Recovery-boiler leak detection using a waterside chemical-mass-balance method

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ABSTRACT

Water leaks in a black-liquor recovery boiler can cause explosions if the water reaches the molten smelt bed of the boiler. This paper describes a system that detects boiler leaks using a waterside chemical mass balance. A microprocessor-based chemical-feed system meters chemicals to match the losses that occur via blowdown, and boiler-water chemistry is monitored continuously. A water loss is indicated when the expected and measured chemical concentrations diverge. Field experience with this system is presented.

Application:

A new system for automatic detection of recovery-boiler leaks.

EARLY DETECTION OF WATER leaks in recovery boilers is critical to the prevention of explosions that can occur when boiler water reaches the molten smelt bed. Early detection is especially important, since small leaks tend to grow into larger leaks and can cause additional leaks in adjacent tubes.

If the recovery-boiler operator suspects that water is leaking into the furnace, an emergency shutdown procedure (ESP) can be initiated to avert the risk of explosion *(1)*. However, initiation of an ESP is not without risks, including extended downtime and possible boiler damage from the stress imposed by the ESP. Operators, therefore, need to have as much confidence as possible that a leak exists prior to initiating an ESP. If a leak can be detected and the boiler shut down before the leak develops into a large leak, explosions can be avoided *(2)*.

Currently available automated leak-detection tools use a range of techniques, including acoustic detection *(3)*, water mass balance *(4)*, and chemical mass balance *(5)*. There are also expert systems incorporating many boiler operating parameters *(6)*. Many mills rely partially, if not solely, on the vigilance of operators, who are expected to be alert to changes in parameters that are affected by leaks (water mass balance, sound in the furnace, visual evidence in the furnace, water chemistry, and various fireside parameters).

CHEMISTRY-BASED LEAK DETECTION

When a boiler-water leak occurs, it affects the boiler-water chemistry because the leak carries chemicals out of the boiler. In effect, a boiler-water leak represents an unexpected increase in boiler blowdown. If a known quantity of chemical is fed to a boiler, the chemical concentration in the boiler water can be predicted if the blowdown flow rate is known. If the chemical concentration in the boiler water is less than expected, this is evidence of an increase in the flow of liquid water leaving the boiler (via a leak, for example).

The absolute leak size that can be detected using a chemistry-based leak indicator (CBLI) system—and the time required to detect it—will differ for individual boilers. A CBLI system does not respond to the absolute leak size but, rather, to the leak size relative to the boiler blowdown flow rate and the mass of the liquid recirculating in the boiler. Also, in contrast to a water-mass-balance detection scheme, the response to a leak does not occur immediately, since the change in chemical concentration develops over time.

Based on fundamental material-balance principles, the following three relationships govern the responsiveness of a CBLI system:

1. The ability to detect leaks improves with increasing leak size.
2. The ability to detect a leak improves as blowdown flow rate decreases.
3. The time required to detect a leak decreases as boiler size decreases.

These relationships are illustrated in Figs. 1–3, respectively. Table I shows the boiler operating conditions for Figs. 1–3.

SYSTEM FEATURES

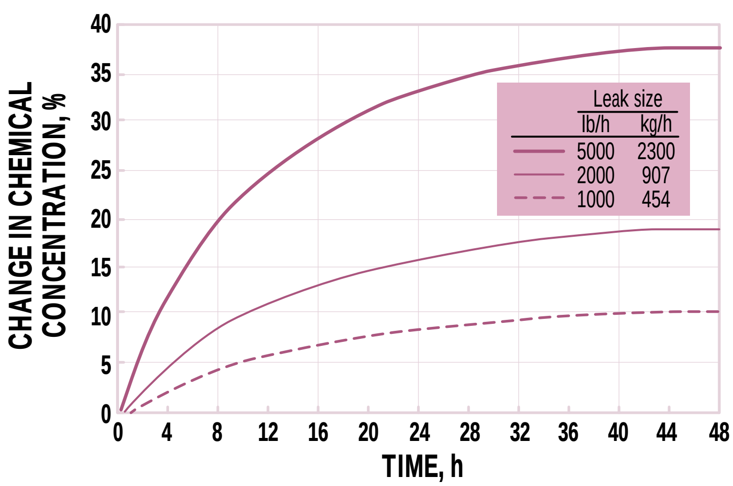
This paper describes a recently developed tool that uses chemical mass-balance principles to indicate water loss from the boiler. This chemistry-based leak indicator offers the following features:

- *Indication of small boiler-water loss that is not indicated by another method.* The sensitivity of the CBLI permits detection of relatively small leaks that can go undetected by other methods.
- *Verification of a boiler-water loss that is indicated by another method.* The CBLI can also be used to verify the presence of a leak detected by an independent method, thus increasing operator confidence in the result.
- *Leak location identification.* Since the CBLI depends on the

	Fig. 1	Fig. 2	Fig. 3
Steam flow rate			
400,000 lb/h (181,000 kg/h)	✔	✔	✔
Boiler size (liquid mass)			
150,000 lb (68,000 kg)	✔	✔	*
Boiler cycles			
50 [blowdown flow = 8200 lb/h (3700 kg/h)]	✔	*	✔
Leak size			
2000 lb/h (907 kg/h)	*	✔	✔

* Variable; see individual figure legend

I. Boiler operating conditions for Figs. 1–3



1. Change in boiler chemical concentration at various leak sizes. Boiler operating conditions are given in Table I.

loss of concentrated boiler water, when a leak occurs in the economizer or superheater, the CBLI response will be weak or nonexistent. Thus, the combination of a water mass balance responding to any significant boiler leak (including economizer and superheater leaks) and the CBLI, which only responds to a leak of concentrated boiler water, allows one to narrow down the possible leak locations. This is important, since superheater leaks and economizer leaks may not require an ESP *(1)*.

A CBLI system can be constructed using different combinations of chemical analyzers and flowmeters. Common sense dictates that minimizing the number of components leads to the most reliable system. This approach not only minimizes maintenance and repair costs, but also reduces the level of background noise, since each added component contributes some background noise to the system. A low level of background noise effectively increases the accuracy of the CBLI signal.

Besides minimizing noise and maintenance, the CBLI system described here offers the following additional advantages:

- *Operation in the presence of normal boiler transients.* Some leak-detection schemes require long periods of steady-state conditions *(5)* or "quiet time" *(3)*. No such restrictions are placed on this CBLI detection scheme.
- *Minimal impact on normal boiler chemistry.* As discussed in the next section of this paper, chemical feed is ratioed to blowdown flow rate. This greatly reduces the variation in boiler-water chemical concentration during boiler transients compared with systems where chemicals are ratioed to feedwater flow.

This method of chemical feed is especially important for coordinated phosphate/pH-control programs. During steam-load swings, if blowdown flow rate does not change, the chemical feed rate should not change. This minimizes variation in boiler-water chemistry. When blowdown flow rate does change, the chemical feed rate should be changed proportionally to maintain steady boiler chemical concentrations.

SYSTEM DESCRIPTION

Figure 4 shows a schematic of the system (patent pending) that uses a chemical mass balance around the waterside of the boiler. Blowdown water chemistry is monitored continuously, and this measured value is compared with an expected value based on the combined information from a microprocessor-based chemical-feed system and measurement of blowdown flow. A water loss is indicated when the two values diverge.

The method uses the following approach:

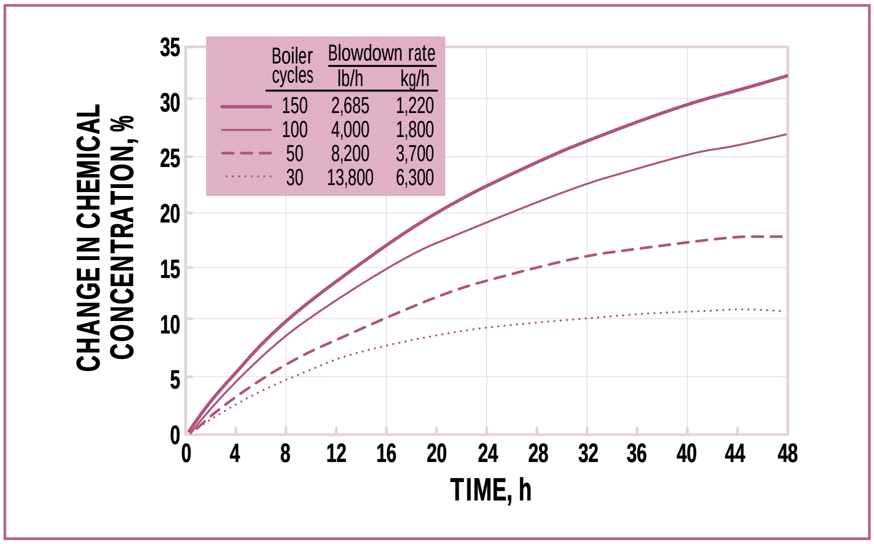
1. *Measure the blowdown flow.* Blowdown flow rate is measured continuously with a flowmeter, and the signal is input into the data-acquisition system. The flowmeter can be calibrated using a chemical tracer in a shot-

feed or a steady-state study. We have used both molybdate and phosphate tracers successfully.

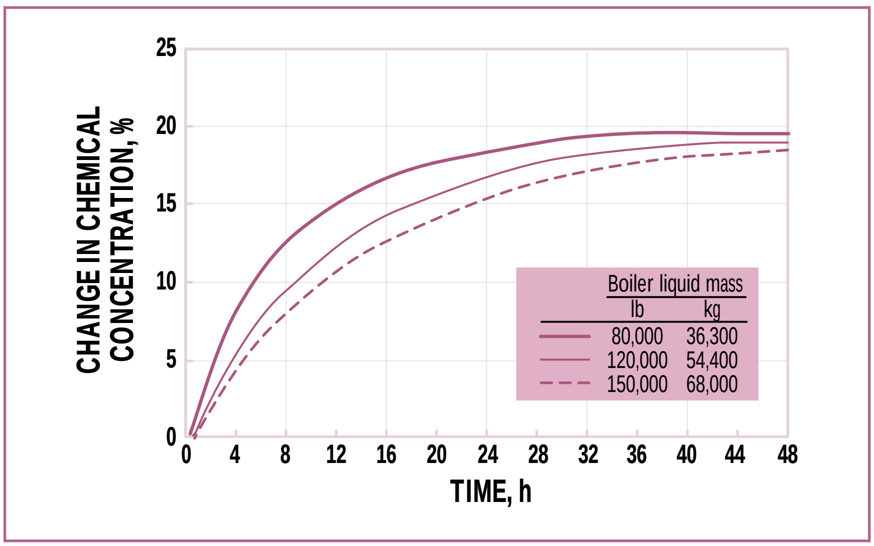
2. *Measure the amount of chemical delivered to the system with a calibrated chemical-feed system.* The chemical feed rate is continually measured using an automated drawdown assembly. This signal is also input into the data-acquisition system. The desired chemical feed rate, determined by the blowdown flow rate, is maintained by modulating the chemical pump speed to achieve the appropriate feed rate as measured by the automated drawdown assembly. The chemical-feed system is illustrated in Fig. 5.
3. *Calculate the expected chemical concentration in the blowdown.* The expected chemical concentration is determined using the blowdown flow rate, chemical feed rate, and the mass of liquid water in the boiler. One feature of this CBLI system is that the expected concentration can be calculated during steady state or during the following transient conditions:

- *Chemical feed rate changes and startup conditions.* The mass of liquid in the boiler constitutes a chemical accumulator that must be accounted for during changing chemical concentrations. These changes include boiler startups and changes in feed rate. Because the boiler volume is occupied by both liquid and vapor, the mass of the liquid portion must be determined empirically. This value is determined using a chemical-tracer shot-feed study.
- *Blowdown flow-rate changes.* Feeding chemical in proportion to blowdown results in maintenance of a steady boiler concentration during blowdown flow-rate transients.
- *Boiler-load transients.* With this scheme, variations in chemical concentration during changes in steam load are minimized by feeding chemical in proportion to blowdown. A secondary, but still significant, effect is observed as the operating mass of liquid water in the boiler varies with load *(7)*. This affects boiler-water chemical concentration. Although recovery boilers are typically base-loaded, load swings do occur.

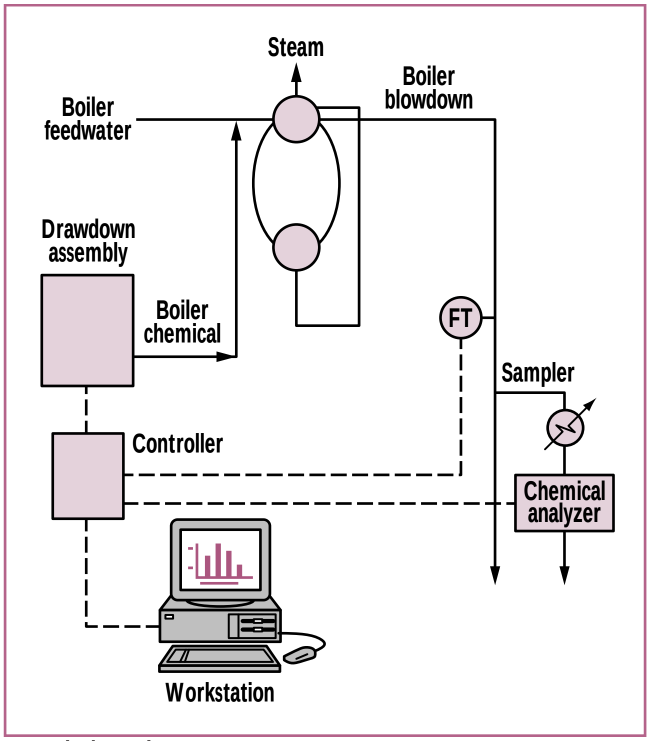
4. *Measure the blowdown chemical concentration.* An analyzer continually measures the chemical concentration in the boiler blowdown. The signal from the analyzer is sent to the controller. For this study, phosphate was used as the tracer chemical.



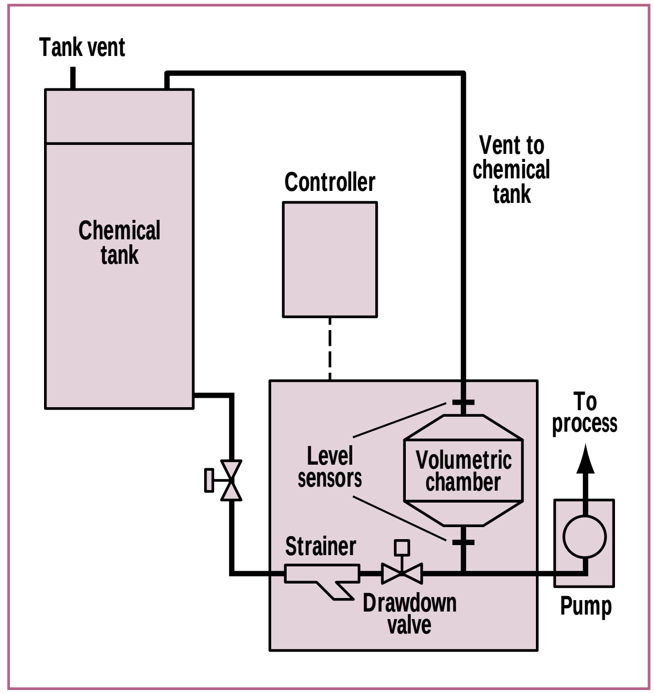
2. Change in boiler chemical concentration at various blowdown rates for a boiler with a 2000-lb/h leak. Boiler operating conditions are given in Table I.



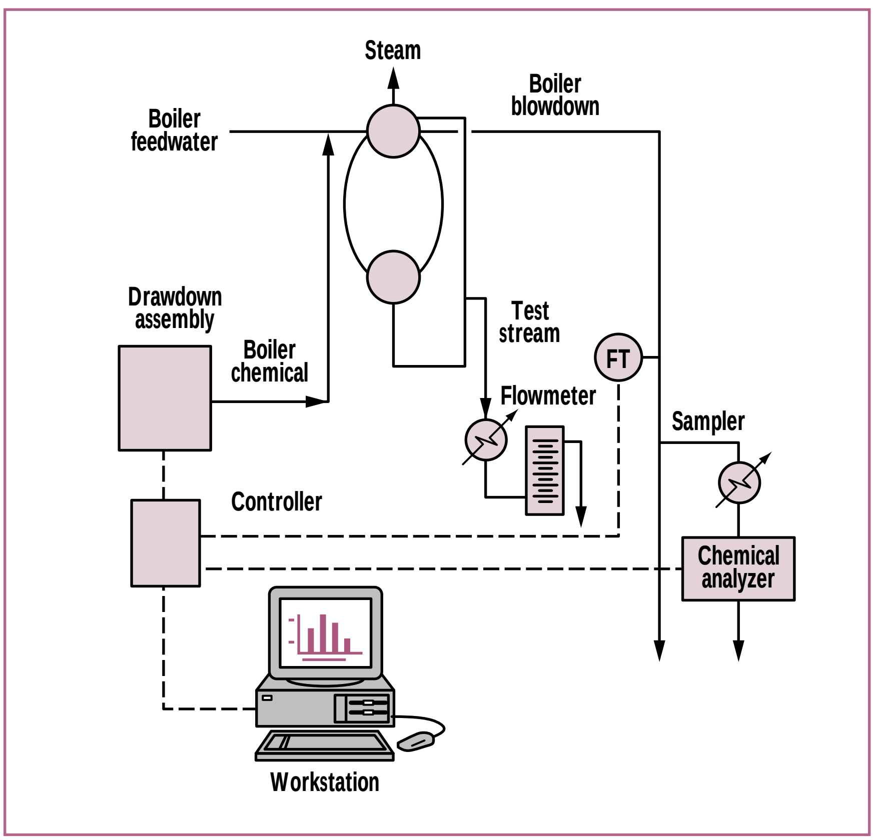
3. Change in boiler chemical concentration at various boiler sizes for a boiler with a 2000-lb/h leak. Boiler operating conditions are given in Table I.



4. Leak-detection system



5. Chemical-feed system



6. Leak-detection system at southeastern pulp mill

5. *Compare the actual concentration with the predicted concentration*. The measured blowdown chemical concentration is compared with the expected concentration. The percent difference is calculated and recorded once per minute. This percent difference will be referred to as the chemical leak indicator. An increase in the value of the chemical leak indicator is an indication of an unexplained loss of chemical.

SYSTEM EVALUATION

Basic questions

A proper evaluation of any leak-detection scheme must answer two basic questions that are statistical in nature.

1. What is the smallest leak signal that can be detected above the background noise generated during normal boiler operations?

This could be termed the "detection limit" for a method. Normally, detection limits are defined as three times the standard deviation of the background noise. Statistically, this corresponds to assurance that a false positive reading (i.e., a false report of a leak) will occur only once in 100 times. This detection limit must be tested over a range of boiler operating conditions. Transient conditions (load swings, changes in blowdown flow rate, changes in chemical feed rate) must all be accounted for.

2. How stable are the signals from the components of a leak-indication scheme over a given period of time?

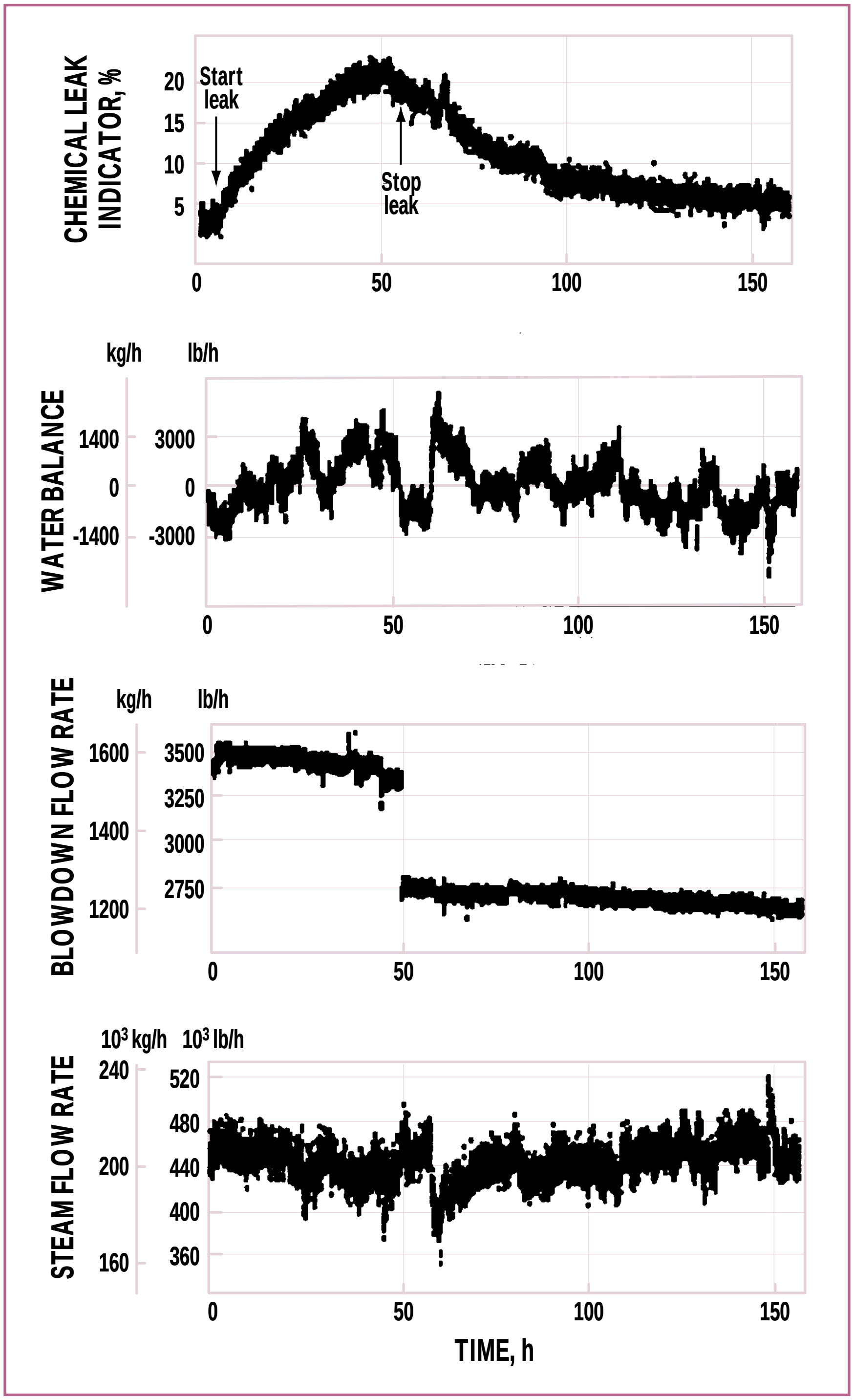
In the absence of a leak, the leak-indication signal must not drift over time. Changes in calibration contribute to long-term background noise, which diminishes the effectiveness of the leak indicator. Although corrective methods can be developed, such complications should be avoided whenever possible.

Field conditions

Tests for the subject CBLI system were conducted entirely in the field on a recovery boiler at a pulp mill in the southeastern United States. Although simulations and lab tests could have been conducted first, it was decided that the main problems in developing this system were practical in nature, relating to the interactions of the CBLI with an actual operating boiler. In retrospect, this appears to have been the correct way to proceed.

The boiler and leak-detection equipment configurations are shown in Fig. 6. The boiler-water chemical treatment is phosphate-based, so phosphate was used as the tracer for the leak-detection scheme. The treatment was metered to the boiler water using an automated chemical-feed system.

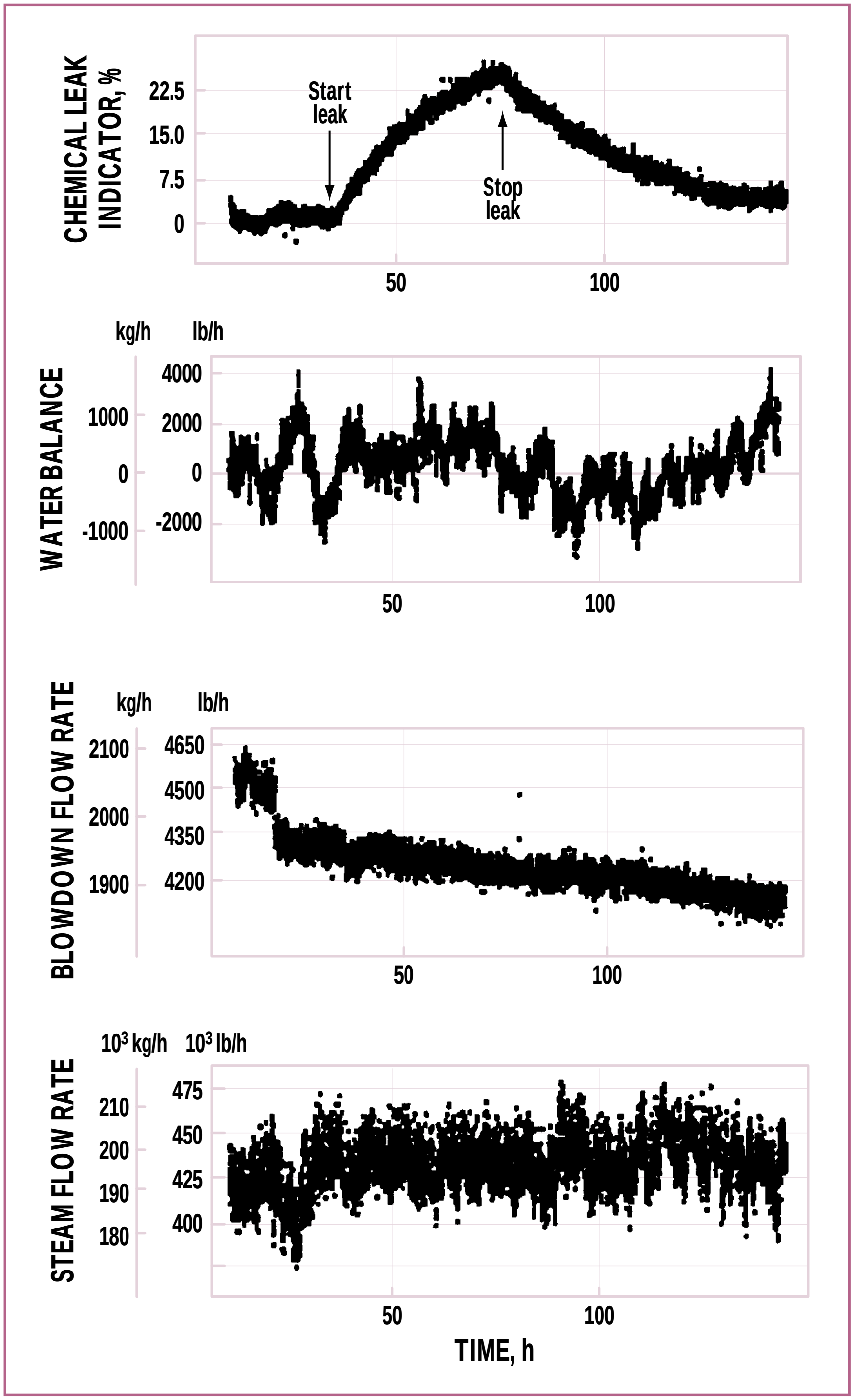
A phosphate analyzer was installed on a conditioned boiler blowdown sample stream. An orifice-plate flowmeter was installed in the blowdown line. The phosphate formulation was fed proportional to the blowdown flow to achieve a boiler phosphate concentration within a specified range *(8)*.



7. Sensor readings for leak test at 1000 lb/h (454 kg/h)

The liquid mass of the boiler was determined to be 150,000 lb (68,000 kg) using a shot-feed tracer study with molybdate. This value was incorporated into the algorithm.

To provide a convenient way to simulate leaks, an auxiliary blow-



8. Sensor readings for leak test at 2000 lb/h (907 kg/h)

down stream was installed on a drain line from a water-wall header. Based on the available cooling capacity, it was possible to simulate leaks of up to 2000 lb/h (907 kg/h).

The water mass balance was also monitored using the feedwater, blowdown, sootblower steam, and main steam flow rates. Because of the considerable background noise in the water mass balance, the output was filtered using a one-hour moving average.

SYSTEM RESPONSE TO LEAKS

Water-wall leaks

Leaks of 1000 lb/h (454 kg/h) and 2000 lb/h (907 kg/h) were simulated using the auxiliary blowdown test stream. These "leaks" corresponded to approximately 28% and 46% of blowdown flow. Figures 7 and 8 show the chemical leak indicator, water mass balance, blowdown rate, and steaming rate for simulated leaks of 1000 lb/h and 2000 lb/h, respectively.

For the 1000-lb/h leak, the leak-indicator signal increased from 3% to 20% in approximately 50 hours. The arbitrarily defined alarm level for a leak in this CBLI system is 10. The signal for the alarm level was reached 14 hours after initiating the leak. For the 2000-lb/h leak, the leak-indicator signal increased from 2% to 23% in approximately 37 hours. The signal for the alarm level was reached 12 hours after initiating the leak.

There are several points to note concerning these test leaks. First, while the leaks were easily detected by the CBLI, they were too small to be detected above the background noise using a simple water-balance approach. Figures 7 and 8 show that the water balance ranged from –3000 lb/h up to +3000 lb/h (±1400 kg/h) before, during, and after both tests.

Second, the leak-indicator signals are not simply proportional to absolute leak size. As already discussed, the strength of the signal is dependent on other factors such as blowdown flow rate.

Third, note that the blowdown flow was decreased by 20% in the middle of the 1000-lb/h leak with little effect on the leak-indicator signal for the next five days. If there were to be an effect, it would have shown up during that time period. This shows that boiler cycles can be changed without affecting the leak-detection scheme.

Economizer leaks

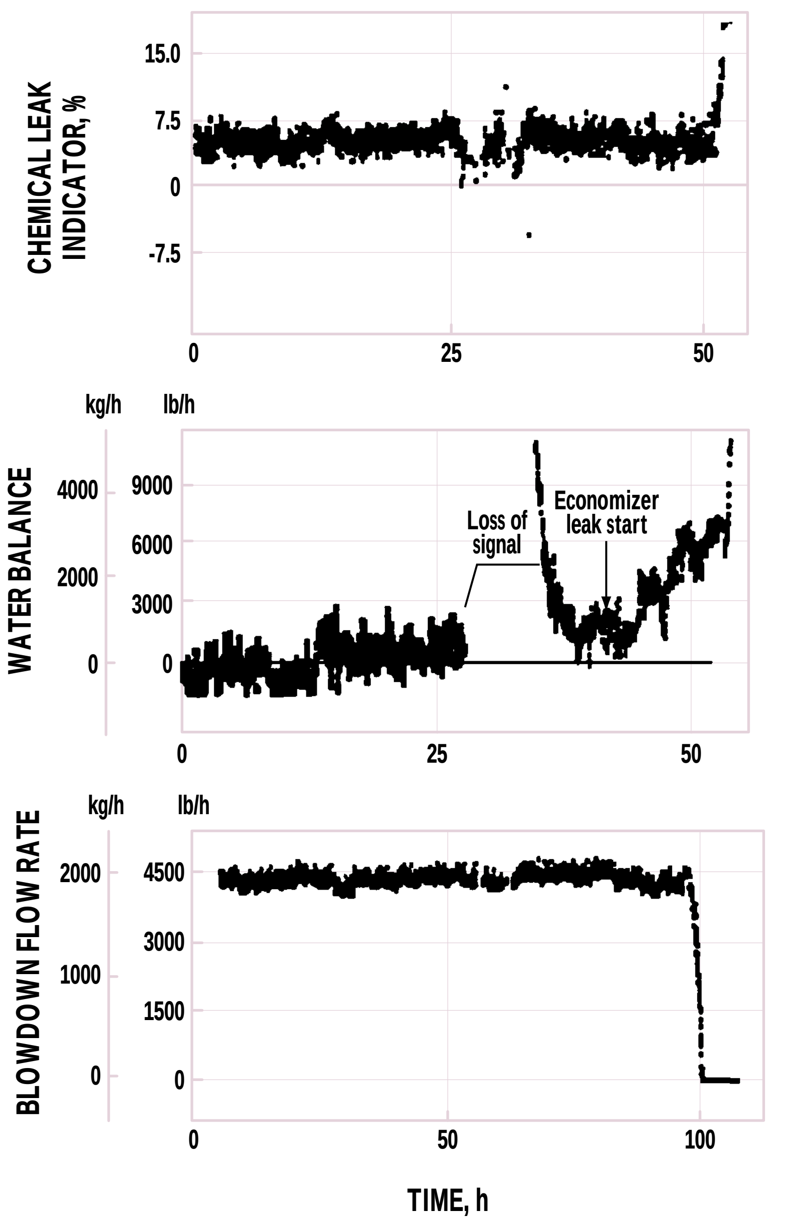
This particular boiler had been experiencing economizer leaks. On two occasions, leaks were indicated by the water mass balance, but operators were unable to see or hear the leak during a "walk down" of the boiler. The first leak grew to 20,000 lb/h (9100 kg/h) before shutdown of the boiler. The second leak, shown in Fig. 9, grew to 7000 lb/h (3200 kg/h). If either leak had been in the boiler waterwall or generating bank, the effect on the chemical leak indicator would have been dramatic. In both cases, the chemical leak indicator showed no significant change.

Both of these leaks were subsequently found in the economizer. The combined information of a water mass balance and the chemical leak indicator told the operators that there was a leak, but that the leak was not in a water-wall tube or in the generating bank. Therefore, the leak had to be in the economizer or the superheater. There was no ESP in either instance.

Note that in this particular boiler, the treatment chemicals are added upstream of the economizer. Therefore, some chemical is lost in an economizer leak. However, the effect of this lost chemical on the chemical leak indicator is insignificant because the concentration of chemical in the economizer is very low. In many boiler systems, the treatment chemicals are added to the steam drum, which eliminates the possibility of losing any chemical as a result of an economizer leak.

SYSTEM RESPONSE TO CHANGES IN OPERATING CONDITIONS

Any CBLI must be capable of working in the presence of other changes to the boiler system. The three changes of greatest interest are blowdown flow rate, chemical feed, and steam load. The effects of each were tested in the field.

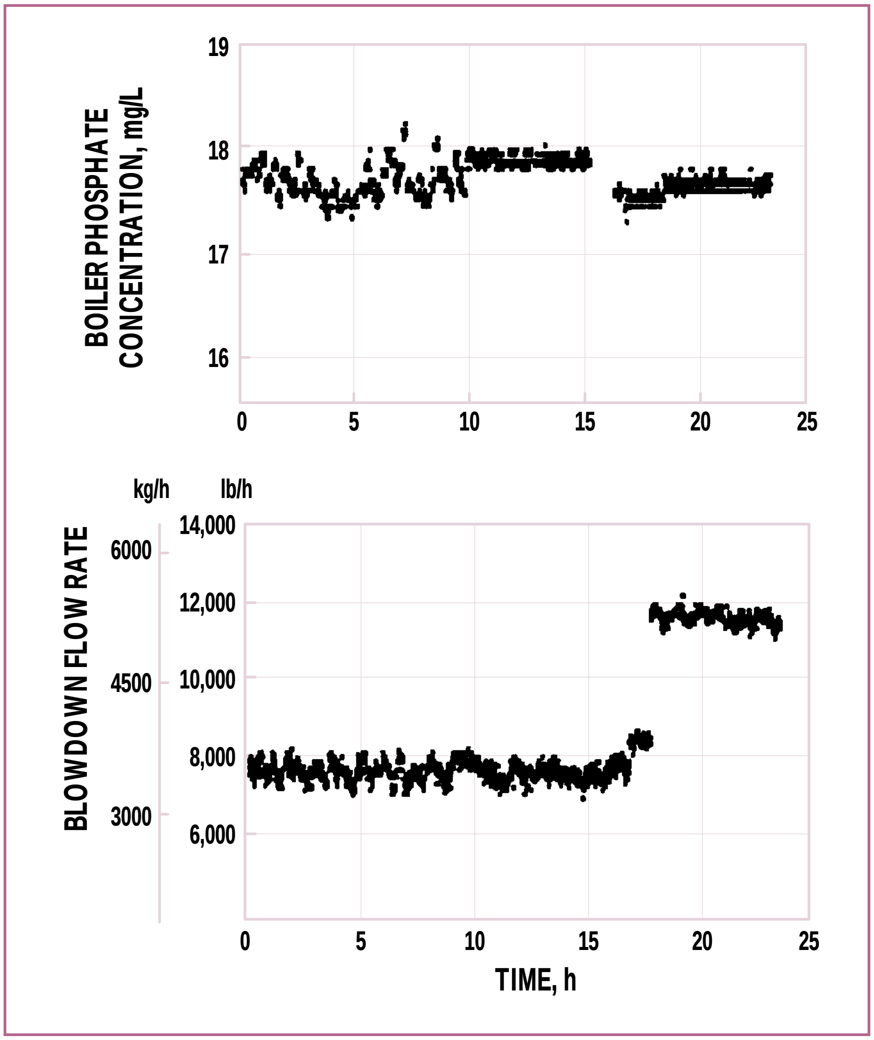


9. Effect of economizer leak on water balance and chemical leak indicator

Blowdown flow rate

Changes in blowdown flow rate were studied extensively in a previous field trial for a coordinated phosphate/pH chemistry controller (CPPC) for boilers *(8)*. Figure 10 shows the effect of a 55% increase in blowdown flow through a previously calibrated flowmeter [7500 lb/h (3400 kg/h) to 11,600 lb/h (5300 kg/h)]. The result was a change in phosphate concentration from 17.7 ± 0.2 mg/L to 17.6 ± 0.1 mg/L.

The effects of changes in blowdown flow rate were also tested during a leak test at the CBLI test site. During the 1000-lb/h (454 kg/h) leak, the blowdown flow rate was reduced 20%, from 3400 lb/h (1500 kg/h) to 2700 lb/h (1200 kg/h). As seen in Fig. 7, this had minimal effect on the development of the leak curve.



10. Effect of blowdown flow change on phosphate concentration

Chemical feed

Changes in chemical feed can introduce background noise into the indicator signal during chemical-feed transients if the boiler operating mass is not correctly estimated. A test validating the calculated boiler mass was performed just after a system startup. The initial phosphate concentration in the boiler water was 17 mg/L. The chemical feed was then set to achieve 24 mg/L. As expected, the phosphate concentration increased gradually, as seen in Fig. 11. The chemical leak indicator remained level, verifying the accuracy of the algorithm and the value representing boiler liquid mass. Also, note the 42% increase in blowdown flow at the end of the week. Little or no effect on the chemical leak indicator can be seen.

Steam load

Steam-load changes have been studied extensively. Most of the steam-load effects are minimized by the coupling of chemical feed and blowdown flow. There are some secondary effects of boiler steam load on the leak indicator because of changes in boiler liquid mass *(7)*. These effects also can be seen in Fig. 11 at ≈40 hours. The effect is to increase the background noise level around the load change. Work is currently underway to minimize this effect.

REPEATABILITY AND ACCURACY

In essence, any leak-detection scheme is an exercise in minimizing background noise and maximizing useful signal. Repeatability and accuracy—the normal methods for evaluating the success of such an exercise—can be applied for both the individual components and the overall system *(9)*. Accuracy refers to the closeness of a measured or controlled variable to the true value. Repeatability can be divided into short-term and long-term components. Short-term repeatability is the variability over a relatively short period of time (hours to days), while long-term repeatability refers to an instrument's tendency to drift over time (weeks to months) between calibrations.

In the system described in this paper, there are three key components: the feed system, the flowmeter, and the analyzer with its associated sample-conditioning system. Where required, repeatability and accuracy were assessed.

The feed equipment used in this CBLI system has been evaluated in the field many times *(8)*. No further evaluation was thought necessary.

The measured short-term (one hour to one day) flowmeter repeatability at average blowdown flow rates ranged from 1.5% to 3.0% (expressed as one standard deviation). Similar variability was noted at the CPPC trial site *(8)*. Long-term drift is currently being assessed as part of the CPPC trial.

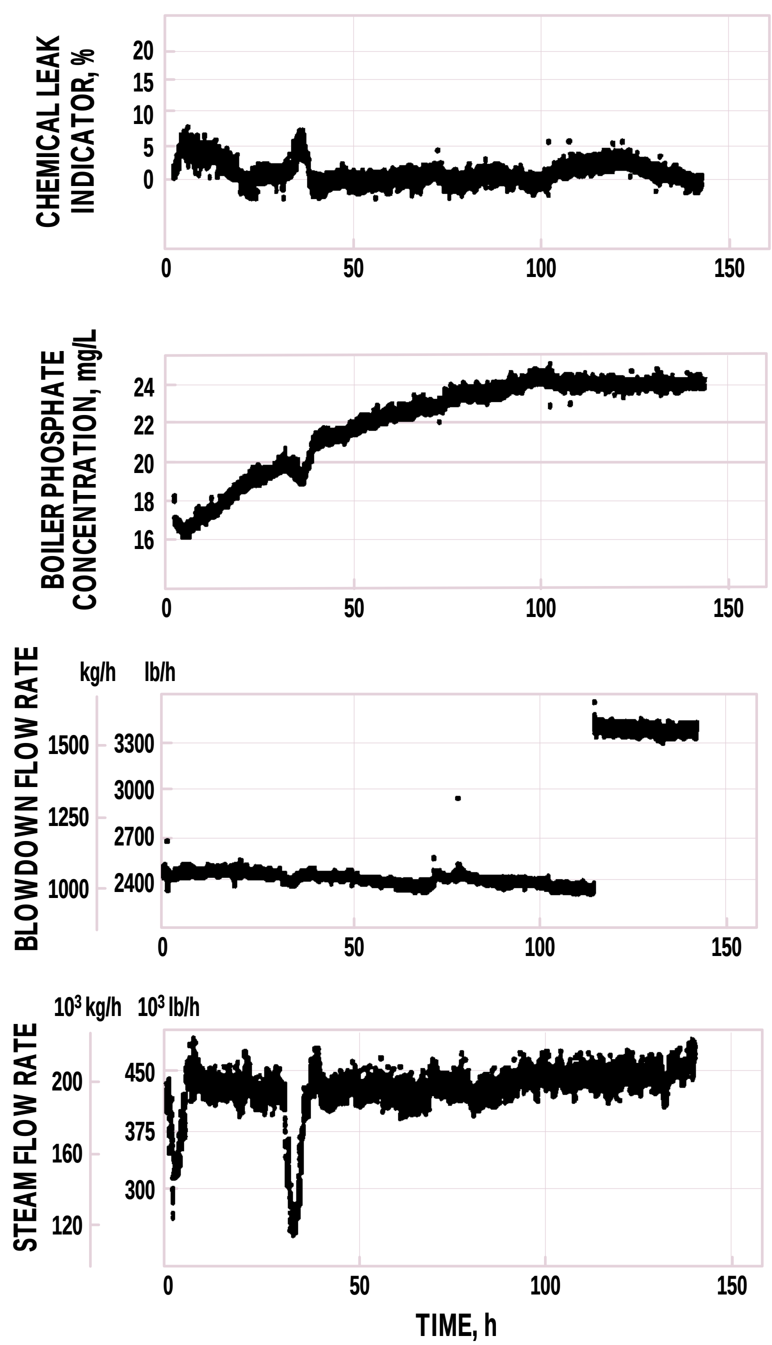
Flowmeter accuracy was assessed indirectly during the blowdown flow-change studies shown in Figs. 7 and 11. Although these tests do not provide an absolute accuracy number, the fact that the chemical leak indicator changed very little in response to a fairly large change in blowdown flow indicates that the flowmeter accuracy is acceptable for this leak-detection scheme.

KEYWORDS
Detection, evaluation, feed water, furnaces, leakage, materials balance, recovery furnaces, water.

Short-term variability of the phosphate analyzer during steady-state conditions has been excellent, averaging 1–2% (expressed as one standard deviation) over one-day periods. Long-term variability was assessed using the change in the blowdown phosphate signal from just before to just after weekly calibrations. The results of this study over a four-month period are shown in Fig. 12. After some initial instability, the weekly change has generally been less than 2.5%.

Accuracy of the phosphate analyzer was not specifically assessed. Any significant accuracy problems would be seen as an offset from zero in the chemical leak indicator signal. During this study, there were small positive offsets (0–7%) in the chemical leak indicator. Given that the methodology for wet chemical phosphate analysis is well established, analyzer accuracy is not believed to contribute significantly to these offsets.

The repeatability and accuracy of the overall CBLI system are currently under investigation.



11. Effect of phosphate concentration changes on leak indicator

RELIABILITY AND MAINTENANCE

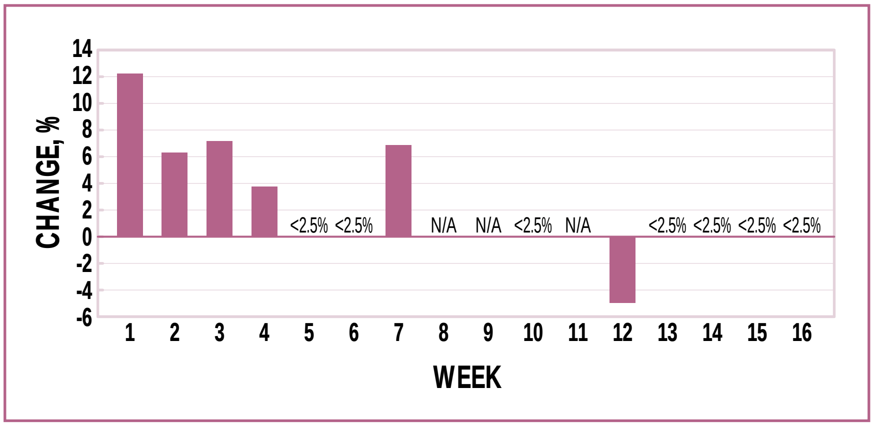
A leak-detection system is useless if one of its components is not working. Thus some assessment of reliability (percent availability) also needs to be considered. Associated with this reliability is the maintenance time required to keep a leak-detection system operating. Where possible, reliability assessments have been performed for most of the equipment.

The availability for the feed equipment has been above 99% for the past year. Maintenance on the calibrated feed equipment consists of normal pump maintenance and cleaning of the drawdown assembly sensors every six months.

The flowmeter has operated 100% of the time.

Initially, the reliability of the phosphate analyzer and its sample-conditioning panel was unsatisfactory. The nature of the downtime was analyzed to pinpoint the problem. It was found that most of the downtime was associated with startup of the sample-conditioning system after boiler startups.

Two steps were taken that seem to have eliminated most of the prob-



12. Weekly change in phosphate analyzer calibration

lems. First, an operator is assigned the task of starting up the analyzer system after a boiler startup. Second, a daily walk-by is scheduled for the operators. Thus, any problems can be quickly addressed. Monthly maintenance is performed on the phosphate analyzer, which consists of cleaning the spectrophotometric cell, changing reagent bottles, and checking the sample conditioning system.

The reliability of the overall system could not be assessed because of the trial nature of the work completed to date. Now that system design has stabilized, the next task is to assess its long-term reliability. TJ

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The authors thank the mill personnel at Weyerhaeuser (New Bern, NC) and Weyerhaeuser Co. for their cooperation and assistance in this project.

Received for review June 28, 1995.

Accepted Oct. 3, 1995.

Presented at the TAPPI 1995 Engineering Conference.

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