

Mill experience of calcium carbonate scale formation in green liquor pipelines

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ABSTRACT: Experience of hard calcite (CaCO_3) scale formation in green liquor pipelines at four kraft pulp mills was systematically investigated to determine if there is any correlation between the severity of the scaling problem at each mill and the design and operating conditions of its causticizing plant. The results show that the high degree of supersaturation of calcium ions (Ca^{2+}) in the liquor is the main contributing factor. Mills that operate at a lower green liquor total titratable alkali (TTA), higher causticity, and a larger liquor temperature drop are more likely to produce a green liquor that is supersaturated with Ca^{2+} , and thus experience more severe scaling problems. In order to minimize CaCO_3 scaling, the green liquor handling equipment should be operated as steady as possible to avoid conditions that allow Ca^{2+} to be supersaturated. The strategies include minimizing variations in liquor TTA, insulating the green liquor pipelines to reduce temperature gradients, and adding lime mud to weak wash to provide seeds for precipitation to occur on mud particles instead of on metal substrate.

Application: By understanding the main cause of hard scale formation in green liquor pipelines, mills can devise viable solutions to the problem.

In kraft pulp mills, wood is cooked in a digester with white liquor, a hot aqueous solution of sodium hydroxide (NaOH) and sodium sulfide (Na_2S), to make pulp. These cooking chemicals are regenerated by i) concentrating the spent liquor (weak black liquor); ii) burning the concentrated black liquor in a recovery boiler to produce smelt that consists of mostly sodium carbonate (Na_2CO_3) and Na_2S ; iii) dissolving smelt in a dissolving tank to produce green liquor; and iv) causticizing the green liquor with lime (CaO) in the causticizing plant to convert Na_2CO_3 to NaOH . The resulting white liquor is then reused in the pulping process.

One of the major problems in causticizing plant operation is the formation of hard scale in the green liquor handling system. Scale has been found to form virtually everywhere, from the dissolving tank walls, floor, and agitators to green liquor filter cloths, pipelines, pumps, heat exchangers, slaker walls, and screws, and to causticizer walls and agitators. The severity of scaling varies from mill to mill. Massive scale formed on dissolving tank agitators can throw the agitators off balance, causing them to vibrate; hard scale formed on slaker classifier screws makes it difficult to remove grits, while hard scale formed in green liquor pipelines can severely obstruct the liquor flow, resulting ultimately in reduced white liquor production, and hence, low mill productivity. **Figure 1** shows examples of scale formation in green liquor pipelines. These scales consisted of 80% to 90% calcium carbonate (CaCO_3). They were hard, stratified and so massive that they almost completely blocked the 8 in. (20.3 cm) internal diameter (ID) pipe.

CaCO_3 , mostly in the form of calcite, has been identified as the main component of the hard scale, particularly at



1. Calcite (CaCO_3) scale formation in green liquor pipelines at two kraft mills. Pipe inner diameter = 8 in. (20.3 cm) in both cases.

locations downstream of the dissolving tank [1-4]. A systematic study was conducted at the University of Toronto to examine how CaCO_3 scale forms and what makes it hard [5]. The study consisted of two parts. Part 1 investigated the solubility of CaCO_3 in green liquor and incorporated the obtained solubility data into OLI (a commercially available thermodynamic simulation software from OLI Systems, Cedar Knolls, NJ, USA) to develop a predictive model for CaCO_3 precipitation. The model was then used to predict how operating variables affect the solubility of CaCO_3 and hence scale formation. Part 2 analyzed the scaling experience in green liquor pipelines at several kraft pulp mills (i.e., how scales form) and how the problem was affected by operating conditions of the causticizing plant at each mill.

Solubility experiments performed in Part 1 of this study showed that the solubility of CaCO_3 in green liquor is extremely low (<6 ppm Ca^{2+}) and that it increases with in-

RECOVERY CYCLE

	Mill A	Mill B	Mill C	Mill D
Country	Canada	Canada	Sweden	Sweden
Startup year	1989	1970	1917	1895
Pulp production, a.d. metric tons/day	1650 (NBHW) 1300 (NBSW)	500	1080	1550
Wood type	56% HW/46% SW	SW	SW	2/3 SW/1/3 HW
Antiscalants used	Yes	Yes	No	No
GL pipeline material	304 SS	304 SS	304 SS	304 SS
Pipeline insulation	Partial	Complete	Complete	Complete
Pipeline internal diameter	20 cm (8 in.)	15–20 cm (6–8 in.)	20 cm (8 in.)	20 cm (8 in.)
Scale formation locations	Dissolving tank, raw green liquor pipelines	Raw green liquor pipelines	Pressure filters and causticizers	Pressure filters and causticizers
NB = northern bleached; HW = hardwood; SW = softwood; GL = green liquor; SS = stainless steel.				

1. Main operating conditions and scale formation experience at the four pulp mills studied.

creasing temperature and total titratable alkali (TTA), but decreases with increasing causticity and sulfidity [6]. Since CaCO_3 scale forms on a hard surface as a result of the precipitation of Ca^{2+} and carbonate (CO_3^{2-}) ions, these findings suggest that the scaling tendency is greater for green liquor systems with lower temperature, lower TTA, higher causticity, and higher sulfidity.

This paper discusses the results obtained from Part 2 of the study. Four kraft pulp mills, two in Canada (Mill A and Mill B) and two in Sweden (Mill C and Mill D), were visited to obtain a better understanding of the scaling problems at each mill. Causticizing plant layouts and operating conditions were compared to determine if the experience at each mill could be explained using the experimental solubility results found in Part 1 of the study and if there is any correlation between the severity of the scaling problem at each mill, and the design and operating conditions of its causticizing plant.

MILL EXPERIENCE

The following sections describe the four kraft pulp mills participating in this study. **Table I** summarizes basic operating conditions and scale formation experience at these mills.

Mill A

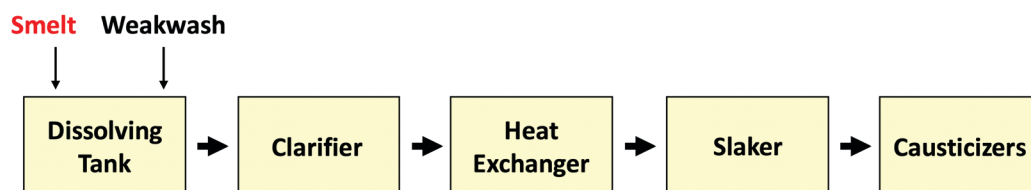
Constructed in 1989, Mill A is a single production line kraft mill in Canada designed to produce 1100 a.d. metric tons/day

of bleached hardwood pulp. The mill has been through several major upgrades and is currently running in campaigns of hardwood and softwood with a production target of 1650 a.d. metric tons/day hardwood and 1300 a.d. metric tons/day softwood. The mill has been experiencing severe CaCO_3 scale problems in its raw green liquor pipeline. Anti-scaling chemicals have been used to prevent scale buildup with little success. The green liquor lines need to be cleaned every 6 months.

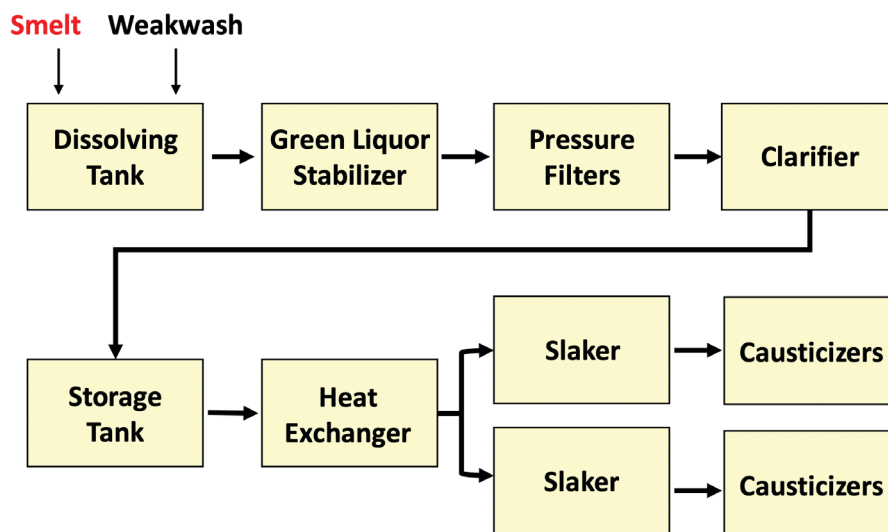
Mill B

Mill B is an older (1970) single production line kraft mill in Canada that currently produces 500 a.d. metric tons/day of high performance unbleached sack kraft paper with a 50/50 softwood mixture of spruce and pine. Hard scale was often found in pipelines that transport raw green liquor (RGL) from the dissolving tank to the green liquor clarifier. To minimize scaling, the mill adopted the commonly used tactic of line-switching between RGL and weak wash (WW), which was mostly successful. In June 2016, the mill stopped practicing line-switching, and instead added an anti-scaling chemical to the RGL to prevent scale buildup. All pipelines were cleaned prior to this implementation.

In October 2017, the mill was forced to shut down due to severe clogging of the lines (Fig. 1, left). Hydroblasting with high pressure, 20000 psi (1380 bars) water for 12 h was carried out without success. The pipelines were even-



2. Block flow diagram of Mill A and Mill B causticizing plants.



3. Block flow diagram of Mill C and Mill D causticizing plants.

tually cleaned with hydrochloric acid. The scale formation appeared to be more severe on the inside elbows of the pipes than the outside, and much of the scaled section was horizontal, although some vertical sections were also affected to some extent. In the spring of 2018, the mill terminated the anti-scaling chemical use, and resumed its line-switching practice. No scale formation has been experienced since.

Mill C

Mill C is a 1917-era Swedish mill with a current production capacity of 1080 a.d. metric tons/day of bleached/unbleached kraft pulp from softwood. Hard scale is present, but rarely affects the causticizing plant operation.

Mill D

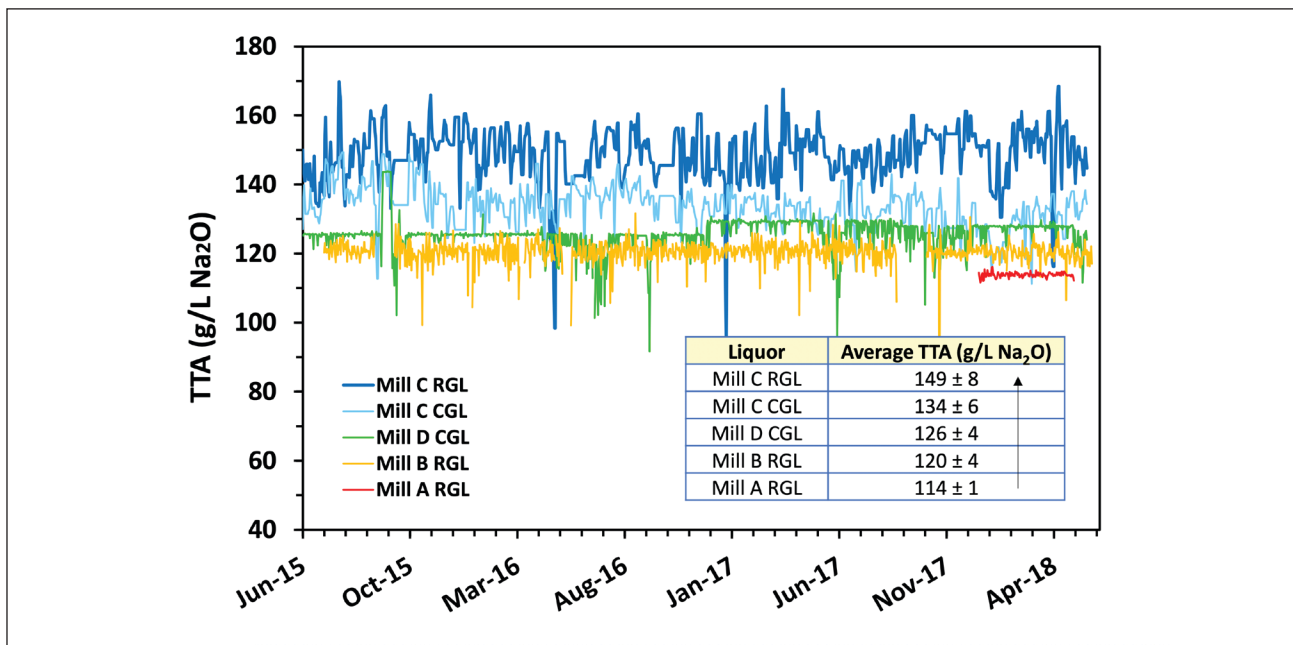
A non-integrated Swedish kraft mill, Mill D first began production in 1895 and has grown to have a current capacity of 1550 a.d. metric tons/day. As with Mill C, some scale is always present, but it does not result in unscheduled causticizing plant shutdowns.

CAUSTICIZING PLANT DESIGN

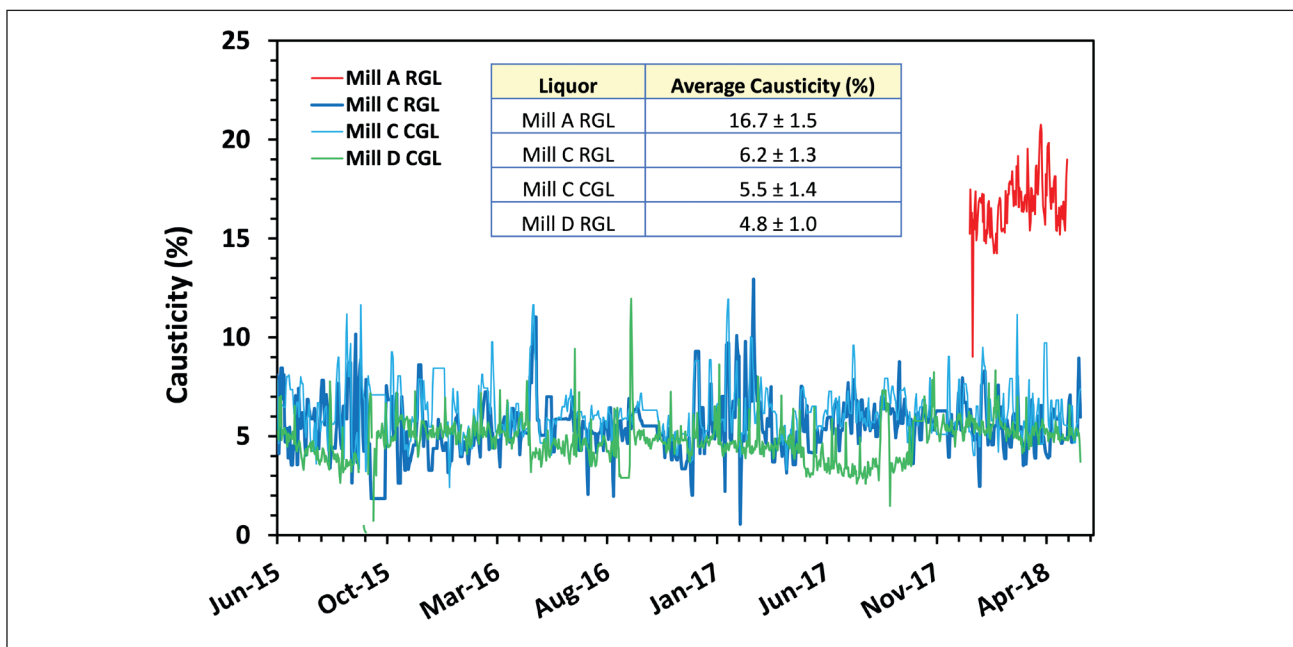
The causticizing plant at Mill A and Mill B (**Fig. 2**) has a much simpler design compared to that at Mill C and Mill D (**Fig. 3**). The design consists of a dissolving tank, a green liquor clarifier, a heat exchanger, slaker, and a single line of causticizers. There are no green liquor surge tanks. The pipelines between the dissolving tank and clarifier at Mill A are switched between raw green liquor and weak wash every 12 h to facilitate cleaning of the lines. Mill B did not switch the raw green liquor and weak wash lines during the period from June 2016 to October 2017, but resumed the line-switching practice after this time. Both Mill A and Mill B added antiscalants to their raw green liquor at the outlet of the dissolving tank.

Mill C and Mill D are equipped with a stabilizing (or surge) tank after the dissolving tank and use pressure filters (4 in parallel) and a clarifier to clean the raw green liquor. Mill C uses an old type cassette filter with filter tubes covered with socks that need to be replaced 3 times a year, while Mill D uses white liquor Clarifil & Eco filters that need to be washed periodically with sulfamic acid to re-

RECOVERY CYCLE



4. Green liquor total titratable alkali (TTA) at studied mills (RGL=raw green liquor, CGL=clarified green liquor).

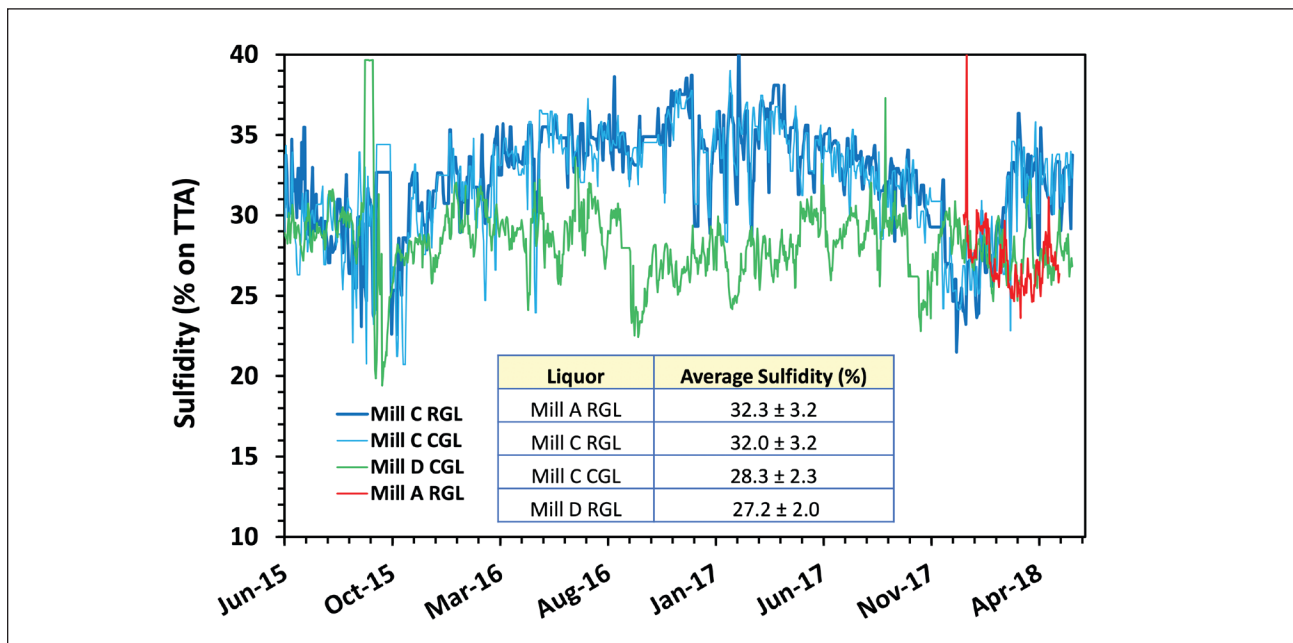


5. Green liquor causticity for studied mills.

move scale. The raw green liquor and weak wash lines between the dissolving tank and the stabilizing tank are switched every day at both mills to prevent hard scale from building up in the pipelines. After the green liquor heat exchanger, the system is split into parallel slaking and causticizing lines.

Mills A and B typically experience scale formation in the dissolving tank and raw green liquor lines, while Mills C and D experience more scale buildup downstream in their green liquor pressure filters and causticizers. The designs

of the causticizing plants at Mills C and D allow for the implementation of scale cleaning procedures that do not impact daily mill production, since the smaller green liquor pressure filters at Mills C and D can be taken off line individually to remove scale. The dual line of causticizers at these mills helps keep scale buildup manageable, particularly when cleaning procedures are introduced into the daily operations of the mill. For these reasons, Mills C and D reported less scaling problems compared to Mills A and B.



6. Green liquor sulfidity for studied mills.

OPERATING DATA ANALYSIS

A site visit to Mill A was completed in February 2018 and to Mills C and D in June 2018. Four months of operating data (January–April 2018) were gathered for Mill A, while nearly 3 years of operating data (June 2015–April 2018) were gathered for Mills B, C, and D.

Process data (green liquor TTA, causticity, sulfidity, temperature, and suspended solids) was analyzed to identify any abnormalities in the mill liquor, which could be used to explain the scaling observations in the mills. Plots of the variation in these parameters over the past 3 years are shown in **Figs. 4, 5, and 6**.

Mills A and B have the lowest green liquor TTA, with average values of 114 and 120 g/L sodium oxide (Na_2O), respectively. Mill D has a somewhat higher average TTA of 126 g/L Na_2O , while Mill C has what is considered a high TTA with an average value above 134 g/L Na_2O . Compared to TTA trends, causticity trends are the opposite, with Mills A, C, and D having an average causticity of 16.7%, 6.2%, and 4.8%, respectively. Causticity is not measured at Mill B. Average sulfidity values are similar for all mills, varying between 27% and 32% on TTA.

Figure 7 shows the ΔT (temperature drop) across the clarified green liquor heat exchanger for Mills A, C, and D. Heat exchangers are typically used to cool the clarified green liquor to control the temperature in the slaker between 101°C–104°C. The average ΔT across the heat exchanger at Mills A, C, and D is 5.7°C, 3.1°C, and 2.2°C, respectively. The larger ΔT could be the cause of more severe scaling at the outlet of the heat exchanger at Mill A compared to Mills C and D.

Figure 8 shows the suspended solids in weak wash, raw green liquor, clarified green liquor, and white liquor at

all four mills. As expected, the raw green liquor has the highest suspended solids concentration compared to other liquors. It is interesting to note that compared to Mills A and B which had almost no suspended solids in weak wash, Mills C and D had a much higher concentration of suspended solids in weak wash (200–500 mg/L). The lower suspended solids content in Mills A and B's weak washes compared to that in Mills C and D was presumably due to the fact that Mill A has a white liquor tube filter and Mill B has a white liquor clarifier, while Mills C and D have white liquor pressure disc filters.

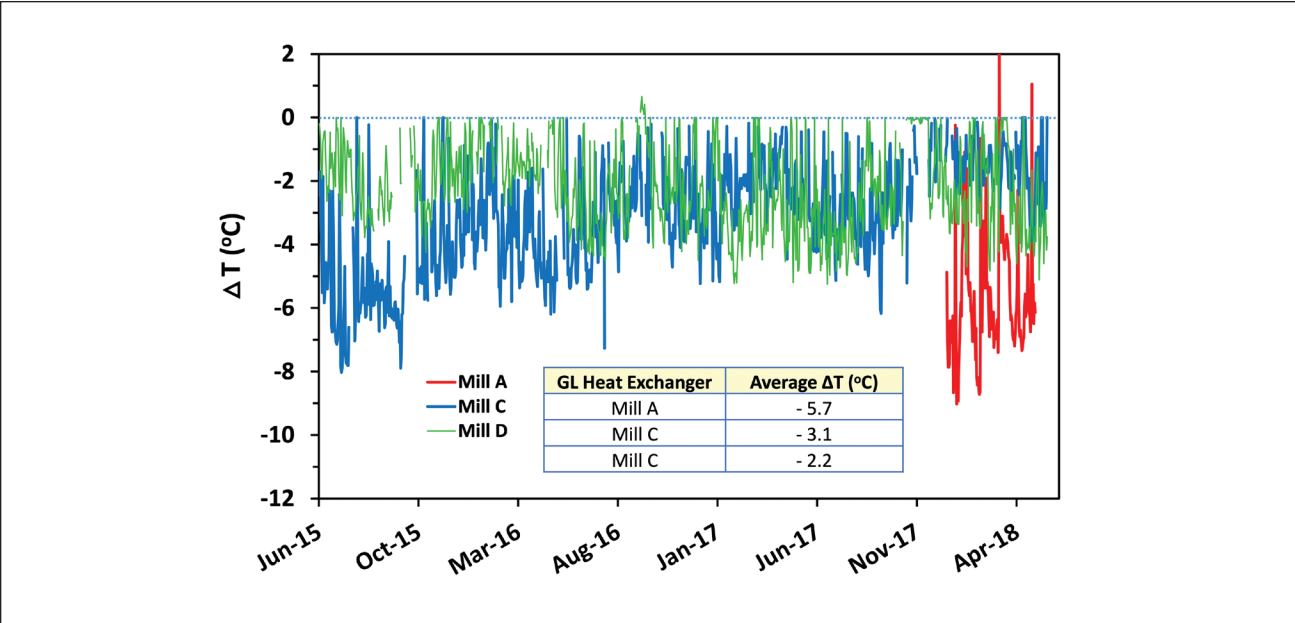
White liquor pressure disc filters generally produce weak wash with higher suspended solids (mostly CaCO_3) particles content than pressure tube filters and clarifiers. This may help reduce scale formation in the green liquor system at Mills C and D, as they can act as seeding sites for Ca^{2+} in the green liquor to precipitate in the bulk rather than on equipment walls.

SCALE SAMPLES ANALYSIS

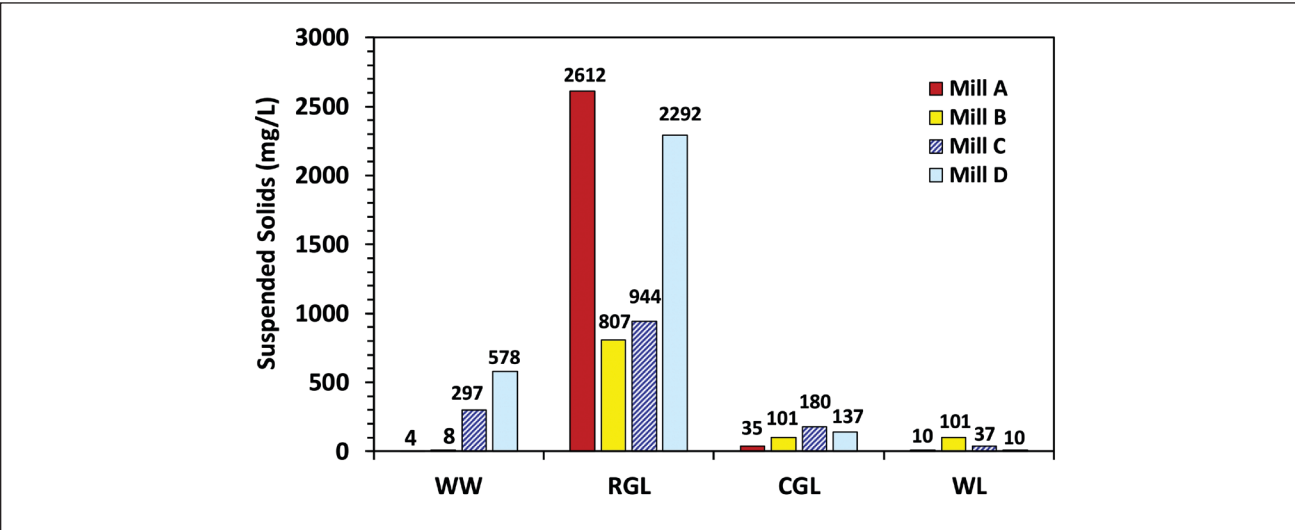
Figure 9 shows the appearance of three scale samples from Mill A. Sample 1 was a light-grey hard scale collected from the RGL pipeline near the exit of the dissolving tank where the RGL and WW lines were switched every 12 h. Sample 2 was obtained from the RGL “switching tee” where the RGL and WW lines are switched. It was black, not as hard as Sample 1, and could be broken readily with a minimal force. Sample 3 was a very hard scale collected from the outlet of the CGL heat exchanger leading to the slaker.

The chemical composition of these samples was determined using an X-ray fluorescence (XRF) spectrometer. The thermal behavior was examined using a simultaneous thermogravimetric analyzer and differential scanning calorim-

RECOVERY CYCLE



7. Temperature drop across the green liquor (GL) heat exchanger at studied mills.



8. Suspended solids concentration in weak wash (WW), raw green liquor (RGL), clarified green liquor (CGL), and white liquor (WL) for all four mills.

eter (TGA/DSC), while the crystal structure was determined by means of X-ray diffraction (XRD).

Chemical analysis

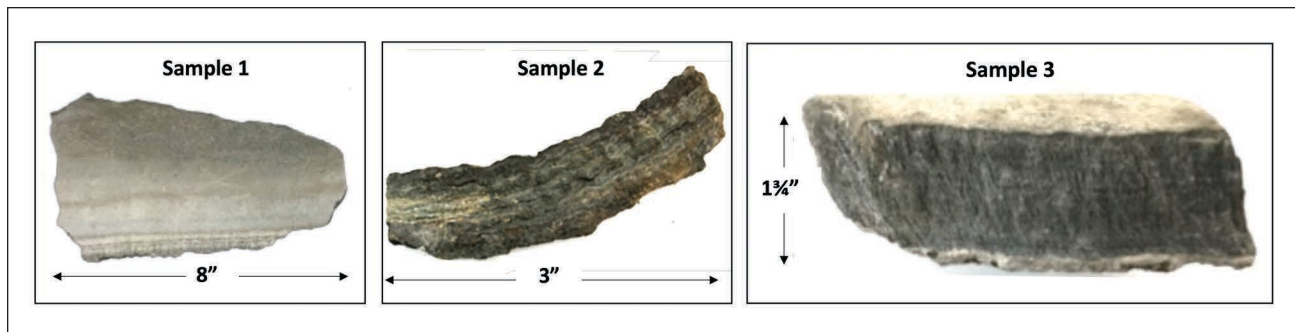
Table II summarizes the results obtained from XRF elemental analysis. All three scale samples from Mill A have a similar composition, consisting of about 36 wt% calcium (Ca) and less than 9 wt% of all other elements listed in the table.

Thermal analysis

All three samples have similar TGA/DSC profiles. An example of the profile is shown in **Fig. 10** for Sample 3. Three thermal events were observed as the sample was

heated from room temperature up to 1000°C. The first event occurred at 350°C, resulting in a small weight loss (1.5 wt%) on the TGA curve and a small endothermic peak on the DSC curve. It was likely caused by the decomposition of $\text{Mg}(\text{OH})_2$ into MgO and H_2O . The second thermal event was also small, resulting in 1.5 wt% weight loss and an endothermic peak at 420°C. This was likely a result of the decomposition of calcium hydroxide ($\text{Ca}(\text{OH})_2$) into calcium oxide (CaO) and water (H_2O).

The third thermal event between 630°C and 820°C was large, with a 35 wt% weight loss and a strong endothermic peak. It is characteristic of the decomposition of CaCO_3 into CaO and carbon dioxide (CO_2). This weight loss suggests that Sample 3 contained $35.0/44 \times 100\% = 80 \text{ wt}\% \text{ CaCO}_3$.

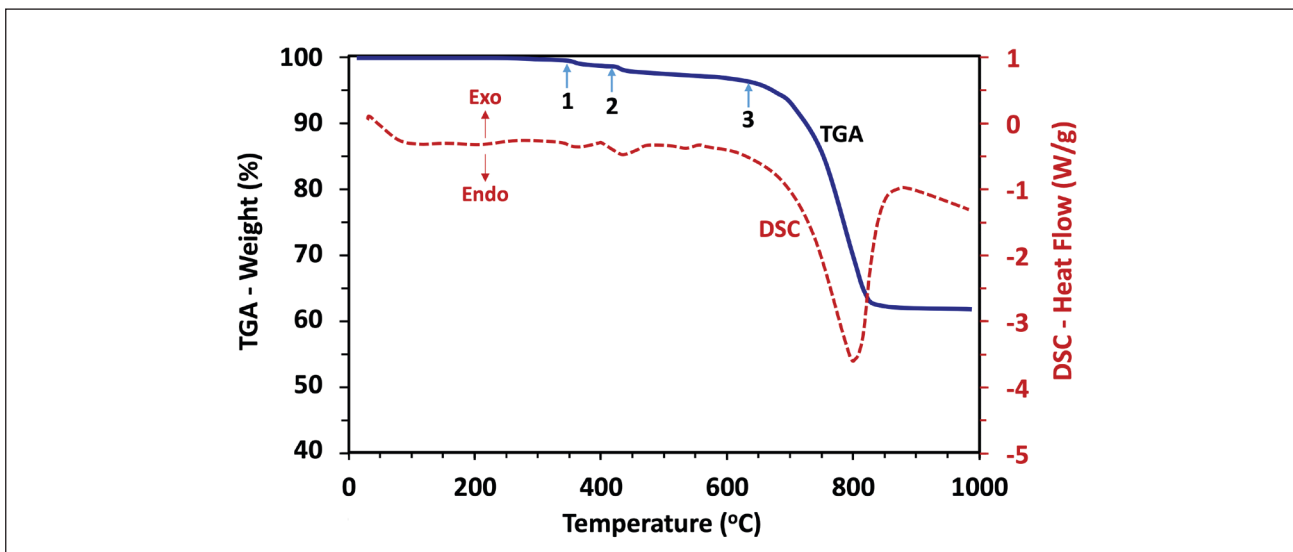


9. Appearance of scale samples from green liquor pipelines at Mill A.

Element	Sample 1, wt%	Sample 2, wt%	Sample 3, wt%	Average, wt%
Calcium (Ca)	36.41	35.60	36.31	36.11
Sulfur (S)	1.48	2.70	3.20	2.46
Magnesium (Mg)	1.06	1.45	1.94	1.48
Barium (Ba)	1.45	1.19	0.69	1.11
Phosphorous (P)	0.53	0.38	0.36	0.42
Silicon (Si)	0.26	0.42	0.58	0.42
Zinc (Zn)	0.39	0.56	0.13	0.36
Sodium (Na)	0.31	0.47	0.47	0.42
Chlorine (Cl)	0.37	0.31	0.34	0.34
Iron (Fe)	0.24	0.41	0.85	0.50
Aluminum (Al)	0.17	0.20	0.18	0.18
Manganese (Mn)	0.25	0.89	0.44	0.53
Potassium (K)	0.26	0.41	0.37	0.35
Vanadium (V)	0.08	0.06	0.03	0.06
Others*	56.74	54.95	54.11	55.27

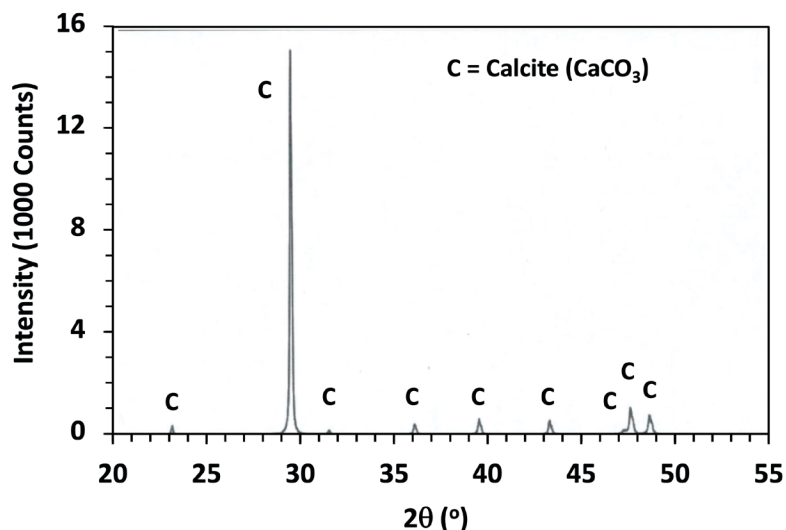
* Balance

II. X-ray fluorescence (XRF) elemental analysis of scale samples from Mill A.

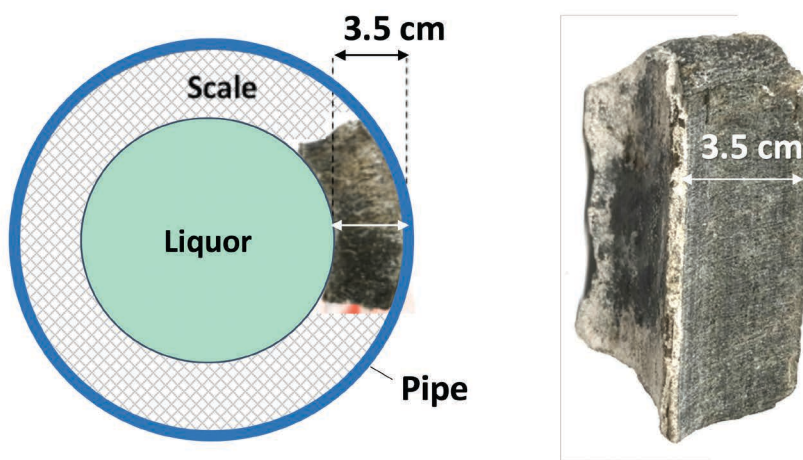


10. Thermogravimetric analyzer and differential scanning calorimeter (TGA/DSC) analysis of scale Sample 3.

RECOVERY CYCLE



11. X-ray diffraction (XRD) pattern (with copper target) of scale Sample 3 from Mill A.



12. Scale formed in the clarified green liquor pipeline at Mill A. Scale thickness = 3.5 cm.

Crystal structure analysis

Figure 11 shows the XRD pattern of scale Sample 3, which is similar to that of other samples and pure CaCO_3 [5]. Only calcite (CaCO_3) was identified. Other compounds are either amorphous or too little to be detected.

Scale composition

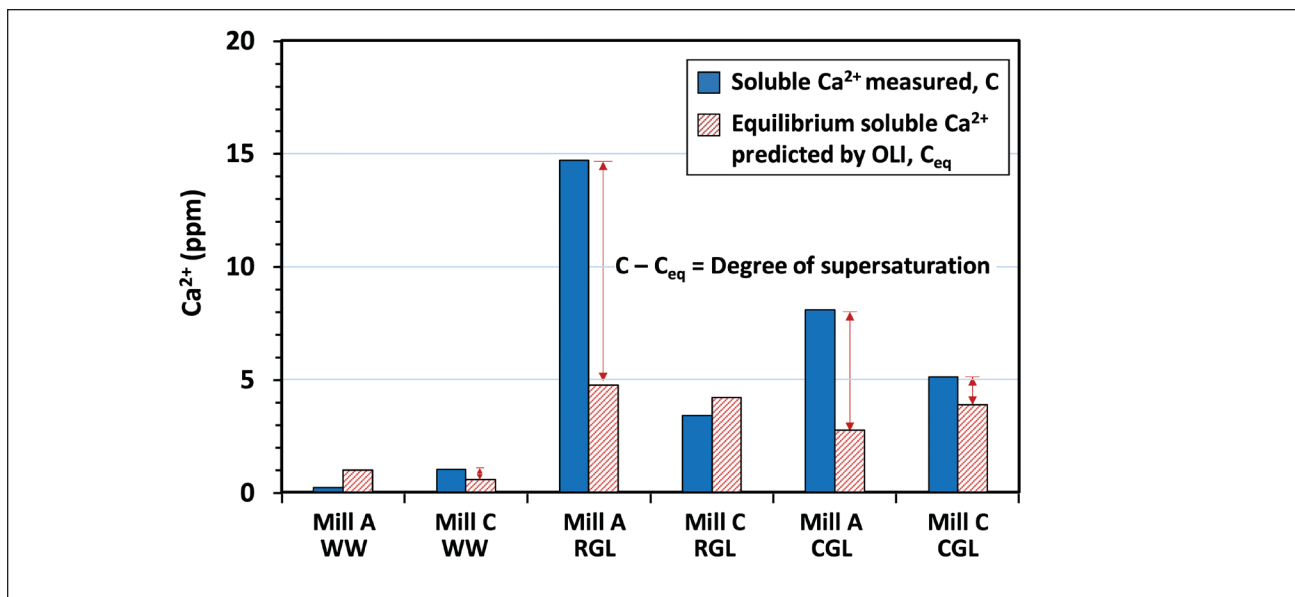
The previously described chemical analysis using XRF, thermal analysis using TGA/DSC, and structural analysis using XRD show that the scales in this study, on average, consisted of 80 wt% CaCO_3 (calcite), 6 wt% $\text{Ca}(\text{OH})_2$, 2 wt% magnesium hydroxide ($\text{Mg}(\text{OH})_2$), and 12 wt% other impurities (i.e., metal oxides, hydroxides, sulfides, silicates, sulfides, etc.)

Note that these scale samples contained very little so-

dium (Na) (less than 0.5 wt%), despite them being constantly in contact with green liquor, which contains a large amount of Na (typically 90 g/L Na). This indirectly implies that these hard scales were more likely formed by precipitation of dissolved Ca^{2+} and CO_3^{2-} in the green liquor onto the pipeline surface and not by chemical reactions involving lime mud particles and green liquor, which would have entrapped Na into the scale structure. The low Na content in the scale also means that there was little or no pirssonite ($\text{CaCO}_3 \cdot \text{Na}_2\text{CO}_3 \cdot 2\text{H}_2\text{O}$) present.

SCALE GROWTH RATE

The formation of CaCO_3 scale in green liquor pipelines is a relatively slow process. Mill experience is that once the scale was completely removed by hydroblasting, it would



13. Degree of calcium supersaturation for various liquors at Mill A and Mill C. (WW = weakwash, RGL = raw green liquor, CGL = clarified green liquor).

take a few months for it to grow back again. The exact scale growth rate is not well understood.

In this study, an attempt was made to estimate the scale growth rate, based on the size and shape of a 1.4 in. (3.5 cm) thick scale sample collected from an 8 in. (20 cm) ID clarified green liquor pipeline at Mill A as shown in **Fig. 12**. Assuming the scale grew uniformly around the pipe circumference at a constant rate, the growth rate would be about 0.2 mm/day in order to cover 43% (nearly one-half) of the cross section of the pipe in 6 months. The stratified layer shown in the scale suggests that scale formation is an on-and-off process, i.e., it grows rapidly for a short period, stops and grows again.

CACO₃ SCALE FORMATION MECHANISMS

For dissolved Ca^{2+} in the liquor to precipitate to form hard CaCO_3 scale on a metal substrate, the following three criteria must be met [7]:

1. Supersaturation
2. Nucleation
3. Crystal growth

Supersaturation is the primary cause of sudden precipitation. As the concentration of a particular solute in a solution exceeds its saturated concentration, the solute precipitates out in order to maintain its equilibrium concentration in the solution. Under transient or process upset conditions, however, equilibrium is not sustained, allowing the solute to stay in the solution without precipitation, even after its concentration exceeds its saturated concentration at the same temperature and pressure. Such a solution is said to be supersaturated.

A supersaturated solution is always in a metastable state.

This means that when the solubility of CaCO_3 exceeds the metastable limit, crystals will start to form, initiating the precipitation process [8]. A saturated solution can be made supersaturated by changing temperature, pressure, and pH; or by adding a solid seeding material into the solution; or by changing solution flow rates. Supersaturation can be localized. The rate of scale precipitation depends strongly on the degree of supersaturation [7]. The greater the degree of supersaturation, the more abruptly precipitation can occur.

In this study, the degree of supersaturation of the weak wash, raw green liquor, and clarified green liquor of Mill A and Mill C was determined by measuring the dissolved soluble Ca^{2+} content using inductively coupled plasma (ICP) spectrometry and comparing that value to the theoretical equilibrium soluble Ca^{2+} content calculated by the OLI thermodynamic program. The difference between the measured value and the equilibrium value ($C - C_{eq}$) is considered to be the degree of supersaturation of the liquor. A plot of this analysis is shown in **Fig. 13**. The degree of supersaturation, and, hence, the driving force for CaCO_3 precipitation, is significantly higher in Mill A compared to Mill C, particularly in the raw and clarified green liquor lines. This is likely the reason why Mill A experiences more scale formation than Mill C.

SCALE PREVENTION STRATEGIES

Calcium in the raw green liquor originates from smelt and weakwash. It is present mostly in the form of lime mud (CaCO_3) particles. Depending on the type and the efficiency of the lime mud washers employed at individual mills, the Ca content in green liquor can vary widely, from 100 ppm to 4000 ppm as Ca. Since CaCO_3 has an extremely low solubility, < 5 ppm Ca^{2+} , green liquor is always satu-

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rated with Ca^{2+} . In order for CaCO_3 to precipitate and form hard scale, the green liquor must first be supersaturated with Ca^{2+} ions. The higher the degree of supersaturation, the more rapidly the scale will form. Therefore, lowering the degree of supersaturation of Ca^{2+} is the key to minimizing CaCO_3 scale formation.

The results obtained from this study (Parts 1 and 2) suggest that the formation of hard CaCO_3 scale may be prevented by the following operation strategies:

1. Reducing process fluctuations: If the solubility of CaCO_3 in green liquor decreases (for example, when the TTA of the liquor changes from high to low), precipitation occurs, forming a thin scale layer on the pipe inner surface. When the condition is reversed (i.e., from low to high TTA), the CaCO_3 solubility increases, allowing the formed scale to dissolve. However, it is almost impossible for the formed scale to dissolve because its surface is saturated immediately with Ca^{2+} due to the extremely low solubility of CaCO_3 . It is, therefore, important to reduce process fluctuations (such as temperature and TTA changes) to minimize the CaCO_3 precipitation in the first place.
2. Insulating the green liquor system: The simplest way to reduce temperature fluctuations in the green liquor system is to insulate the liquor pipelines. The insu-

lated layer results in a smaller temperature difference between the temperature of the inner wall of the pipe and the bulk liquor temperature, thus reducing the drive for precipitation. Mills with well-insulated pipelines generally experience less scale formation problems than mills with poorly insulated pipelines.

3. Adding lime mud particles to weak wash: This could help reduce CaCO_3 scale formation in the green liquor lines. Lime mud particles likely act as seed sites for any CaCO_3 to precipitate in the bulk, rather than on the walls, of the causticizing plant equipment. This strategy, however, may increase the mass load of dregs for disposal by 3% to 5%.

SUMMARY

The experience of hard scale formation in green liquor pipelines at four kraft mills in Canada and Sweden was investigated to determine if there was any correlation between the severity of the scaling problem at each mill and the design and operating conditions of its causticizing plant. The results show that scales consist of mostly calcite, which is formed due to the extremely low solubility of CaCO_3 in the highly alkaline green liquor environment that causes dissolved Ca^{2+} in the liquor to precipitate out during a process upset.

ABOUT THE AUTHORS

Following our previous work on the solubility of CaCO_3 in green liquor handling systems (TAPPI J. 18[10]: 595[2019]), we thought that it would be great if we could relate the laboratory results to actual mill experience, so this work complements our previous study. As a young professional, it was great for me (Giglio) to have the opportunity to work in mill settings and to learn about and understand how various mills operated.

The most difficult part of this research was obtaining a quantitative assessment of the scale formed in the mills studied. We addressed this by performing a qualitative assessment of the historical data at each mill. The most interesting (and exciting) finding was that the experience documented from

each of the mills complimented the laboratory solubility experiments.

Mills might use the three operating strategies that we recommended here to prevent calcium carbonate scale formation in the green liquor pipe lines.

Giglio is a former graduate student and Tran is professor emeritus in the the Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, ON, Canada. Björk is research advisor and Wadsborn is team manager, Biomass Separation, for Stora Enso-Biomaterials Innovation in Karlstad, Sweden, and Nacka, Sweden, respectively. Lagimodiere is manager, Steam and Recovery, at Canadian Kraft Paper, The Pas, MB, Canada. Dion is process specialist at Mercer Peace River Pulp, Peace River, AB, Canada. Email Tran at honghi.tran@utoronto.ca



Giglio



Tran



Björk



Wadsborn



Lagimodiere



Dion

Supersaturation of Ca^{2+} ions in the liquor is likely the main cause of scale formation. This implies that mills operating at a lower green liquor TTA, higher causticity, and a larger drop in liquor temperature are more likely to produce green liquor supersaturated with Ca^{2+} , accelerating the rate of hard scale formation. Thus, in order to minimize scale formation, the green liquor handling systems should be operated as steady as possible. This can be accomplished by minimizing variations in green liquor TTA, insulating the green liquor pipelines to reduce temperature gradients, and adding lime mud to weak wash to provide seeds for precipitation to occur on mud particles instead of on metal substrate. **TJ**

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