

Nonprocess-element control in the liquor cycle using an ash leaching system

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ABSTRACT: To lengthen run time between washes and reduce thermal cycling of the recovery boiler, the Evadale, Texas, mill has been attempting to reduce the levels of nonprocess elements (NPEs) in the liquor cycle. The mill has periodically purged electrostatic precipitator ash in an effort to reduce and control potassium (K) and chloride (Cl) concentrations. Additional efforts to lower chloride concentrations involved changing the makeup chemical from diaphragm- to membrane-grade caustic and improving the operation of the chlorine dioxide generator spent acid salt filter. The change in makeup chemical NPE content successfully reduced the amount of boiler plugging due to sticky ash formation, but did not provide the desired amount of time between boiler washes.

In an effort to further reduce the amounts of potassium and chloride in the liquor cycle, an ash leaching system was installed. The leaching system partially dissolves precipitator ash in hot water. The potassium and chloride are selectively leached into the liquid phase and remain in solution. Sodium sulfate crystals are separated from the leaching slurry using a decanting centrifuge and returned to the liquor cycle via a mix tank. The potassium- and chloride-rich liquid is sewerred.

Since the implementation of these nonprocess-element reduction methods, the chloride content of the incoming electrostatic precipitator ash has been reduced by roughly 55% and the potassium content by approximately 50%. Approximately 80% of the soda entering the ash leaching process is recovered into the liquor cycle.

Application: Only mills with an effective potassium and chloride control strategy are able to maintain well-operating recovery boilers with high steam attenuation temperatures. An overview of the various methods for controlling K and Cl and the benefits of a Cl and K removal system could help pulp mills devise strategies for improving their recovery boiler operations.

The recovery boiler is the most expensive single unit operation in a kraft pulp mill. It is commonly the process limiting operation that dictates the overall production process economics. The requirements for high unit efficiency and availability are therefore critical to the bottom line of any mill. Unscheduled recovery boiler outages result in excessive costs and widespread effects across the entire mill operation. As the boiler fouls, it loses operating efficiency, and over time, significant plugging will occur, requiring operations personnel to take the boiler down for water washing. While the mill allows the plugged recovery boiler to cool down for water washing, it cannot burn black liquor. Therefore, the mill is forced to burn fossil fuels or extra bark to support the mill steam demand. In addition, significant maintenance costs are incurred for the unscheduled boiler wash. If a mill is tight on black liquor storage capacity, pulp production could also be negatively impacted by unscheduled boiler outages.

In an effort to extend the time between scheduled recovery boiler outages, reduce boiler thermal cycling and tube corrosion, and eliminate unscheduled shutdowns due to boiler plugging, many mills have been attempting to control the buildup of potassium and chloride in their liquor cycles. The major sources of potassium and chloride entering the mill are wood fed to the digester and makeup chemicals used in the liquor cycle to maintain the sodium and sulfur balance [1]. In

bleached pulp mills, significant amounts of chloride may enter the liquor cycle with makeup spent acid from the chlorine dioxide generator (when this material is used as a source of sodium and sulfur) and with makeup caustic added to the liquor cycle [2]. Mill water may also be a source of chloride entering the liquor cycle [3]. The amounts of potassium and chloride entering the mill with the wood vary by location. Typically, mills obtaining most of their wood from coastal areas will have a significantly larger chloride input than mills obtaining wood from upland regions [4,5]. Mills processing predominantly hardwoods will tend to have higher potassium concentrations than mills pulping mainly softwoods [1,6].

Potassium and chlorides typically leave the liquor cycle through losses in pulp washing operations, with liquor spills, and with the recovery boiler flue gas [7]. In pulp mills with tightly closed liquor systems, chloride and potassium concentrations can build up, pushing NPE concentrations to levels 4 to 12 times higher than in mills with fairly open water systems or sloppy liquor management [5,8]. With the advent of increased mill water-cycle closure, best management practices (BMP) compliance, maximum achievable control technology (MACT) compliance, and elemental-chlorine-free bleaching as part of the U.S. Environmental Protection Agency Cluster Rules promulgated in the 1990s, many mills have experienced elevated levels of potassium and chloride in the liquor cycle, resulting in increased unscheduled downtime due to boiler

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plugging and decreased boiler performance [9].

Fouling and gas-path plugging in recovery boilers are caused by deposition of carryover particles or fumes. The rate and extent of deposition and fouling depends on the boiler geometry, on the operating parameters associated with the firing of black liquor, and on the liquor chemistry which drives the eutectic behavior of the deposits that form in the upper furnace. Carryover particles consist of smelt or black liquor particles that become entrained in the flue gas, whereas fume deposits are formed from the condensation of vapors of sodium and potassium salts. It has been well documented that increased levels of chloride and potassium in the liquor cycle result in a lowering of the sticky temperature of the recovery boiler deposits, or ash [10,11]. The lower sticky temperature (T_{15}) is defined as the temperature at which 15% of the particle weight is in the molten form; it represents a threshold for deposit formation. It has been shown that particulate liquid content is the most significant parameter affecting particle deposition, and in turn that particulate chloride content and temperature are the most significant factors driving particle melting behavior and liquid content [12,13].

To improve recovery boiler operation, a continuous effort to monitor and control kraft liquor cycle chemistry should be made. By monitoring and controlling potassium and chlorides, deposit formation and fouling will be reduced. Thus, the mill will increase run times between boiler outages while avoiding unscheduled boiler downtime for water washes. A combined effort focusing on tuning of the boiler air system and the black liquor combustion parameters to control carryover will result in improved boiler efficiency. Boiler air system and black liquor firing parameters are commonly adjusted during daily recovery boiler operation, but liquor cycle chemistry is not and is often subject to changes outside the control of recovery operations personnel. Mills that use systems for active management and control of liquor cycle chemistry successfully maintain high and consistent superheated steam temperatures [14]. These mills are also able to maintain continuous operation of recovery boilers between scheduled outages [14].

Mills may use a variety of methods to decrease potassium and chloride concentrations in their liquor cycles. In mills that do not have excessive levels of these NPEs, it may be possible to manage the liquor cycle chemistry simply by controlling the system inputs. This can be done by using low-chloride makeup caustic and paying attention to the amount of chloride carryover in the spent acid from the chlorine dioxide generator. If a mill has moderate chloride and potassium concentrations in the liquor cycle, it may be possible to manage these to acceptable levels by means of a small continuous purge or larger periodic purges of the electrostatic precipitator ash. In cases where these simple methods are not sufficient, a mill may have to resort to an ash treatment system, which selectively purges the potassium and chlorides from the liquor cycle while preserving most of the sodium and sulfur [15]. The current work examines the impact of each of these control strategies on mill operation and profitability.

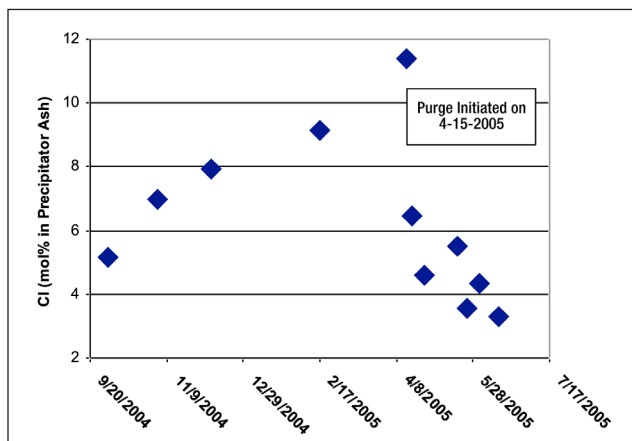
METHODS FOR CONTROLLING LEVELS OF Cl AND K

Long-term potassium and chloride concentration data have been obtained from three operating kraft mills. Because two of these mills are no longer part of MWV, it would not be proper to divulge their specific locations. Hence, these mills will be referred to as Mill A and Mill B. The third mill is the Evadale, TX, mill.

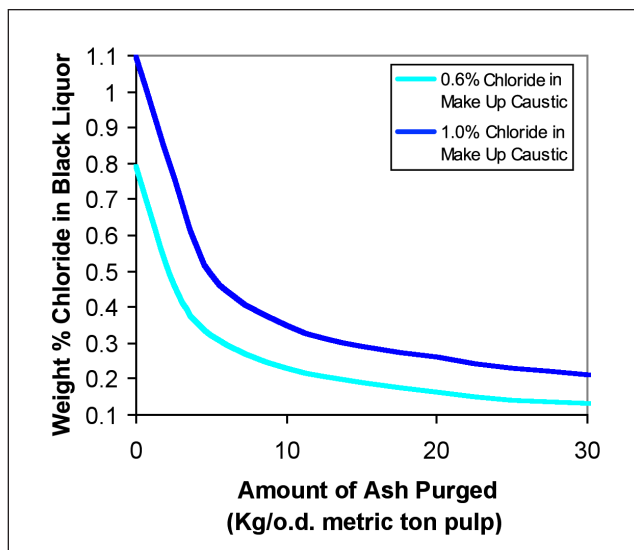
Electrostatic precipitator (ESP) ash purging

Over the years, various mills have developed strategies to minimize the concentrations of potassium and chloride in the liquor cycle. Several mills simply monitor these concentrations and perform a substantial purge of their ESP ash when levels become excessive. Other mills perform a continuous small purge of ash over time. Because of their higher volatility relative to sodium, potassium and chloride become enriched in the deposits formed in the upper regions of a recovery furnace [16]. As levels of potassium and chloride increase, the first melting point and the sticky ash temperature decrease. Chloride has a much greater impact on the melting temperature than potassium. However, chloride and potassium tend to act synergistically to lower the melting point substantially, more than either one alone [3].

Because the concentrations of both potassium and chloride are higher in the ESP ash than in any other part of the liquor cycle, selective purging of the ash will reduce the concentrations of these NPEs in the liquor cycle. Tightly closed mills with low levels of potassium and chloride that slowly accumulate over time are able to rely on periodic purges to control boiler plugging. **Figure 1** shows the chloride concentration in a mill's ESP ash before and after a periodic purge. The data in Figure 1 were obtained from Mill A. Mills with larger inputs of chloride and potassium may require a continuous purge of ESP ash to control boiler plugging [17]. A negative economic aspect of purging the ESP ash is an increase in the amount of makeup chemicals (NaOH and NaSH) required to replace the lost sodium and sulfur in the ESP ash sent to the sewer.



1. Impact of substantial ash purging on chloride concentration in mill ESP ash. Purging started on 4-15-2005.



2. Impact of dust purging and chloride content of makeup caustic on the steady-state chloride concentration of black liquor entering the recovery boiler.

To obtain a better understanding of the impact of purging on a mill's potassium and chloride levels and on makeup chemical demands, a computer model of a single-line mill operating at 775 metric tons/day of bleached pulp was developed using Modular Analysis of Pulp and Paper Systems (MAPPS). Two distinct sets of long-term operating data, obtained from Mill B, were used in the construction of this model. The first condition represented no ash purge. The second condition represented a purge of approximately 45.5 kg/h of ESP dust. A dust loading of 54.67 metric tons/day of ash to the ESP was incorporated into the model. The dust loading value is consistent with literature references that suggest that 3.5%–10% of the solids content of the black liquor ends up as dust in the precipitator [18]. The default chloride and potassium enrichment ratios suggested in the MAPPS recovery boiler module were found to be well correlated with the actual mill operating conditions. Various rates of ash purge (from none up to 227.3 kg/h) were simulated. Steady-state values of chloride and potassium in the black liquor to the recovery boiler (including recycled saltcake added at the mix tank and makeup chemicals added at white liquor storage) were calculated for different purge rates.

According to the model, purging 5 kg of ESP ash per metric ton of pulp produced results in a rapid decrease in the potassium content of the black liquor from 4.4 wt% potassium to approximately 2.9 wt%. Increasing the purge rate above 5 kg/metric ton of pulp was found to produce diminishing returns. Doubling the purge rate from 5 to 10 kg of ash per metric ton of pulp decreased the potassium content in the black liquor going to the recovery boiler by only an additional 0.2 wt%, to 2.7 wt%.

An additional complication was discovered while attempting to model the impact of an ESP ash purge on the chloride concentration in the liquor cycle. The chloride concentrations in the makeup caustic and in the spent generator acid

Purge Rate	Na	K	Cl	K/(K + Na)	Cl/(K + Na)
kg ESP ash/h (kg ash/o.d. metric ton of pulp)	% by Wt	% by Wt	% by Wt	% by Mol	% by Mol
0 (0)	28.54	8.79	7.80	15.34	15.00
45.5 (1.41)	28.70	8.05	5.22	14.16	10.11
90.9 (2.82)	28.95	7.41	4.06	13.09	7.90
181.8 (5.63)	29.41	6.37	2.81	11.30	5.49
272.7 (8.45)	29.80	5.59	2.18	9.94	4.27
363.6 (11.27)	30.11	4.97	1.80	8.85	3.53
454.5 (14.09)	30.37	4.48	1.56	7.98	3.06
636.4 (19.7)	30.77	3.74	1.24	6.67	2.44
818.2 (25.4)	31.06	3.21	1.05	5.73	2.06
1000 (31.0)	31.27	2.81	0.92	5.02	1.81

1. Impact of purging rate on the weight and mole percent of various components of electrostatic precipitator ash for Mill A (assuming less than 3 ppm chloride in caustic used as a makeup chemical).

used as makeup sodium and sulfur can have a significant impact on the equilibrium values of chloride in the liquor cycle. **Figure 2** shows the impact of the levels of ash purging and chloride contamination of makeup caustic on the chloride content of the black liquor going to the recovery boiler. One grade of makeup caustic contained 0.6 wt% chloride contamination, while the second grade of caustic contained 1.0 wt% chloride. Once again, the optimum purging benefit was obtained at a purge level of approximately 5 kg of ESP ash per metric ton of pulp produced. **Table I** shows model predictions of chloride and potassium concentrations in the ESP ash resulting from purging of 0 to 31 kg of ESP ash per metric ton of pulp produced for a system using low-chloride-grade (ray-on-grade) makeup caustic.

Because ESP ash consists primarily of sodium sulfate, makeups of both sodium and sulfur are required when purging. The higher the purge rate, the more makeup chemical is required. The increased makeup demand must be carefully evaluated to ensure that the economic benefit associated with the reduction of chloride and potassium in the liquor cycle (higher superheated steam temperature, decreased liquor deadload, reduced boiler plugging, and decreased boiler corrosion) is not offset by the cost of the additional makeup chemical.

Controlling system inputs

Another method of controlling the concentration of NPEs in the liquor cycle is to reduce NPE inputs to the process. If the total amounts of potassium and chloride entering the system are substantially reduced, the steady-state values will also be reduced. One important area where chloride control may be possible is the selection of the makeup chemicals used in the

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system [19]. Makeup caustic can be obtained in multiple grades that have very different chloride concentrations [20]. Another potential source of chloride contamination is the spent acid from the chlorine dioxide generator. Careful monitoring and control of both these sources of makeup chemical will reduce the chloride concentration in the liquor cycle.

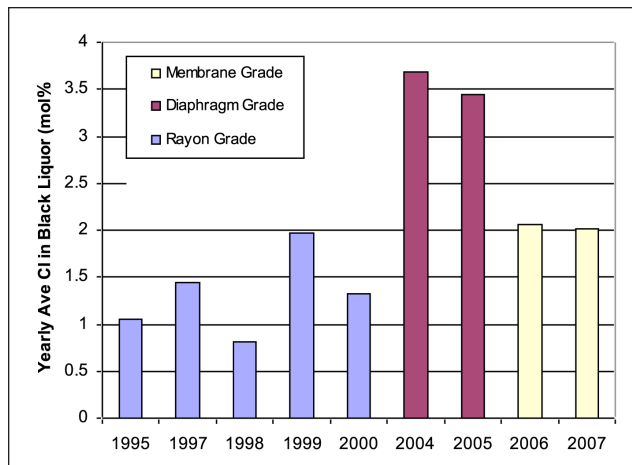
Chlorides in makeup caustic

After years of fairly reliable operation, several recovery boilers within the company started to experience unacceptable frequencies of unscheduled boiler washes due to plugging. Routine ESP ash monitoring indicated a steady increase in the amount of chloride in the liquor cycle. An investigation into potential sources of chloride input to the liquor cycle showed that a change in the procured makeup caustic material was the leading root cause.

Different grades of commercial caustic have different chloride concentrations [20]. A company-wide cost-saving initiative drove a transition in makeup chemicals from a low-chloride caustic to a higher-chloride diaphragm-grade caustic. After several months of operation with diaphragm-grade caustic makeup, multiple recovery boilers in four different mills began to experience plugging. Moving back to a lower-chloride membrane-grade caustic makeup resulted in a gradual decrease in liquor-cycle chloride concentrations over time. This is shown in **Fig. 3** for one recovery boiler, as measured by chloride content in ESP ash. These data were obtained from Mill A. As the chloride levels decreased over a couple of months, a new steady-state liquor-cycle concentration was established, resulting in a reduction of unplanned boiler plugging incidents to acceptable levels. This experience demonstrates the importance of anticipating and understanding the effects of a change in process inputs on the overall process and the liquor cycle over time.

Chlorides in chlorine dioxide generator spent acid

One mill was experiencing difficulty with chloride concentration buildup within the liquor cycle, even while continuously purging a small amount of ESP ash and using membrane-grade caustic as a makeup chemical. Samples were collected of all the typical process inputs. Routine inductively coupled plasma (ICP) analysis was performed on the wood chips, makeup caustic, white liquor, spent generator acid, weak black liquor, fresh-water makeup, and ESP ash. Using these data, a chloride mass balance was attempted. However, the mass balance would not close on chlorides. Finally, it was determined that chloride was entering the liquor cycle through residual chlorite in the spent acid from the chlorine dioxide generator. The chlorine atom in the chlorite ion was not being captured in the ion chromatography analysis and was therefore not reported as a potential source of chloride in the recovery boiler. Once the mill implemented improved washing control on the saltcake filter in the chlorine dioxide generator, the chloride levels in the liquor cycle slowly decreased over time.



3. Annual average chloride concentration in Mill B black liquor resulting from changing the makeup caustic from ultra-low-chloride rayon-grade caustic to high-chloride-content diaphragm-grade caustic to lower-chloride-content membrane-grade caustic.

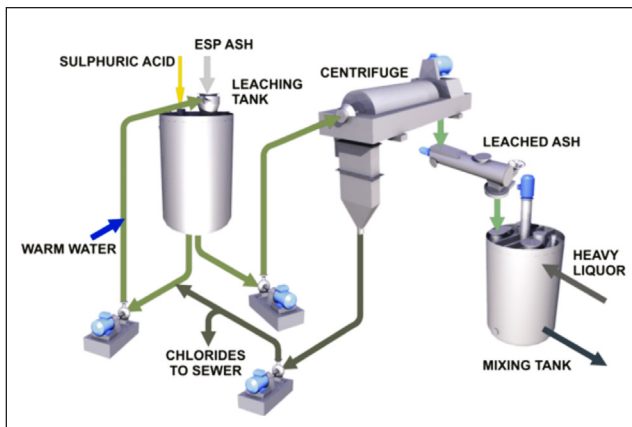
Ash Treatment System

Ideally, a mill would control the NPE concentration in the liquor cycle through minimization of potassium and chloride inputs to the system and through a minimal continuous purge of ESP ash. Because it is not possible to control all the inputs to the system and because purging may be too expensive, some mills, especially coastal mills, may have to resort to selective purging methods to reduce potassium and chloride concentrations in the liquor cycle.

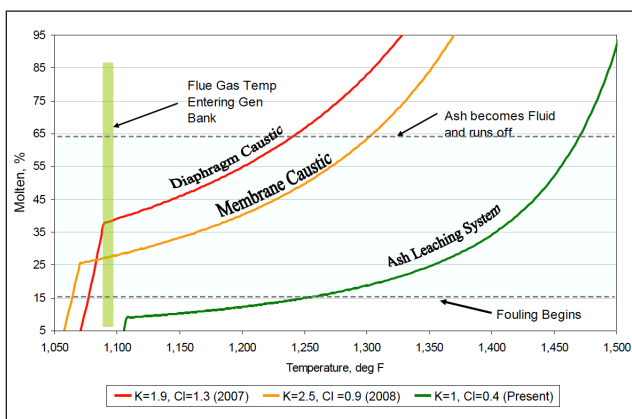
In addition, a mill may want to take advantage of lower-cost makeup material with significant NPE content and to use some sort of selective removal device to control potassium and chloride buildup in their liquor cycle. The Evadale, TX, mill falls into this category. During the second quarter of 2009, the mill commissioned the first North American ash leaching system to purge potassium and chloride selectively from the liquor cycle while maintaining a high level of soda recovery.

THE EVADALE, TX, MILL CASE

The Evadale, TX, mill operates two modern dual-vessel extended modified continuous cooking (EMCC) digesters built in the mid-1990s. One line pulps approximately 1,000 o.d. metric tons/day of mixed southern hardwoods, while the other line pulps approximately 750 o.d. metric tons/day of loblolly pine. The resulting black liquor is blended and processed through a pre-evaporator, three different evaporator trains, two concentrators, and a crystallizer. The heavy black liquor is burned in two 600-psig recovery boilers. One recovery boiler was built in 1995 by Ahlstrom and is designed for a 410-mmph maximum continuous rate (MCR) of steam. The larger boiler was built in 1975 by Combustion Engineering and rebuilt in 1991 by Ahlstrom for a 730-mmph MCR steaming rate. The mill uses conventional green liquor clarifiers and white liquor sock filters to prepare the white liquor for



4. Ash leaching system used at the Evadale, TX, mill.

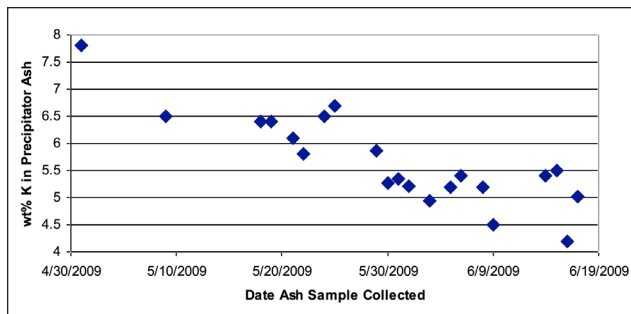


5. Sticky ash temperature for a liquor cycle operating with diaphragm-grade caustic, membrane-grade caustic, and an ash leaching system. Vertical green bar shows the temperature of the flue gas entering the generating bank section of the boiler.

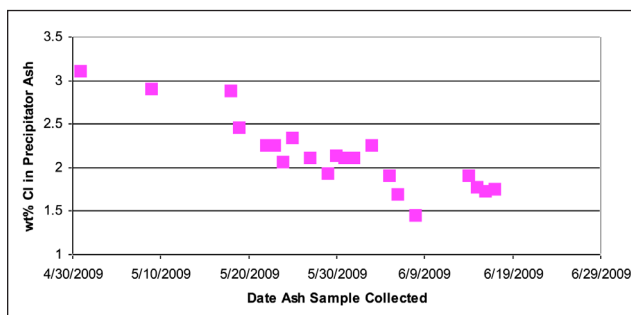
the digester. An ash leaching system was installed in the liquor cycle in 2009.

System Overview

The ash leaching system is composed primarily of an ash leaching tank, a slurry pump, and a decanting centrifuge. **Figure 4** provides details of the system. Roughly 1.4 kg ESP ash is partially dissolved in 1 kg warm water or clean condensate. The resulting slurry contains a mixture of liquid and solids particles. Because chlorides and potassium are more soluble in water than the other components, the liquid phase is enriched in chloride and potassium. The resulting slurry is decanted in a centrifuge, with the crystalline portion returned to the liquor cycle via the heavy black liquor dissolving tank. The leached ash obtained from the decanting centrifuge typically contains less than 10% moisture. A portion of the chloride- and potassium-rich liquid phase is sewerred, while the remainder of the liquid is recycled back to the ash leaching tank via a recycle loop. Most of the heavy metals should stay in the solid phase and be recycled through the system to be removed with the green liquor dregs and the grits.



6. Changes in potassium concentration of ESP ash since startup of the ash leaching system at the Evadale mill.



7. Changes in chloride concentration of ESP ash since startup of the ash leaching system at the Evadale mill.

System Performance

After overcoming several mechanical and process-related issues, the system is performing very well, with excellent chloride and potassium removal efficiencies and minimal soda loss. The idea behind the ash leaching system is that enough chloride and potassium will be removed to substantially shift the temperature at which the salt begins to melt, to a level higher than the temperature of the flue gas entering the generator bank. **Figure 5** shows a plot of the percentage of molten salt as a function of temperature for a liquor cycle using diaphragm-grade caustic with approximately 1 wt% chloride (2007 operation), membrane-grade caustic with approximately 100 ppm chloride (2008 operation), and an ash leaching system (current operation). The flue-gas temperature entering the generator bank is also shown in Fig. 5. As can be clearly seen, the ash leaching system is the only method of operation that yields an operating point outside the sticky ash regime.

To date, the operation of the ash leaching system has been successful. **Figures 6** and **7** show the changes in the potassium and chloride concentrations in the ESP ash as a result of the startup of the ash leaching system. Since the ash leaching system began operation, analysis of the ESP ash has shown that the chloride concentration has been reduced by roughly 55% and the potassium concentration by approximately 50%. Soda recovery has been roughly 80% of the total soda sent to the ash leaching system. As a result of this excellent NPE reduction, the mill has been able to reduce significantly the

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amount of purchased makeup caustic. The mill has also been able to use lower-cost, higher-chloride-content makeup materials in the liquor cycle.

CONCLUSIONS

In many mills, liquor cycle chemistry, in particular the concentration and buildup of NPEs such as chloride and potassium, is not monitored and controlled on a routine basis. Moreover, liquor chemistry is often subject to changes outside the control of recovery operations personnel, in the form of inputs from bleach plant operations and changes in makeup material quality.

Several methods exist for controlling NPE concentrations in the liquor cycle. Selective periodic purging of the ESP ash has been shown to be effective at reducing potassium and chloride concentrations in the liquor cycle. Continuous purging of a small portion of the ash is another effective method for NPE control. Ash purging, whether periodic or continuous, has a negative aspect in that the amount of makeup chemical required for the liquor cycle increases substantially as the level of purging increases. As was shown in the single-line mill case in conjunction with the model, if the makeup caustic used in the system contains more than approximately 1.3 wt% chloride, it may not be economically possible to purge enough ash from the system to prevent unplanned boiler plugging.

The total input of potassium and chloride to the system is also important. The type of caustic makeup material used has been

shown to be extremely important in the control of chloride concentrations in the liquor cycle. As may be seen in Fig. 5, changing from diaphragm-grade to membrane-grade caustic substantially reduced the percentage of molten salt in the ash in the generator bank area. Careful operation of the chlorine dioxide generator saltcake washer also improved recovery boiler operations by lowering chloride concentrations in the liquor cycle.

Finally, implementation of the ash leaching system has successfully raised the initial melting point temperature of the salt to a level higher than the flue-gas temperature entering the generator bank (Fig. 5). The ash leaching system has successfully reduced potassium and chloride concentrations in the ESP ash by over 50% while maintaining a high level of soda recovery (over 80% of the soda entering the leaching process). Boiler inspections since the implementation of the ash leaching system indicate a significant improvement (decrease) in the rate of fouling and plugging in the upper furnace and suggest that the now-cleaner boiler should be able to operate continuously between annual outages. In addition, the mill can use lower-cost, higher-NPE-content makeup chemicals while maintaining a clean boiler and low levels of potassium and chloride in the liquor cycle. **TJ**

AUTHORS' NOTE

The data used in this manuscript were obtained from three different mills and six different recovery boilers and over several years of operation.

ABOUT THE AUTHORS

It has become clear over the years that control of potassium and chloride concentrations in the liquor cycle is directly correlated with recovery boiler operability and mill economics. Mills with good control programs are able to maintain long stretches of boiler operation and high superheater temperatures. Mills with high levels of NPEs tend to experience plugging and fouling.

The current work uses actual mill data to support past research in the areas of purging and controlling process inputs. This paper also describes the implementation of the first ash leaching system in North America, giving details of how that system performs to help control NPEs.

It was interesting to discover that with the system in full operation, the mill can use lower-quality makeup materials and still maintain excellent control of recovery boiler chemistry and avoid plugging.

A better understanding of NPE buildup in the recovery boiler is important for mill economics. The current work details the plusses and minuses of various control technologies from a mill perspective



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using mill data. The implementation of an ash leaching system may be an integral part of the NPE control strategy for a modern, fairly closed mill.

The next step would be to optimize sootblowing and mill operation with the ash leaching system in place. The authors are also planning to develop a full NPE model of the liquor cycle in an effort to identify additional economic opportunities for the mill.

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LITERATURE CITED

1. Casey, J.P., Ed., *Pulp and Paper Chemistry and Chemical Technology*, 3rd edn., Vol. 1, John Wiley, New York, 1980.
2. Frederick, W.J. Jr., *AIChE Symposium Series* 80(239): 21(1984).
3. Hiner, L.A., Blair, M.A., Moyer, S.C., et al., *Proceedings, 2000 TAPPI Engineering Conference*, Atlanta, GA, 2000.
4. Adams, T.N. and Frederick, W.J., *Kraft Recovery Boiler Physical and Chemical Processes*, American Paper Institute, New York, 1988.
5. Tran, H.N., Barham, D., and Reeve, D.W., *Pulp Paper Can.* 91(5): 55(1990).
6. Vakkilainen, E.K., *Paperi ja Puu* 82(7): 450(2000).
7. Grace, T.M. and Tran, H., *TAPPI J.* 92(7): 18(2009).
8. Keitannien, O. and Virkola, N.-E., *TAPPI* 65(7): 89(1982).
9. Jordan, J.M. and Bryant, P.S., *TAPPI J.* 79(12): 108(1996).
10. Tran, H.N., *Tappi Journal* 69(11): 102(1986).
11. Mao, X., Tran, H., and Cormack, D.E., *Tappi Journal* 84(6): 1(2001).
12. Shenassa, R., Kuhn, D.C.S., and Tran, H.N., *J. Pulp Paper Sci.* 29(4): 132(2003).
13. Frederick, W.J., Vakkilainen, E.K., Tran, H.N., et al., *Energy Fuels* 18(3): 795(2004).
14. Grace, T.M. and Clement, J.L., *Recovery Boiler Superheater Investigation*, Final Rept. for the AF&PA Recovery Boiler Research and Development Subcommittee, AF&PA, July 2008.
15. Johansson, U., "Different Methods for the Purge of Chlorides and Potassium from Electrostatic Precipitator Dust in the Kraft Mill," Master's thesis, Department of Chemical Engineering, Lund University, Lund, Sweden, 2005.
16. Reeve, D.W., Tran, H.N., and Barham, D., *Tappi* 64(5): 109(1981).
17. Nunes, W.L., Puig, W., and Lindman, N., *Proceedings, 1995 International Chemical Recovery Conference*, Toronto, Canada, A591.
18. Shenassa, R., Reeve, D.W., Dick, P.D., et al., *Pulp Paper Can.* 97(5): 48(1996).
19. Minday, A.M., Reid, D.W., Burke, M.A., et al., *Proceedings, 1998 International Chemical Recovery Conference*, TAPPI Press, Atlanta, p. 989.
20. Panachem Caustic Soda Product Specifications MSDS, www.panachem.com/msds%20spec.pdf

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