Kraft liquor alkali analysis using an *in-situ* conductivity sensor

Michael A. Paulonis* and A. Krishnagopalan

Graduate student and assistant professor, Dept. of Chemical Engineering, Auburn University, Ala. 36849

ABSTRACT *A study of the conductivity of kraft white liquor, weak white liquor, cooking liquor, and green liquor has been carried out using a conductivity sensor that uses no electrodes. Correlations relating the conductivity to the concentrations of liquor components have been developed for each type of liquor. Functions to compensate for the sensitivity of conductivity to the liquor temperature have been developed over a wide range of temperatures. The effects of sodium sulfide, sodium carbonate, and reaction products on the liquor conductivity are also discussed.*

KEYWORDS
Conductivity
Cooking liquors
Effective alkali
Green liquor
Sensors
Weak liquor
White liquor

The measurement of liquor alkali concentration is important in the kraft process. The alkali concentration in white liquor must be monitored and controlled to avoid introducing disturbances into the digester operation. The residual alkali concentration in cooking liquor can be used as feedback for the process control system. Monitoring the alkali concentration in the weak wash liquor will facilitate good mud washing efficiency and improve the uniformity of the weak liquor supply to the dissolving tank. Monitoring and controlling the green liquor concentration makes it possible to optimize the causticizing efficiency.

In all these instances, a reliable and accurate method of determining liquor alkali concentration is required. Laboratory analysis of liquor samples is acceptable for occasional quality control, but only an automated analyzer with a minimal time lag can provide data quickly enough for direct process control.

Various methods have been developed to automate alkali analysis on kraft liquors. Many of these techniques use electrical conductivity measurements to detect effective alkali. This approach works because the specific conductivity of the hydroxide ion is about four times as large as the specific conductivity of any other anion in kraft liquors (*1, 2*). The large specific conductivity of hydroxide ion is due to a proton transfer mechanism between the hydroxide ion and water in an aqueous solution (*3*).

The most direct way to analyze alkali using conductivity is to measure the conductivity in the actual liquor solution. The conductivity of kraft liquor is proportional to a combination of the sodium hydroxide and sodium sulfide concentrations (*4, 5*). Measuring the liquor conductivity is simple and can be carried out continuously with a number of commercially available sensors.

The conductivity measurement is sensitive to liquor temperature, so a compensation must be included in the alkali correlation for an *in-situ* installation. The temperature effect on conductivity arises mainly through changes in the solution viscosity. Decreased viscosity increases ionic mobility and hence conductivity. Experiments with single ions in pure water indicate that the relationship between solution conductivity and solvent viscosity is useful only to provide an approximation to the measured conductivity variations with temperature (*3*). Thus, accurate data for temperature dependence must be measured for a particular electrolyte solution at the specific conditions of interest.

A disadvantage to the direct conductivity analysis method for kraft pulping liquors is that sodium carbonate, sodium sulfate, and reaction products in the liquor may contribute to the total conductivity and thus bias the alkali measurement. Additional difficulties arise because ions with low mobility, such as carbonate and hydrosulfide, change the mobility of the hydroxide ions (*6*). The mobility of all ionic species in kraft liquors is reduced through the asymmetry and electrophoretic effects caused by the high concentrations of ions (*3*).

Changes in the degree of dissociation and ion pairing effects at high ionic concentrations reduce the

*Paulonis is currently an advanced chemical engineer, Tennessee Eastman Co., Process and Control Systems Engineering, P. O. Box 511, Kingsport, Tenn. 37662.

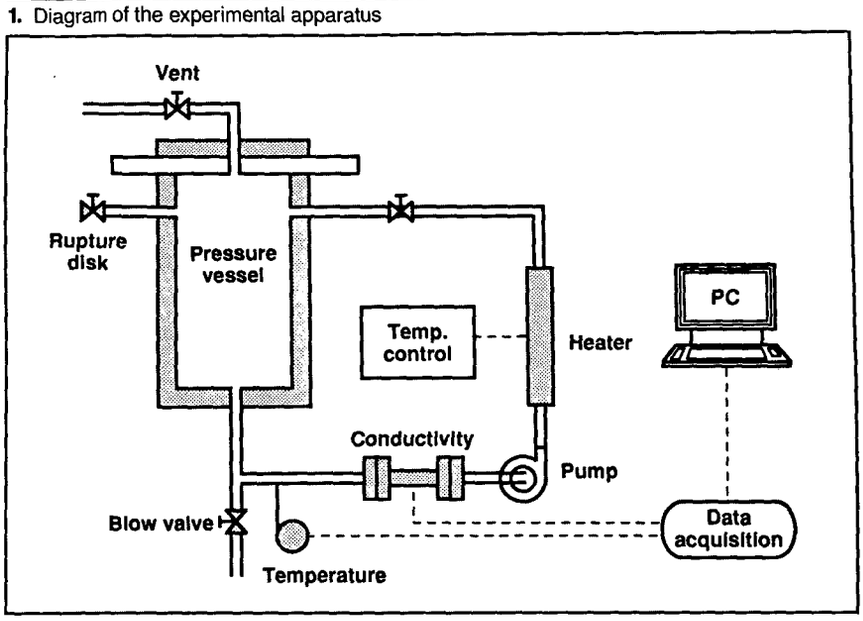
number of ions in solution and lower the electrolyte conductivity (*3*). The most sophisticated chemical theories cannot accurately predict the conductivity of electrolytes of even single-component solutions in the highly nonideal environment of a concentrated solution. If the electrolytic solution is a mixture, this only complicates the matter and further degrades the accuracy of prediction. To determine alkali directly from measurements of conductivity, empirical correlations must be developed based on actual conductivity measurements made in the composition and temperature ranges of interest.

To contend with this problem of interference in the alkali analysis, more sophisticated analysis methods have been developed using conductivity detection. One such method involves measuring the difference in the conductivity of liquor before and after neutralization with carbon dioxide gas (*2*). Another system uses a conductometric titration with sulfuric acid (*7*). The effective alkali concentration is calculated by determining the neutralization point with a conductivity detector. Methods involving detectors other than conductivity have also been developed. One of the first automated methods involves the use of the Technicon AutoAnalyzer (*8*). In this method, dilute cooking liquor is dialyzed to remove solids and large organic molecules. The dialyzate is mixed with an indicator solution, and the effective alkali is determined colorimetrically. Another type of analyzer detects the heat generated when the alkali is neutralized with sodium bicarbonate (*9*).

These methods offer the advantage of being specific toward alkali with proven accuracy, but they have important disadvantages, such as (a) delays before results are available, (b) the need to replenish reagents, and (c) complex designs that can mean the equipment will require frequent maintenance. Furthermore, these alkali analyzers operate only with extracted liquor samples, and the sampling techniques are often less reliable than the analyzers.

Consequently, an *in-situ* method would be preferable for continuous industrial service if the necessary empirical correlations could be developed. Here, we will look at the comprehensive calibration and testing of a conductivity analyzer for the continuous alkali analysis of kraft process liquors.

1. Diagram of the experimental apparatus



Experimental methods and equipment

In this study, we used a Uniloc Model 222 Toroidal Conductivity Sensor with a Model 1054T Toroidal Conductivity Analyzer/Transmitter, a Rosemount Series 78S platinum RTD with a Model 444 Temperature Transmitter, and a 316-L stainless steel pressure vessel with forced recirculation and an external electric heater. A Keithley System 570 data acquisition system and a Zenith 248 microcomputer were used for collecting data. A diagram of the apparatus is shown in **Fig. 1**.

Synthetic liquors were prepared from reagent-grade sodium hydroxide, sodium sulfide, and sodium carbonate. These liquors were used immediately after preparation. The exact liquor composition was determined by titrating a sample taken from the pressure vessel before beginning the experiment. Kraft cooking liquor was generated by performing several kraft cooks inside the pressure vessel using an initial charge of synthetic white liquor. The cooking liquor was analyzed continuously *in situ* for conductivity and was periodically sampled for immediate titration analysis.

Liquor titration procedure

The "ABC" titration method was used for white and green liquors (*10*). A modified "AB" titration procedure was chosen for analyzing the cooking liquor. Standard procedures for the chemical analysis of kraft cooking (black) liquors do not include a method for effective alkali analysis (*11*). The usual test for active alkali results in an overestimation, primarily because of incomplete settling of the precipitate (*12*). Thus, it is necessary to centrifuge the sample to fully separate the precipitate.

We measured the cooking liquor alkali using the following procedure. Barium chloride was added in excess to the sample, and the precipitate was centrifuged. The supernatant liquid was titrated to pH 9.3 to measure effective alkali. [A method of this type has been used successfully by Chiang for effective alkali analysis of black liquor (*13*).]

Formaldehyde solution, adjusted to pH 8.3, was added to the supernatant, and the titration was continued to pH 8.3 to measure active alkali. The formaldehyde complexes the hydrosulfide ion and releases equivalent hydroxide ion (*10*). Experimental trials indicated that the results using this procedure were equivalent to those obtained by direct titration of the supernatant to pH 4.0. However, if the precipitation is incomplete or centrifuging is inadequate to fully separate the sodium carbonate and

reaction products, the titration to pH 4.0 will exhibit greater error from the increased neutralization of acid by these compounds. Thus, we adopted the procedure of adding formaldehyde and titrating to pH 8.3.

Sensor calibration

The first step in the conductivity analyzer testing was sensor calibration. The sensor was calibrated to reagent-grade sodium hydroxide solutions at 25°C. The concentration of each solution was determined by titration with HCl. The cell constant of the analyzer was adjusted for each solution until the reading matched the reference value obtained from correlations provided by Uniloc. Three standard solutions were used in the calibration.

The average cell constant was permanently installed in the analyzer memory. The coefficient of variation for the experimentally determined cell constant was 0.14%.

White liquor analysis

Experiments were conducted to determine a comprehensive alkali correlation for both concentrated and weak white liquor. In the experiments, the liquor was heated from room temperature to 180°C at approximately 2.5°C/min. Temperature and conductivity values were recorded every 5 min throughout the run. The recorded values were averages of 50 readings (5 s) of data from the acquisition system.

Alkali correlations

Base correlations were generated by regressing an equation between the liquor conductivity at 170°C and the concentration of each liquor component as determined by titration. The conductivity at 170°C was interpolated from a curve fit of the conductivity data collected at temperatures near 170°C. The form of the regression equation was chosen to minimize the standard error of the estimate while maintaining randomly distributed residuals with respect to each variable.

Two different base correlations were generated for white liquor. One was for the entire range of white liquor concentrations from 20 g/L to 140 g/L effective alkali as Na_2O. The other correlation was for weak white liquor as would exist in mud washing and smelt dissolving operations. This weak white liquor is also an approximation to the cooking liquor that would exist within the kraft batch digester at the start of a cook. This weak white liquor correlation was generated over the concentration range of 10–50 g/L effective alkali as Na_2O.

Concentrated white liquor

The wide-range correlation is represented by the equation:

$$EA = 3.5495 \times 10^{-5}\, C^2 + 0.70469 C^{0.5} \quad (1)$$

where

EA = effective alkali, g/L as Na_2

C = conductivity measured at 170°C, mS/cm.

The standard deviation of the prediction error for Eq. 1 is 1.2 g/L. The relationship between concentrated white liquor effective alkali and conductivity is shown in **Fig. 2**.

The data regression was also carried out assuming that sodium hydroxide alone was the dependent variable. This regression allowed us to analyze the sodium sulfide concentration as an independent variable to check if it contributed to conductivity in accordance with the effective alkali definition. The regression coefficient for sodium sulfide, in terms of mean and standard deviation, was 0.523 ± 0.025 with respect to sodium hydroxide. The hypothesis that one-half of the sodium sulfide is being measured by conductivity cannot be rejected at the 90% confidence level. Thus, Eq. 1 shows effective alkali (NaOH + 0.5 Na_2S) as the dependent variable. Similarly, the regression was first made without forcing the equation through the origin. The constant was not significant, so Eq. 1 does not include a constant.

The regression analysis indicates that a term involving the sodium carbonate concentration is not justified at a significance level of 0.10. Thus, at high alkali concentrations such as present in white liquor charging lines, the effect of sodium carbonate has been found to be negligible.

Weak white liquor

At lower alkali concentrations, as exists in weak wash liquor or cooking liquor, we determined a different base correlation. This was done for two primary reasons. First, the white liquor regression analysis indicated that the effect of sodium sulfide and sodium carbonate on conductivity may be different at lower alkali concentrations. Second, a correlation over a narrow concentration range should give less error for these weak liquors. The regression of the white liquor data below 50 g/L effective alkali yielded the following equation:

$$\mathrm{NaOH} + 0.773\,\mathrm{Na_2S} + 0.144\,\mathrm{Na_2CO_3} + 1.828\,\mathrm{Na_2CO_3/NaOH} = 1.5271 \times 10^{-5}\, C^2 + 0.04614 C \quad (2)$$

where

NaOH = sodium hydroxide, g/L as Na_2O

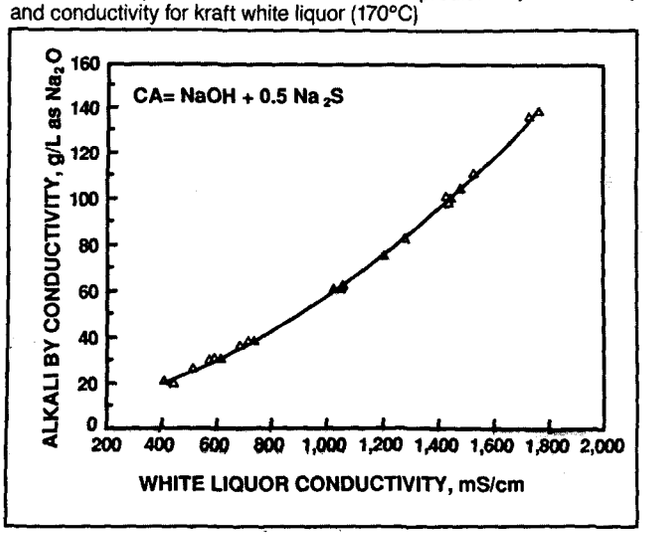
Na_2S = sodium sulfide, g/L as Na_2O

Na_2CO_3 = sodium carbonate, g/L as Na_2O.

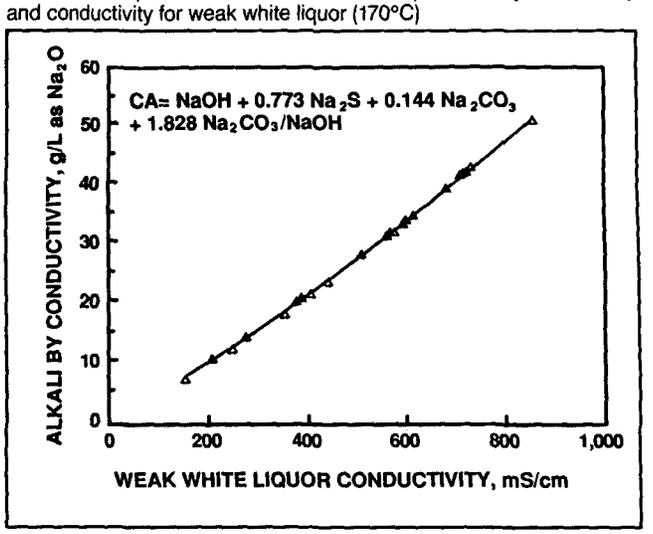
In this case, the conductivity is measuring slightly more than 3/4 of the sodium sulfide with respect to sodium hydroxide. The conductivity is not measuring effective alkali directly. This result supports the results of Lundkvist, where the conductivity was found to measure NaOH + 0.75 Na_2S for kraft cooking liquor (*5*). Furthermore, Lundkvist found that the sodium carbonate contribution to conductivity was linear at approximately 0.25 times its concentration with respect to sodium hydroxide. At an average NaOH concentration of 25 g/L, the sodium carbonate contribution in Eq. 2 is 0.22 times its concentration with respect to sodium hydroxide.

The standard deviation of the prediction in Eq. 2 is 0.26 g/L. This accuracy is much better than that of the wide-range correlation. This improvement is expected because of the narrow range of concentrations represented by an individual equation. This correlation is depicted in **Fig. 3** as the relationship between the left side of Eq. 2 (referred to as "conductivity alkali") versus conductivity. The effect of sodium carbonate on the alkali prediction is shown in **Fig. 4**. In a mill where the sodium carbonate concentration of a liquor is assumed to be constant between laboratory analyses, Eq. 2 indicates that an actual variation of ±1 g/L would

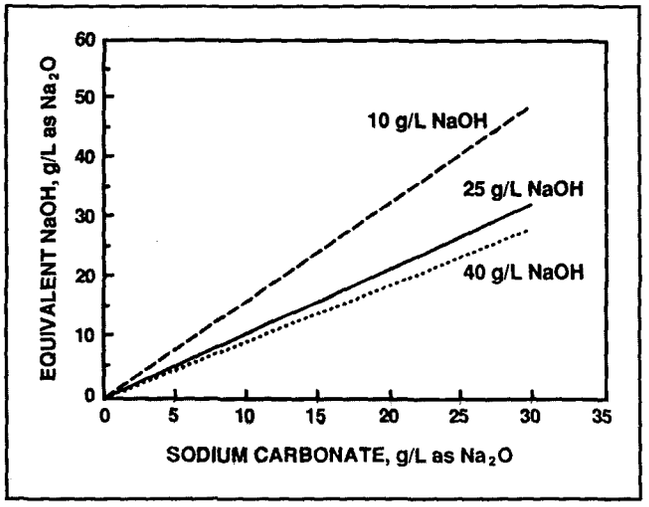
2. Relationship between alkali concentration predicted by conductivity and conductivity for kraft white liquor (170°C)



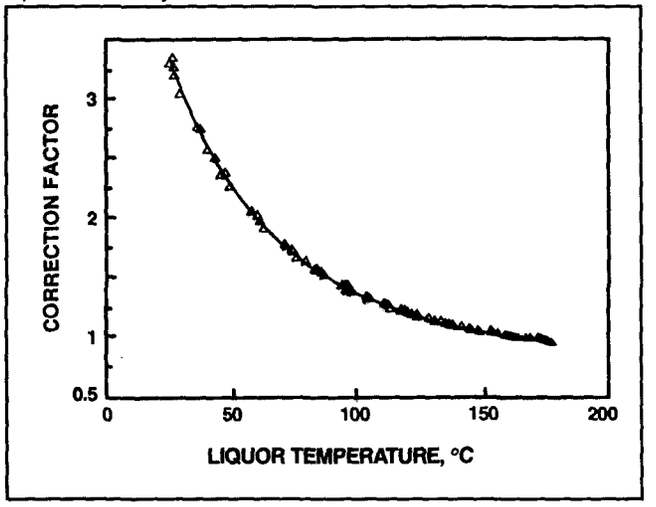
3. Relationship between alkali concentration predicted by conductivity and conductivity for weak white liquor (170°C)



4. Effect of sodium carbonate on the prediction of kraft weak white liquor alkali



5. Temperature compensation for kraft weak white liquor and cooking liquor conductivity



result in an alkali prediction error of only 0.18–0.33 g/L, depending on the alkali concentration.

Temperature compensation

The temperature compensation functions for both white liquor base correlations were determined by regressing the temperature-conductivity data from the experimental runs. The reference temperature was taken as 170°C, corresponding to the base calibrations. We found that the temperature compensation was a function of effective alkali for white liquors having effective alkali concentration greater than 50 g/L. Thus, two separate regressions have been carried out. Furthermore, the regression for weak liquor has been split into two equations over the full temperature range, for increased accuracy.

For effective alkali concentrations below 50 g/L, the following set of equations was found to be suitable for temperature compensation:

For $25°C \leq T \leq 100°C$:

$$CF = 5.0498 - 9.1828 \times 10^{-2}\,T + 8.6444 \times 10^{-4}T^2 - 3.1438 \times 10^{-6}\,T^3 \quad (3)$$

For $100°C \leq T \leq 175°C$:

$$CF = 3.5786 - 3.6925 \times 10^{-2}\,T + 1.8085 \times 10^{-4}T^2 - 3.1096 \times 10^{-6}\,T^3 \quad (4)$$

with

$$C(170°C) = C(T) \times CF(T) \quad (5)$$

where

T = liquor temperature,°C

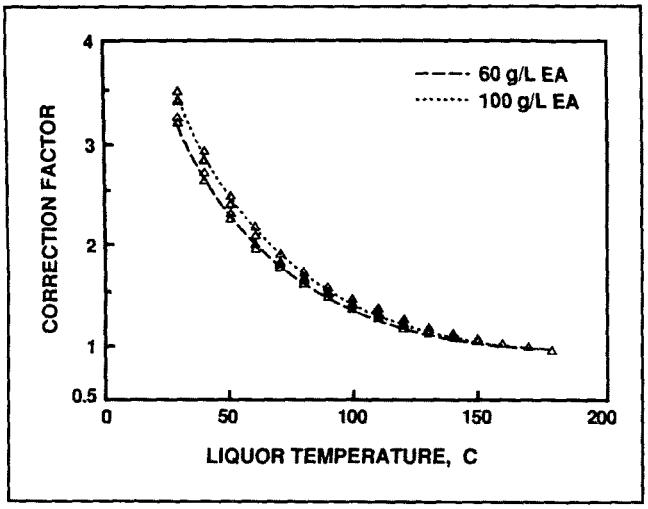
C = liquor conductivity, mS/cm

CF = temperature compensation factor.

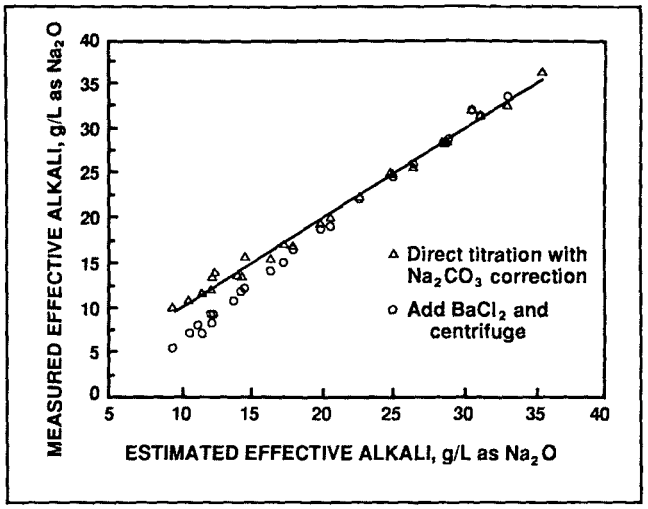
The standard deviation of the prediction is approximately 0.03 for Eq. 3 and 0.006 for Eq. 4. This translates into an average deviation of 7.64 mS/cm for Eq. 3 and 2.64 mS/cm for Eq. 4. The weak white liquor temperature compensation function is shown in **Fig. 5.**

At higher concentrations, the temperature compensation becomes a function of effective alkali concentration. This phenomenon is primarily

6. Temperature compensation for kraft white liquor conductivity



7. Comparison of measured effective alkali in kraft cooking liquor with estimates from the weak white liquor correlation



due to an increase in the solution viscosity at high concentration and low temperature. A higher viscosity gives rise to lower ionic mobility and hence lower conductivity at any given temperature. The correlation developed for temperature compensation in the concentration range of 50–130 g/L effective alkali is:

$$CF = 8.2670 + 8.2794 \times 10^{-3}\,T - 1.6881\,\ln(T) + 0.23865\,EA/T - 1.3671 \times 10^{-3} EA \qquad (6)$$

Above 130 g/L effective alkali, the temperature compensation factor becomes a strong function of concentration, and a general correlation was not developed. The standard deviation of the prediction in Eq. 6 is 0.03. The temperature compensation for concentrated white liquor is depicted graphically for effective alkali concentrations of 60 and 100 g/L in **Fig. 6.**

Cooking liquor analysis

The weak white liquor correlation developed can be considered a first approximation to a conductivity correlation for cooking liquor as it exists in the kraft batch digester. We examined the accuracy of this approximation by generating cooking liquor using Southern pine chips and measuring the conductivity *in situ*. The cooks were carried out over a range of 15–17% effective alkali on dry wood and 25–35% sulfidity. Liquor samples were taken periodically during the cooks and were titrated by three different methods.

The procedure of titrating to pH 9.3 and pH 8.3 was used as the best estimate of effective alkali and active alkali. For comparison purposes, two additional simplified titration methods were used to measure effective alkali. The liquor was titrated directed to pH 9.3 in one case, with a compensation made for the sodium carbonate in the liquor. The other method involved titration to pH 9.3 after addition of barium chloride. In both cases, formaldehyde was added, and the liquor was titrated to pH 8.3 to measure active alkali. These simplified titration methods are sometimes used for routine measurement of cooking liquor alkali in industry.

The relationship between the effective alkali estimated from the weak white liquor correlation (Eqs. 2–5) and the titrated effective alkali is shown in **Fig. 7.** The effective alkali measured by direct titration to pH 9.3 with sodium carbonate compensation shows good agreement with the weak white liquor estimate. The measurements made using the best procedure of titrating to pH 9.3 after adding $BaCl_2$ and removing the precipitate show a divergence from the weak white liquor estimate as reaction products enter the cooking liquor. The effective alkali titrations with barium chloride addition but no centrifuging are not included on the graph, but they fall between the two measurements shown. The results indicate that the method used for titration has a considerable effect on the measured effective alkali concentration. The weak white liquor correlation agrees well with the results from one titration method but not two others. Importantly, the estimate of the effective alkali using the weak white liquor correlation does not agree with the concentration of effective alkali in the cooking liquor as determined by the best titration procedure. This result indicates that reaction products in cooking liquor have a significant effect on the measured conductivity.

Further analysis of the data obtained by the best titration procedure reveals that an excellent alkali correlation can be obtained if a term is included to represent the contribution of reaction products to the conductivity. In this study, ultraviolet absorption data at 280 nm were available as an estimate of the lignin concentration of the cooking liquor (L_{280}). The lignin concentration in the liquor is a measure of the extent of delignification and is thus proportional to the concentration of reaction products in the liquor. With this term included, the correlation for cooking liquor conductivity becomes:

$$NaOH + 0.886\,Na_2S + 0.283\,Na_2CO_3 + 0.0694\,L_{280} = 4.048 \times 10^{-2}\,C + 2.9180 \times 10^{-5} C^2 \qquad (7)$$

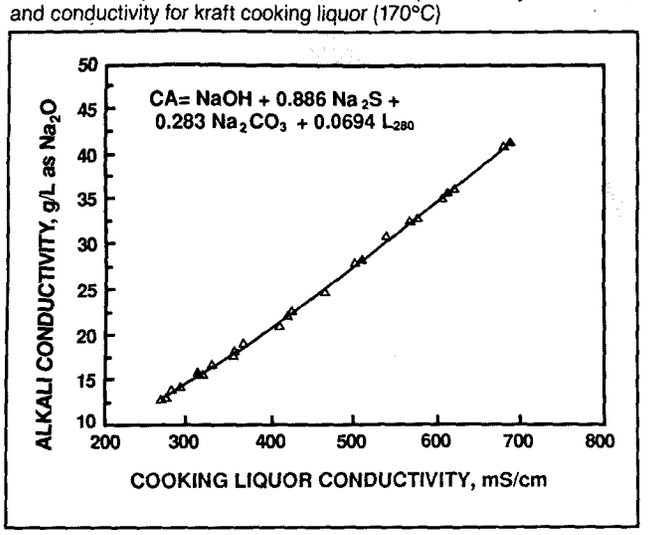
where

$NaOH$ = sodium hydroxide, g/L as Na_2O

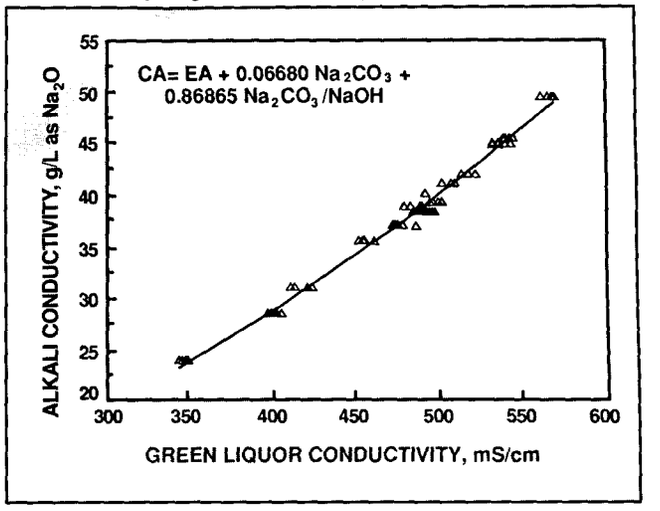
Na_2S = sodium sulfide, g/L as Na_2O

Na_2CO_3 = sodium carbonate, g/L as Na_2O

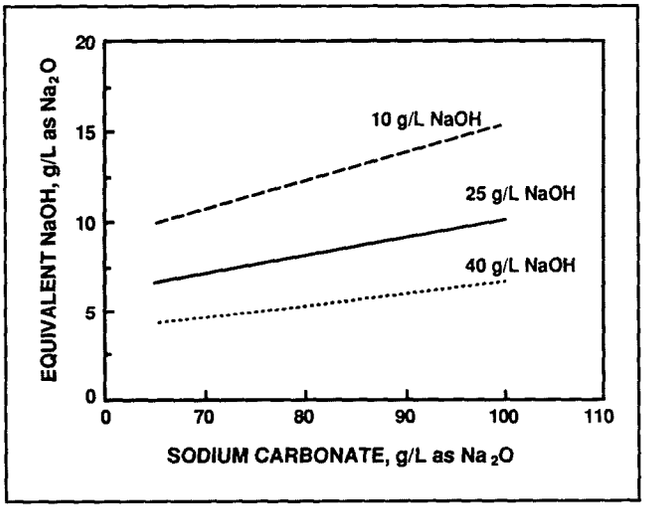
8. Relationship between alkali concentration predicted by conductivity and conductivity for kraft cooking liquor (170°C)



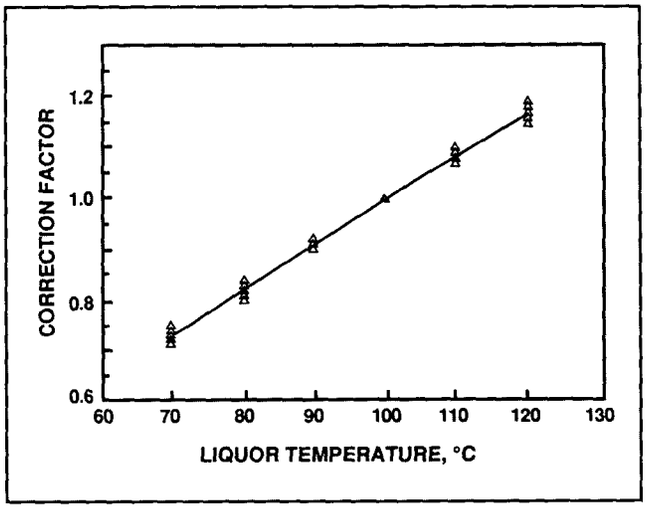
9. Relationship between alkali concentration predicted by conductivity and conductivity for green white liquor (100°C)



10. Effect of sodium carbonate on the prediction of kraft green liquor alkali



11. Temperature compensation for kraft green liquor conductivity



L_{280} = lignin concentration, g/L

C = conductivity measured at 170°C, mS/cm.

Equations 3-5 were used to normalize the cooking liquor conductivity to the standard temperature. The standard deviation of the prediction error for Eq. 7 is 0.29 g/L. This relationship is shown graphically in **Fig. 8**. Note that the coefficients for sodium sulfide and sodium carbonate have increased over those in Eq. 2. These increases arise primarily from the increased dissociation and reduced ion pairing of these components at very low alkali concentrations.

Ultraviolet absorption measurements are not routinely available for estimating lignin at the typical pulp mill. However, an estimation of delignification using a parameter such as the H factor could be substituted to compensate for the effect of reaction products on conductivity. An appropriate relationship between H factor and the concentration of cooking liquor lignin for this study is:

$$L_{280} = -53.91 + 13.02 \ln(\text{H factor} + 70) \quad (8)$$

If this relationship is substituted in Eq. 7, the prediction error is essentially unchanged. This type of correlation between H factor and lignin can be developed for conductivity compensation on a mill-specific basis.

Green liquor analysis

We conducted runs using synthetic green liquor solutions in a manner similar to the white liquor solutions. In this case, however, the temperature range studied was 70°C to 120°C. This temperature range more than covers the expected maximum green liquor temperature range in mill operations. The conductivity at 100°C was taken as the reference value. The effective alkali ranged from 10 g/L to 45 g/L as Na_2O, and the sodium carbonate concentration ranged from 65 g/L to 100 g/L as Na_2O.

Alkali correlation

The best fit of the green liquor con-

ductivity data was:

$$EA + 0.06680\ Na_2CO_3 + 0.86865\ Na_2CO_3/NaOH = 1.1188 \times 10^{-4}C^2 + 0.53442\ C^{0.5} \quad (9)$$

This correlation is similar to that for the white liquor; however, the presence of a large concentration of sodium carbonate in the green liquor creates a significant contribution to conductivity. At an average value of 25 g/L NaOH, the sodium carbonate contribution to conductivity is approximately 0.1 times its concentration with respect to sodium hydroxide. The standard deviation of the prediction for Eq. 9 is 0.71 g/L. This correlation for synthetic green liquor is shown in **Fig. 9**. The effect of sodium carbonate on the alkali prediction is shown in **Fig. 10**.

The green liquor regression analysis was first attempted with sodium hydroxide as the dependent variable, and the regression coefficient for sodium sulfide was 0.540 ± 0.015. Statistically, 0.5 is not within the confidence interval for the sodium sulfide contribution to the measured conductivity. However, the assumption that the sodium sulfide contribution to conductivity is exactly one-half its stoichiometric concentration contributes only 0.02 g/L error to the prediction in Eq. 9. Thus, Eq. 9 includes effective alkali (NaOH + 0.5 Na_2S) on the left-hand side for simplicity rather than NaOH + 0.540 Na_2S.

Temperature compensation

The temperature compensation function for green liquor is:

$$CF = 3.8994 \times 10^{-2} + 1.0523 \times 10^{-2}T - 9.2648 \times 10^{-6}T^2 \quad (10)$$

$$C(100°C) = C(T)/CF(T) \quad (11)$$

The standard deviation in conductivity introduced by this temperature compensation is 1.38 mS/cm. This error is lower than the temperature compensation error for white liquor, primarily as a result of the narrow temperature range for compensation in this case. Including a term to represent the concentration of sodium carbonate or other liquor components did not improve the temperature compensation in the regression analysis. Thus, Eq. 10 does not include a liquor concentration term. The green liquor temperature compensation is shown in **Fig. 11**.

Conclusions

Comprehensive testing of an *in-situ* conductivity analyzer has been carried out for kraft white liquor, weak white liquor, cooking liquor, and green liquor. Correlations have been developed for predicting the liquor alkali concentration from a conductivity measurement made within a wide liquor temperature range. The objective was to develop these useful correlations for process monitoring and control in kraft pulping liquor systems.

The effective alkali of concentrated white liquor can be predicted from conductivity directly, without any compensation for sulfidity or sodium carbonate. To predict effective alkali of weak white liquor requires compensation for both sulfidity and sodium carbonate. For cooking liquor, compensations for sulfidity, sodium carbonate, and lignin are required to measure effective alkali in agreement with the procedure using addition of $BaCl_2$ and removal of the precipitate followed by titration to a pH of 9.3. For green liquor, only a sodium carbonate compensation is required for estimating the effective alkali.

Compensation has to be made for the variable liquor temperature to accurately predict alkali. Weak white liquor, cooking liquor, and green liquor exhibit a consistent temperature compensation over the entire concentration range tested. White liquor requires a temperature compensation that is variable with effective alkali concentrations above 50 g/L.

These correlations have been used successfully for laboratory research in kraft pulping and causticizing control. Liquor dead load components other than sodium carbonate have not been included in the study. Large concentrations of potassium or sulfate ions can add to the conductivities of mill liquors (*14*). However, the concentration of these ions typically changes very little over time. Thus, a mill-specific correction term could be applied to the correlations presented here to accommodate a large concentration of a dead load component.□

Literature cited

1. Quesinberry, G. D., Tappi 51(10): 40A(1968).
2. Crowl, D. A., 1976 ISA Advances in Instrumentation Annual Conference, ISA, Research Triangle Park, N.C., Part 4, p. 875.
3. Levine, I. N., Physical Chemistry, 2nd edn., McGraw-Hill, New York, 1983.
4. Rekunen, S., Jutila, E., Lahteenmaki, E., Lonnberg, B., and Virkola, N. E., Paperi Puu 62(2): 80(1980).
5. Lundkvist, G., Svensk Papperstid. 75(13): 524(1972).
6. Dorris, G. M. and Allen, L. H., Conductivity sensors for slaker control. Part I. Laboratory results, 1988 Fall Conf., CPPA/TS, Montreal, 1988.
7. Lodzinski, F. P. and Karlsson, T., Tappi 59(9): 88(1976).
8. Kesler, R. B., Tappi 49(2): 71(1966).
9. Seymour, G. W., Tappi 60(7): 130(1977).
10. Pulp and Paper Manufacture, Vol. 1: The Pulping of Wood, 2nd edn. (MacDonald, R. G., Ed.,), McGraw-Hill, New York, 1969.
11. TAPPI Test Method T 625 cm-85, TAPPI PRESS, Atlanta.
12. Grace, T. M., Sachs, D. G., and Grady, H. J., Tappi 60(4): 122(1977).
13. Chiang, V. L., Cho, H. J., Puumala, R. J., Eckert, R. E., and Fuller, W. S., Tappi J. 70(2): 101(1987).
14. Dorris, G. M., Conductivity sensors for slaker control. Part II. Probe calibration and performance at a mill site, 1988 Fall Conf., CPPA/TS, Montreal, 1988.

The assistance of R. Kamarthi in collecting the green liquor data is appreciated. The authors also wish to acknowledge Rosemount, Inc. and the Pulp and Paper Research and Educational Center at Auburn University for support of this project.

Received for review Aug. 21, 1989.

Accepted Dec. 7, 1989.