of steam-generating banks in the upper boiler, most of the acoustic sensors were located in the upper furnace of each boiler. To reduce the effects of path obstructions, sensors were generally positioned in alleys between neighboring tube banks.

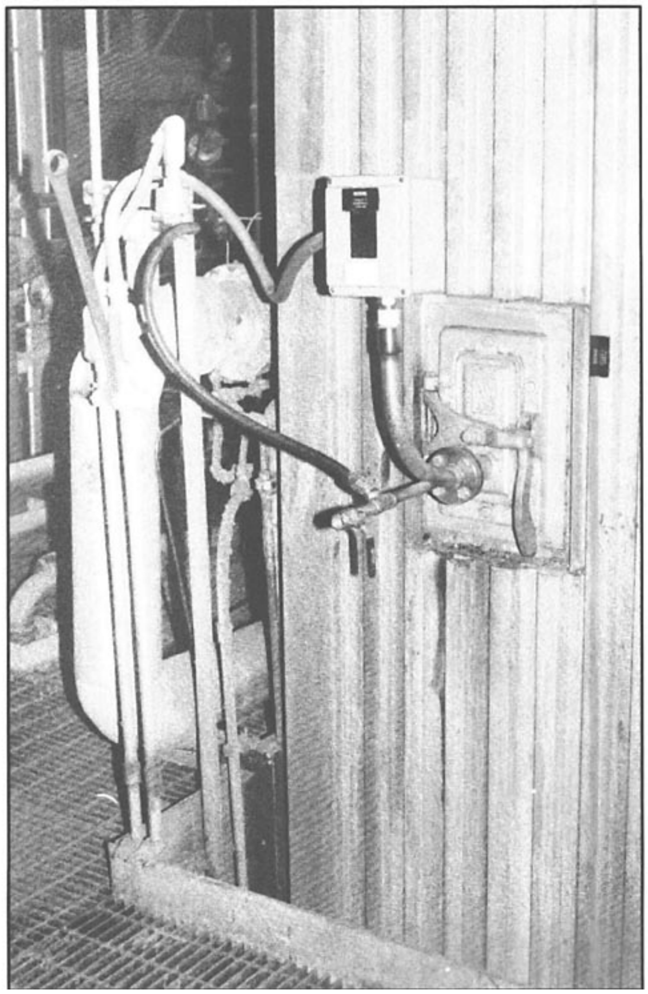
To assess the adequacy of each 12-sensor distribution, extensive system confirmation tests were conducted at the first two installation sites. The first boiler was a 1350-ton/day Combustion Engineering (CE) boiler, and the second was a 1500-ton/day Babcock & Wilcox (B&W) boiler. Simulated leaks were introduced at various locations on each boiler to ensure that all leaks would generate system alarms.

Leaks were simulated by using an electronic driver, powered by a white-noise generator, and an amplifier. The driver was equipped to fit securely inside inspection-port doors located around each boiler perimeter. The driver was positioned sequentially in selected inspection ports. A total of 12 different leak locations were tested on the CE boiler, and 16 locations were tested on the B&W boiler. Sound levels were selected to simulate superheated-steam leaks through 1/8-in. circular orifices at the operating pressure of each boiler. Sensor responses were evaluated by comparing the background and simulated leak-noise energy levels (**Fig. 4**). The signal energies were computed as the total rms energy between 700 and 7000 Hz. The "sensor response ratio" for a given sensor was defined as the ratio of simulated leak energy to normal background energy.

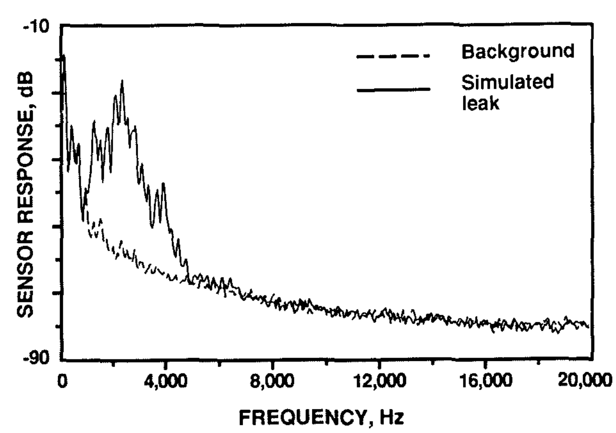
The results of simulated leak testing, compiled in **Tables I and II**, reveal the adverse influences of flue gas drafts, path obstacles, and combustion noise on sensor response ratios. In cases where the sensor was "downstream" from the simulated leak, and the signal was not obstructed by tube banks, the sensor responses were excellent. Combinations of flue-gas drafts and signal obstructions substantially affected the response of some sensors to some simulated leaks. Even in some cases where the signal distance was relatively short, the response to simulated leaks was insignificant. In other cases, the sensor response was enhanced by drafting effects; some sensors far away from the simulated leak source responded substantially to the simulated leak.

Sensors located near the combustion bed were generally unresponsive to most leak tests. Only when the simulated leak was placed in the immediate vicinity of these sensors

3. Typical installation of waveguide and sensor



4. Typical sensor response to background and simulated leak noise



I. Influences on sensor response for Combustion Engineering boiler

Simulated leak test	Maximum sensor response ratios	Signal distance, ft	Signal path obstacles	Relative sensor and leak positions: Draft currents	Relative sensor and leak positions: Boiler wall
A	5.8	5.0	None	Same	Same
	3.2	23.5	None	Upstream	Same
B	7.4	5.0	Same	None	Same
	3.7	25.0	Tube bank	Same	Adjacent
C	16.2	8.0	None	Same	Same
	11.6	5.4	None	Downstream	Same
D	8.8	31.2	Tube bank	Same	Opposite
	6.8	3.0	None	Same	Same
E	6.6	28.0	None	Downstream	Same
	2.5	30.0	None	Same	Same
F	7.7	15.0	None	Same	Same
	1.6	23.5	None	Downstream	Same
G	4.5	5.0	None	Same	Same
	4.2	50.6	Tube bank	Same	Adjacent
H	2.3	28.6	None	Downstream	Same
	2.1	25.5	None	Downstream	Same
I	2.5	23.5	None	Downstream	Same
	2.2	31.0	None	Same	Same
J	26.6	8.5	None	Same	Same
	3.5	30.1	Tube bank	Same	Opposite
K*	1.6	36.1	None	Same	Adjacent
	1.4	27.3	None	Same	Adjacent
L*	1.5	28.3	None	Same	Adjacent
	1.2	36.1	None	Same	Adjacent

*Lower boiler tests.

was the sensor response ratio greater than 1.5, the level necessary to generate a system alarm. In each simulated leak test, however, at least one sensor had a sensor response ratio of 1.5 or greater, as shown in **Figs. 5 and 6**.

The simulated leak tests validate the configuration of 12 acoustic sensors in detecting boiler-tube leaks of 1/8-in. diameter or greater, even on boilers of different design and capacity. In every test case, the system response was sufficient to generate an alarm, regardless of the simulated leak location. The adverse influences of flue-gas drafts, signal distance, obstacles, and combustion noise on system response are apparent. Near the combustion bed, acoustic sensors are effective in detecting only lower-furnace leaks. Work is needed to enhance the sensitivity of lower-boiler sensors.

Performance to date

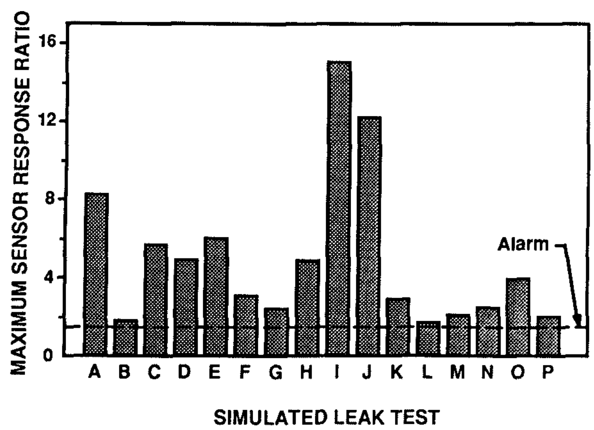
Six acoustic leak-detection systems are operating effectively on both B&W and CE black liquor recovery boilers that range in capacity from 500 tons/day to 1500 tons/day.

The first system, installed in September 1988, detected a wall-tube leak within the first 24 h that it was operational. The leak was caused by a failed attachment weld to the tube. Inspection of the failed tube section revealed a tear measuring approximately 1/8 by 1/4 in. long. During this incident, the system began to indicate a possible leak roughly 1 h before detection by traditional methods was possible. The boiler was taken off-line safely according to BLRBAC emergency shutdown procedures. The response of the leak-detection system to this incident was reported at the Fall 1988 BLRBAC Conference.

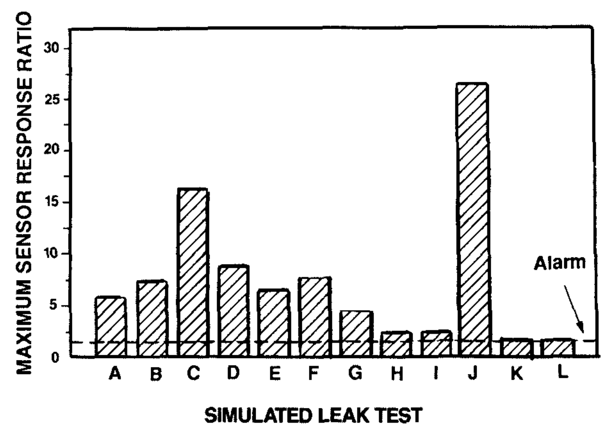
The systems have been effective in detecting soot blowers that failed to retract fully from the boiler. By monitoring soot blower steam flow, the system generates a "stuck blower" alarm if the flow has not dropped to zero within a specified period of time. Numerous stuck blowers have been detected by the leak detection system. In some of these cases, the soot blower controller, which monitors soot blower motor current, provided no indication of the problem. The systems have been modified and tuned to eliminate the occurrence of any appreciable number of false alarms.

The performance of the piezoelectric sensors has not degraded under normal continuous service. The frequency responses of six sensors removed from service were compared in laboratory tests with those of two new identical sensors. No appreciable differences in the quality of sensor response were observed.

5. Maximum sensor response ratios for Babcock & Wilcox boiler



6. Maximum sensor response ratios for Combustion Engineering boiler



II. Influences on sensor response for Babcock & Wilcox boiler

Simulated leak test	*Maximum sensor response ratios*	*Signal distance, ft*	*Signal path obstacles*	*Relative sensor and leak positions*	
				Draft currents	*Boiler wall*
A	8.2	10.0	None	Same	Same
	3.1	29.0	Tube bank	Same	Adjacent
B	1.5	32.0	Tube bank	Same	Adjacent
	1.2	33.2	Tube bank	Downstream	Adjacent
C	5.7	41.3	Tube bank	Downstream	Opposite
	4.0	26.9	Tube bank	Same	Adjacent
D	4.9	9.8	None	Upstream	Same
	3.3	39.5	None	Same	Opposite
E	6.0	13.5	None	Upstream	Same
	2.0	50.4	Tube bank	Same	Opposite
F	3.1	33.2	Tube bank	Upstream	Adjacent
	1.8	32.0	Tube bank	Same	Adjacent
G	2.4	10.8	None	Upstream	Same
	2.1	40.4	Tube bank	Same	Adjacent
H	4.9	40.3	Tube bank	Same	Opposite
	3.1	28.7	Tube bank	Upstream	Adjacent
I	15.1	39.3	None	Same	Opposite
	5.0	11.4	None	Upstream	Same
J	12.2	43.0	Tube bank	Same	Opposite
	11.6	10.8	None	Upstream	Same
K	2.9	16.6	None	Downstream	Same
	1.5	37.6	Tube bank	Upstream	Adjacent
L	1.7	23.3	None	Downstream	Same
	1.4	34.7	None	Downstream	Opposite
M	2.1	20.9	None	Upstream	Same
	1.7	32.3	Tube bank	Same	Adjacent
N	2.5	10.0	Tube bank	Same	Adjacent
	2.3	41.7	Tube bank	Upstream	Adjacent
O	4.0	23.3	Tube bank	Upstream	Opposite
	1.8	22.0	None	Same	Same
P	2.1	45.4	None	Upstream	Opposite
	1.2	31.0	None	Upstream	Opposite

Summary and conclusions

A commercially viable acoustic leak-detection system has been developed for black liquor recovery boilers. This system uses 12 piezoelectric sound-pressure transducers to monitor interior noise levels. The system is capable of continuous surveillance during all normal boiler operations, including the use of auxiliary burners in the boiler. Based on the results of extensive confirmation tests, the system has proven effective in detecting simulated leaks.

The acoustic leak-detection system has been installed on all Westvaco recovery boilers in the United States and has been licensed to NDT International, Inc., for manufacture and sale throughout the paper industry. The system was effective in detecting the only furnace-tube leak that has occurred since installation.

Future work

Although economizer-tube leaks do not pose the same threat of smelt-water explosions as do furnace-tube leaks, early detection and maintenance would reduce potential damage. Extended coverage in the economizer will be evaluated.

Current developmental efforts are focused on providing stable coverage under transient boiler conditions that are encountered during cold boiler startups.

Lower-boiler leak detection must be studied in greater depth. Although lower-boiler sensors respond to simulated leak noise inserted into this area of the boiler, their sensitivity to localized leaks is significantly less than that of the upper-boiler sensors.□

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