

Evaluating the effect of recovery boiler operation of green liquor dregs concentration using multivariate analysis

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ABSTRACT: Poor settling and filterability of green liquor dregs has been a persistent problem in many kraft pulp mills. While the concentration and settling/filtering behaviors of dregs are expected to be related to how black liquor is burned in recovery boilers, the effect of boiler operation is not well understood. A systematic study was conducted to examine how recovery boiler operation may affect the dregs concentration in the raw green liquor (RGL) at three kraft pulp mills using SIMCA, a multivariate data analysis (MVDA) program. Daily average boiler operating data from three kraft mills were analyzed over a 3-year period. Results of both principal component analysis (PCA) and partial least squares regression (PLS) suggest that the main boiler operations contributing to high dregs concentrations in RGL are low liquor firing load, low bed temperature, poor char burning, and unstable char bed.

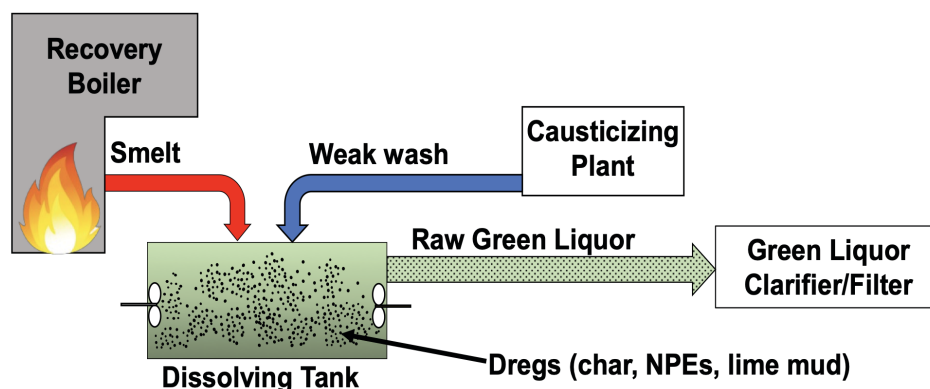
Application: Understanding the main boiler operating parameters that result in excessive dregs formation can help mills correct the excessive dregs problem.

In kraft pulp mills, black liquor (spent liquor from the pulping process) is burned in a recovery boiler to recover the pulping chemicals and generate steam and power for use in mill processes. The combustion produces a large amount of molten smelt, which flows out of the boiler through smelt spouts. Molten smelt is broken up into smaller droplets by shatter steam jets before entering the dissolving tank underneath the boiler where it is dissolved in weak wash from the causticizing plant and makeup water to form raw green liquor (RGL), as schematically shown in **Fig. 1**.

The RGL typically contains 1000–3000 mg/L suspended particles, commonly known as “dregs.” The amount is equivalent to about 4–11 kg/ton pulp that need to be removed either by sedimentation in the clarifiers and/or by filtration in pressure filters to produce clean or clarified

green liquor (CGL) [1]. Dregs are a mixture of: i) partially burned char particles and particles of insoluble compounds of non-process elements (NPEs) from the molten smelt stream; and ii) lime mud, char, and insoluble compounds of NPEs from the weak wash stream. The amount of dregs produced by a mill varies depending on wood species and the design and operation of the recovery boiler. Older and overloaded recovery boilers generally produce more dregs than newer boilers operated at the design capacity.

Efficient dregs removal is essential to mill operation. Clarified green liquor must be as free of dregs as possible to ensure the white liquor and lime produced from it are of high quality. If dregs are not adequately removed from green liquor, it will show up in lime mud and white liquor, and this ultimately can contaminate the reburned lime and pulp. Since dregs contains a large amount of non-process



1. Dissolving tank flow diagram (NPEs = non-process elements).

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	Mill A	Mill B	Mill C
Pulp production, a.d. metric tons/year	310,000	347,000	525,000
Wood type	100% hardwood or 100% softwood	100% hardwood or 100% softwood	85% hardwood/ 15% softwood or 100% hardwood
Recovery boiler type	Combustion Engineering	Babcock & Wilcox	Combustion Engineering
Black liquor flow rate, metric tons/h	40	75	140
Green liquor flow rate, m³/h	86	173	225
Average RGL dregs concentration, mg/L	1800	2300	700
Settling aid usage	Yes	Yes	Yes

ds = dry solids; RGL = raw green liquor.

1. Mill summary.

elements (NPEs), such as magnesium (Mg), silicon (Si), aluminum (Al), iron (Fe), manganese (Mn), etc., inadequate dregs removal enables these NPEs to accumulate in the liquor cycle. This, in turn, can make dregs more difficult to settle and to filter. In severe cases, it can clog up the filter cloth, substantially hinder green/white liquor production, and compromise pulp production.

About 10 wt% to 20 wt% of dregs on dry basis is char derived from molten smelt. How the recovery boiler is operated will have a great impact on the amount of char, and hence, the amount of dregs in the raw green liquor. A general belief is that a higher firing rate in the boiler would likely result in a greater amount of dregs produced.

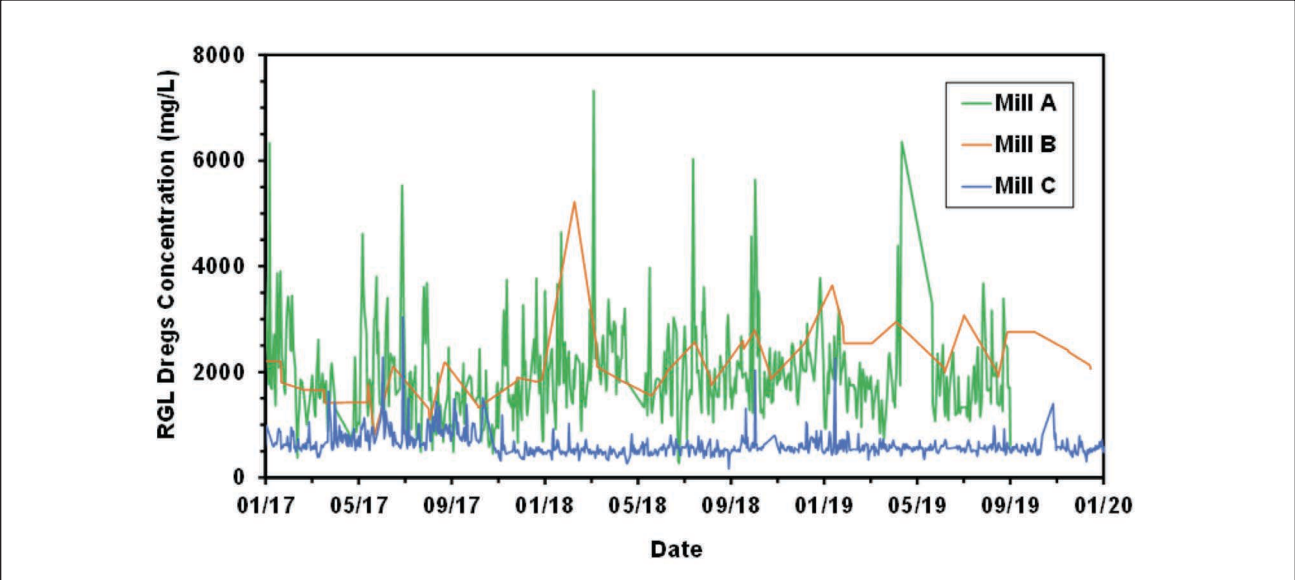
A systematic study was conducted at the University of Toronto to examine the effect of recovery boiler operation on the amount and the settling/filtering behaviors of dregs [2]. The study consisted of two parts. Part 1 involved laboratory experiments conducted to examine the effect of various black

liquor burning conditions on the settling and filtering behaviors of the char produced. Part 2 involved field studies to collect recovery boiler/mill operating data from three kraft mills and analyze the data using a multivariate data analysis (MVDA) program to determine if there are correlations between recovery boiler operating variables and the amount of dregs in the RGL. The preliminary results from Part 1 were presented at the 2020 TAPPI PEERS Conference [1].

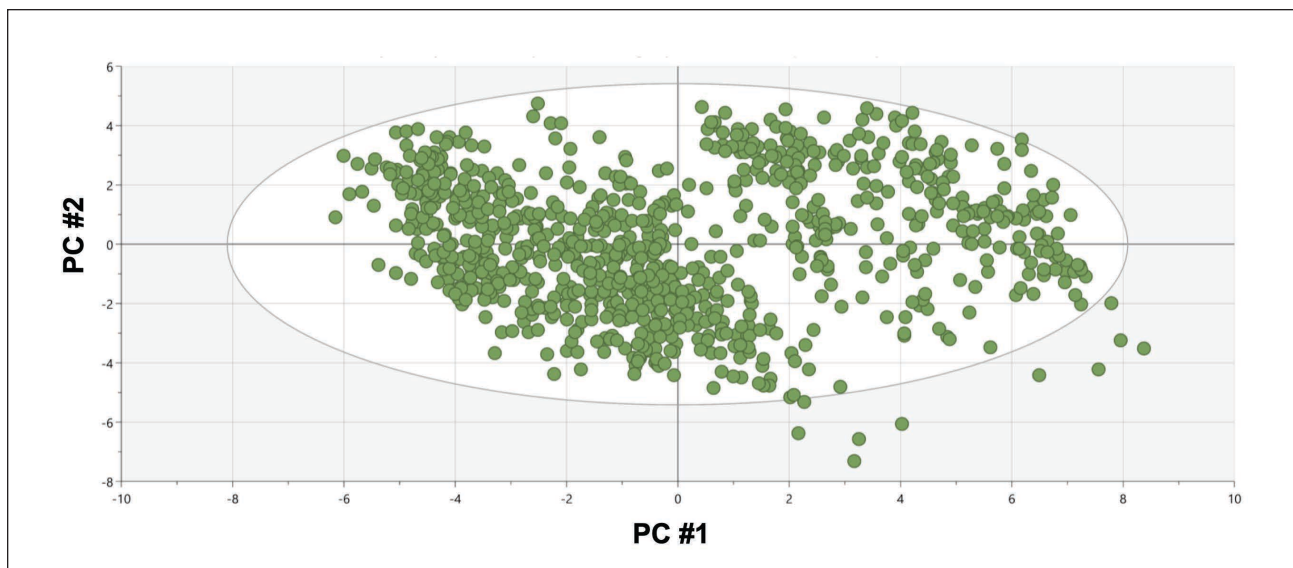
This paper summarizes the work performed in Part 2 of the study. The dregs problems at the three kraft mills involved in the study, the methodology behind MVDA, and the key results obtained from the investigation will be discussed in the following sections.

DREGS ISSUES EXPERIENCED

Table I summarizes the daily average operating data from three mills over a three-year period. Mills A and B have experienced persistent problems with poor dregs settling



2. Raw green liquor (RGL) dregs concentration at each mill.



3. Example scores plot (PC = principal component).

and filterability, whereas Mill C has experienced no dregs issues.

Figure 2 shows the RGL dregs concentration at each mill over a 3-year period. The RGL dregs concentration was consistently higher and varied significantly more at Mills A and B compared to Mill C. This implies that Mills A and B have more dregs issues than Mill C.

MULTIVARIATE DATA ANALYSIS (MVDA)

MVDA techniques have been used by our research group to identify and understand the causes of various problems in kraft pulp mills [3-5]. The techniques systematically analyze large datasets to reveal possible operating conditions that lead to a specific process issue. In this study, the impact of recovery boiler operation on dregs behavior at each of the previously described three mills was investigated using two MVDA techniques: principal component analysis (PCA) and partial least squares regression (PLS). The MVDA was carried out using SIMCA 15 (Umetrics AB; Umeå, Sweden), a commercially available software package [6]. The basic principles of each technique will be discussed briefly in the following sections. More information on PCA and PLS can be found in the SIMCA user guide [7].

Principal component analysis

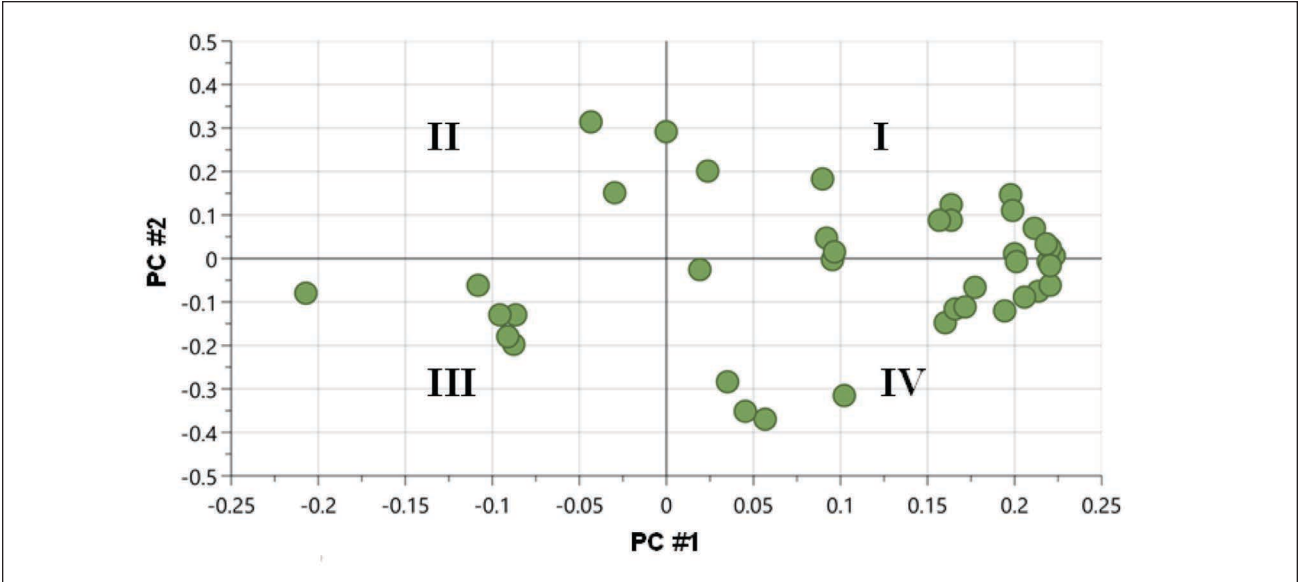
Principal component analysis (PCA) uses matrix algebra to calculate principal components and explain variability in datasets [6]. Each principal component that is calculated accounts for a percentage of the total variability in the dataset. The first principal component (PC #1) is a weighted linear combination of the variables calculated such that it maximizes the amount of variability in the dataset it accounts for. The second principal component (PC #2) is orthogonal to PC #1. The calculation of subsequent principal components, such as PC #3 and PC #4, aims to account for

as much of the remaining variability in the data as possible while maximizing the predictive power of the model [6]. The data points can be projected onto a plane formed by the lines of PC #1 and PC #2 to obtain a scores plot, an example of which is shown in **Fig. 3**. Scores plots help with identifying deviations from normal operation conditions. The center (origin) of the plot represents a combined average of all the data, and a 95% confidence interval of the data is represented by the ellipse. Observations located outside the 95% confidence interval of the ellipse represent deviations from normal operation.

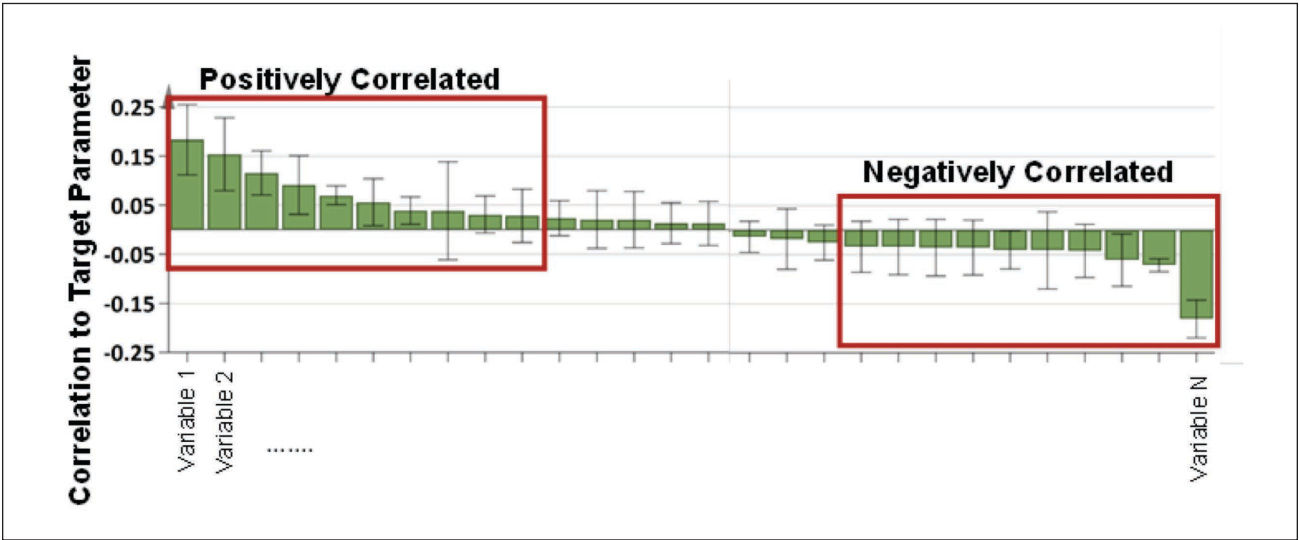
Figure 4 shows an example of a loadings plot, which is another type of useful plot obtained via PCA. Loadings plots can be used to identify correlations between variables. Variables located close together are positively correlated to each another, meaning when the value of one variable increases or decreases, the value of the other variable will change in the same manner. Variables located in opposite quadrants of the plot (i.e., one variable in quadrant I and one variable in quadrant III) are negatively correlated, which means that when the value of one variable changes, the value of the other variable will change in the opposite manner.

Partial least squares regression

Partial least squares regression (PLS) uses a combination of PCA and multiple linear regression to identify correlations between variables in a dataset and develop predictive models [6]. The dataset is split into two matrices: X and Y, with X containing all the variables except for the target parameter, which is what Y consists of. The target parameter is a variable that provides a good indication of occurrences of the process issue of interest. The model helps explain correlations between X and Y and expresses the ability of X to accurately predict Y. A coefficient plot is obtained through



4. Example loadings plot.



5. Example coefficient plot.

PLS that shows the influence each variable in X has on Y, which is helpful for identifying correlations. The coefficient values in the plot are centered around zero; values greater than zero indicate a positive correlation and values smaller than zero indicate a negative correlation. Higher absolute coefficient values indicate the variable is more likely to cause variations in the target parameter. Error bars of coefficient values passing through the zero line indicate the correlations found for those variables are inconclusive. **Figure 5** shows an example of a coefficient plot.

Operating parameters used as variables

Three years of daily average data for over 40 operating parameters related to recovery boiler operation at each mill were used as the variables in this study. The operating pa-

rameters that were used are listed in **Table II**. The RGL dregs concentration was used as the target parameter in this work. Any periods of recovery boiler shutdown and startup were removed from the datasets. The data from any days where the target parameter was not measured were removed from the dataset used in each model.

RESULTS AND DISCUSSION

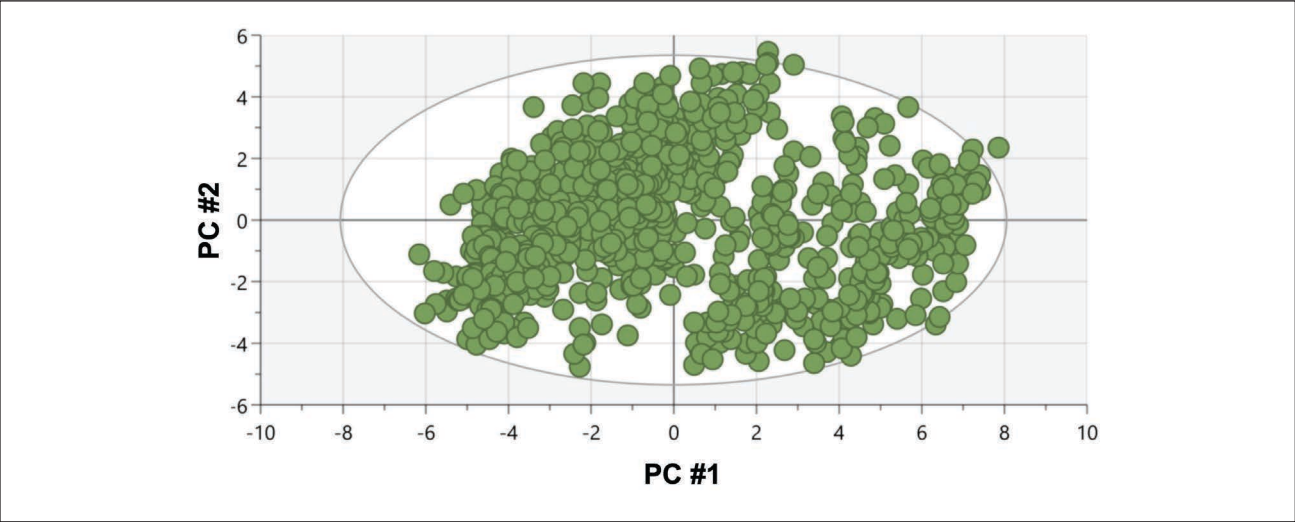
Mill A results

Figure 6 shows the scores plot in the first two principal components for the 916 data points in the PCA model for Mill A. Sixty-five percent of the variability in the data was captured by the six principal components calculated via cross-validation by the model. Twenty-eight percent and 13% of the total variability was captured by the first two

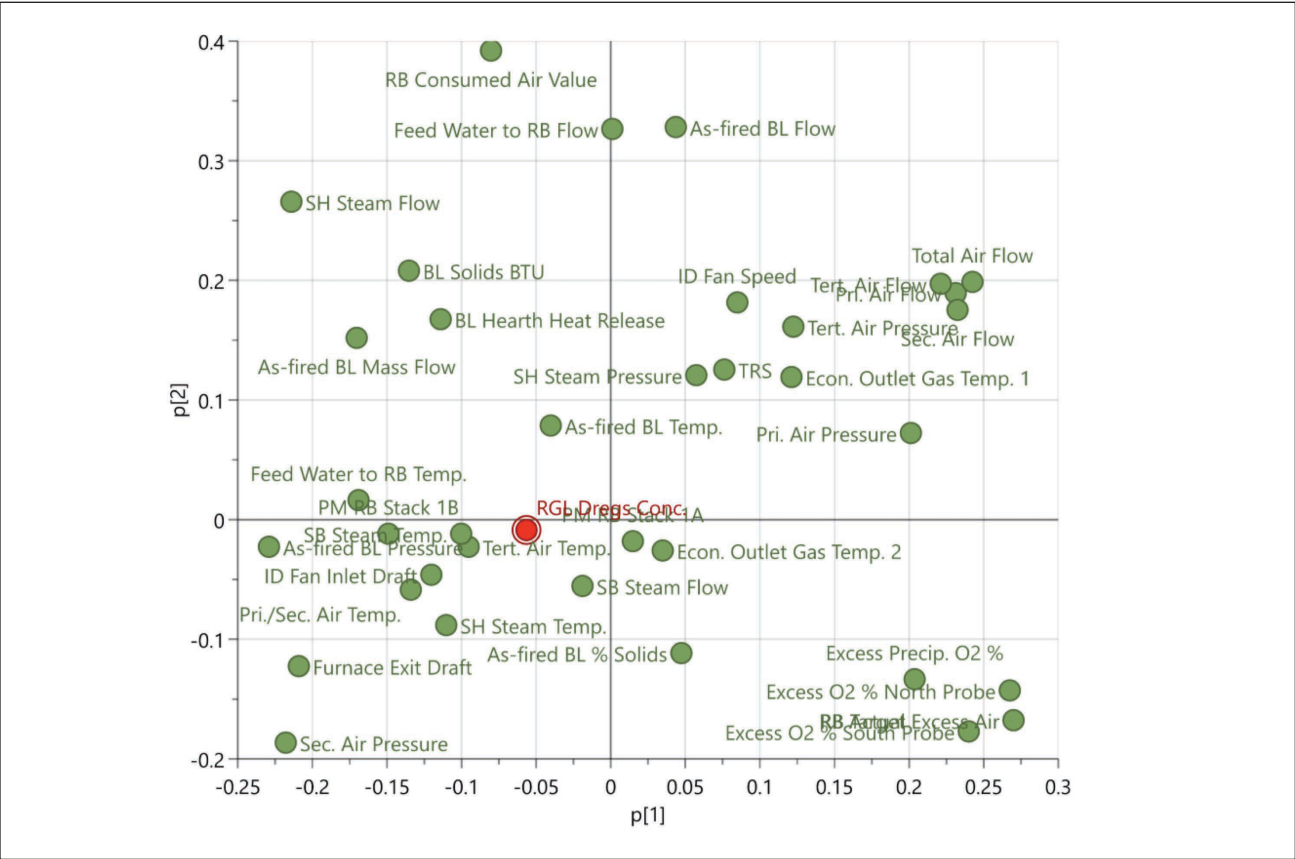
X Variable	Operating Parameter, Unit
Virgin BL Flow	Virgin black liquor flow rate, gal/min
Virgin BL % Solids	Virgin black liquor percent solids, %
As-fired BL Flow	As-fired black liquor flow rate, gal/min
As-fired BL % Solids	As-fired black liquor percent solids, %
As-fired BL Mass Flow	As-fired black liquor mass flow rate, lb/min
As-fired BL Temp.	As-fired black liquor temperature, °F
As-fired BL Pressure	As-fired black liquor pressure, psig
Pri. Air Flow	Primary air flow rate, Mlb/h
Sec. Air Flow	Secondary air flow rate, Mlb/h
Tert. Air Flow	Tertiary air flow rate, Mlb/h
Total Air Flow	Total air flow rate, Mlb/h
Pri. Air Temp.	Primary air temperature, °F
Sec. Air Temp.	Secondary air temperature, °F
Tert. Air Temp.	Tertiary air temperature, °F
Pri. Air Pressure	Primary air pressure (in H ₂ O)
Sec. Air Pressure	Secondary air pressure (in H ₂ O)
Tert. Air Pressure	Tertiary air pressure (in H ₂ O)
Feed Water to RB Flow	Feed water to recovery boiler flow rate, Mlb/h
Feed Water to RB Temp.	Feed water to recovery boiler temperature, °F
SH Steam Flow	Superheater steam flow rate, Mlb/h
SH Steam Temp.	Superheater steam temperature, °F
SH Steam Pressure	Superheater steam pressure, psig
SB Steam Flow	Sootblower steam flow rate, lb/h
SB Steam Temp.	Sootblower steam temperature, °F
SB Steam Pressure	Sootblower steam pressure, psig
GB Gas Temp.	Generating bank gas temperature, °F
Excess O ₂ %	Excess oxygen percent, %
Furnace Exit Draft	Furnace exit draft (in H ₂ O)
Boiler Bank Inlet Draft	Boiler bank inlet draft (in H ₂ O)
Boiler Bank Outlet Draft	Boiler bank outlet draft (in H ₂ O)
Econ. Outlet Gas Temp.	Economizer outlet gas temperature, °F
Econ. Outlet Draft	Economizer outlet draft (in H ₂ O)
ID Fan Inlet Draft	Induced draft fan inlet draft (in H ₂ O)
ID Fan Speed	Induced draft fan speed, rpm
CO Conc.	Carbon monoxide concentration, ppm
SO ₂ Conc.	Sulfur dioxide concentration, ppm
TRS Conc.	Total reduced sulfur concentration, ppm
NO _x Conc.	Nitrogen oxides concentration, ppm
Particulate (Opacity) RB Stack	Particulate opacity from recovery boiler stack, %
RB Actual Excess Air	Recovery boiler actual excess air, %
RB Target Excess Air	Recovery boiler target excess air, %
RB Consumed Air Value	Recovery boiler consumed air value, lb/min
BL Hearth Heat Release	Black liquor hearth heat release, MBtu/h

II. Operating parameters used as variables in multivariate data analysis (MVDA).

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6. Mill A principal component analysis (PCA) model scores plot for 3 years of daily average data.



7. Mill A PCA model loadings plot. See Table II for acronyms.

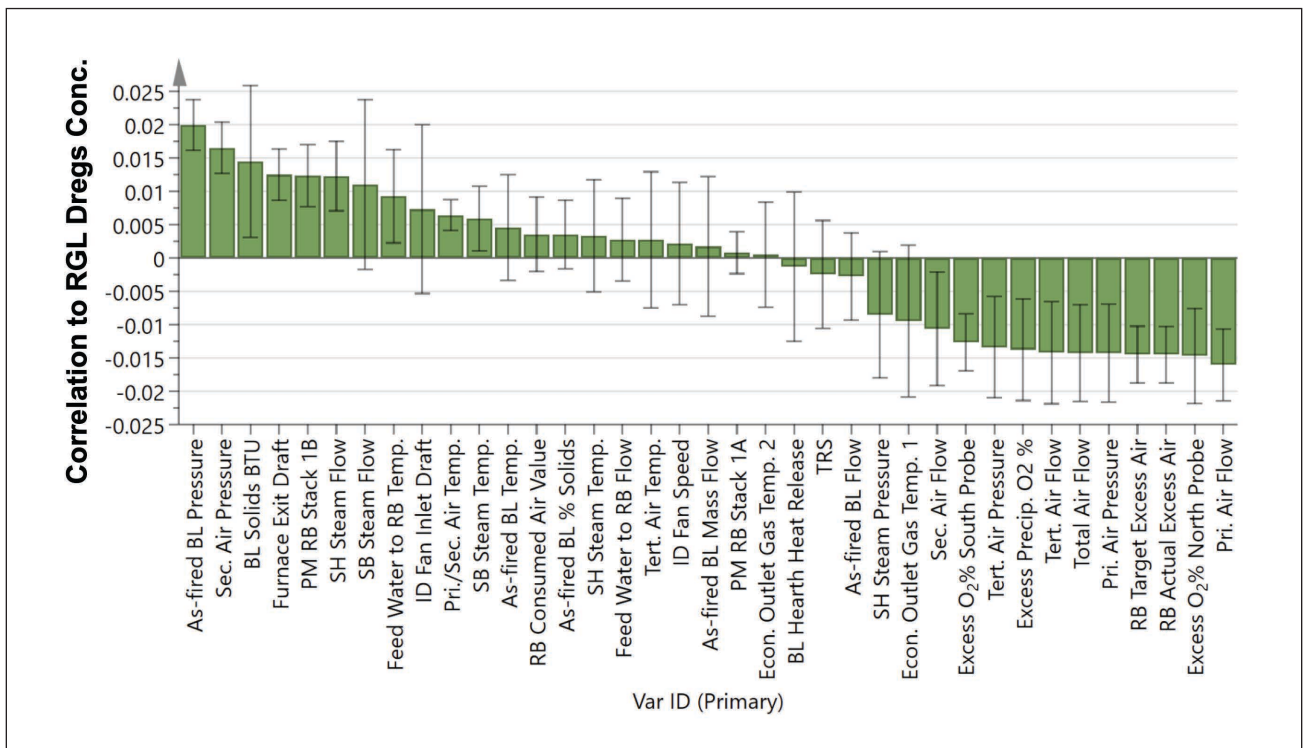
components, respectively. Most of the data points are within the 95% confidence interval, indicating that the model is a good representation of the operating data for the boiler.

Figure 7 shows the loadings plot for the model, and **Table III** lists the correlations that are implied by the position of the RGL dregs concentration on the plot in relation to other variables. The positive correlations of particulate matter (PM RB Stack 1A and PM RB Stack 1B) to RGL dregs

concentration suggests that char bed instability leads to high dregs concentrations at Mill A. During periods of char bed instability, more particulate matter is emitted from the recovery boiler. A PLS model was built based on the PCA model by assigning RGL dregs concentration as the target parameter. The resulting coefficient plot in **Fig. 8** shows the correlation of the variables in the model with RGL dregs concentration. Air flow rates (Pri. Air Flow, Tert. Air Flow,

Positive Correlations	Negative Correlations
Sootblower Steam Temperature	Economizer Outlet Gas Temperature 1
Tertiary Air Temperature	Total Reduced Sulfur
PM Stack 1A	SH Steam Pressure
Sootblower Steam Flow	Primary Air Pressure
ID Fan Inlet Draft	
Primary/Secondary Air Temperature	
PM Stack 1B	
Economizer Outlet Gas Temperature 2	
PM = particulate matter; SH = superheater; ID = induced draft.	

III. Mill A principal component analysis (PCA) model loadings plot correlations.



8. Mill A partial least squares regression (PLS) model coefficient plot. See Table II for acronyms.

Total Air Flow) and excess air and oxygen at different locations (Excess O₂ % North Probe, RB Target Excess Air, RB Actual Excess Air, Excess Precip. O₂%, Excess O₂% South Probe) were negatively correlated to RGL dregs concentration. This implies that a low extent of char burning leads to high dregs concentrations at the mill. When air flow rates and excess oxygen and air are low, the combustion does not proceed well, and hence, more char will end up as dregs in raw green liquor.

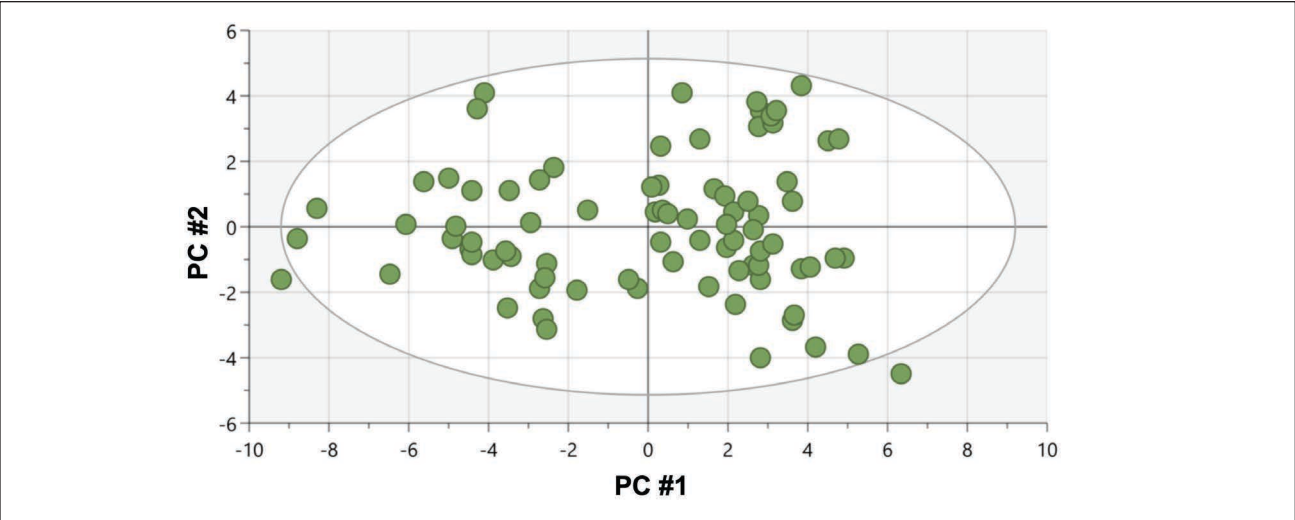
Particulate matter (PM RB Stack 1B) was again positively correlated to RGL dregs concentration, further suggesting that char bed instability leads to high dregs concentrations

at Mill A. The positive correlation of superheater steam flow rate (SH Steam Flow) to dregs concentration was also of interest. The correlation implies that a high recovery boiler load leads to high RGL dregs concentrations, as high superheater steam flow is generally a result of burning more liquor in the recovery boiler.

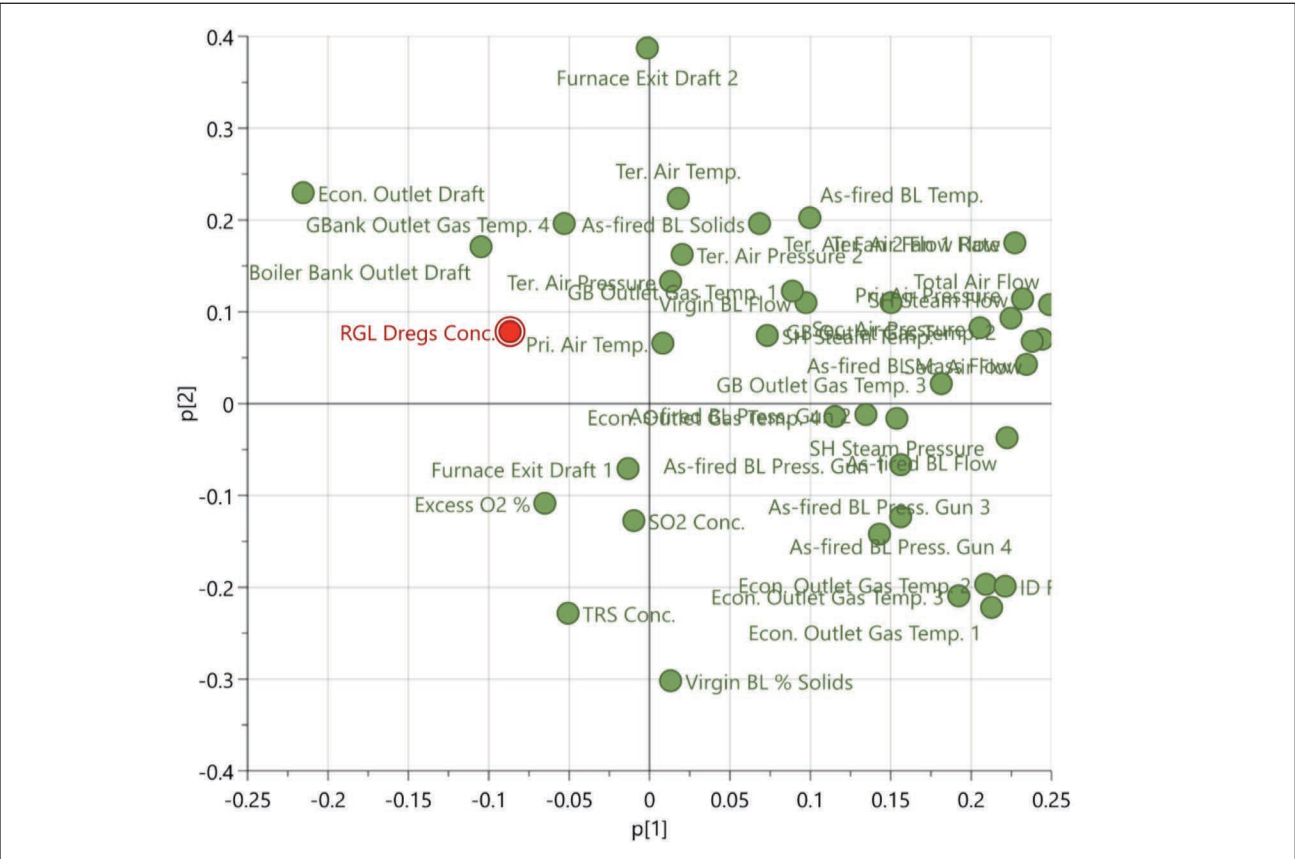
Mill B results

The PCA model built based on the data collected from Mill B contained 40 variables and 82 observations. The model calculated two principal components. The first component accounted for 33% of the variability in the data, and the

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9. Mill B PCA model scores plot.



10. Mill B PCA model loadings plot. See Table II for acronyms.

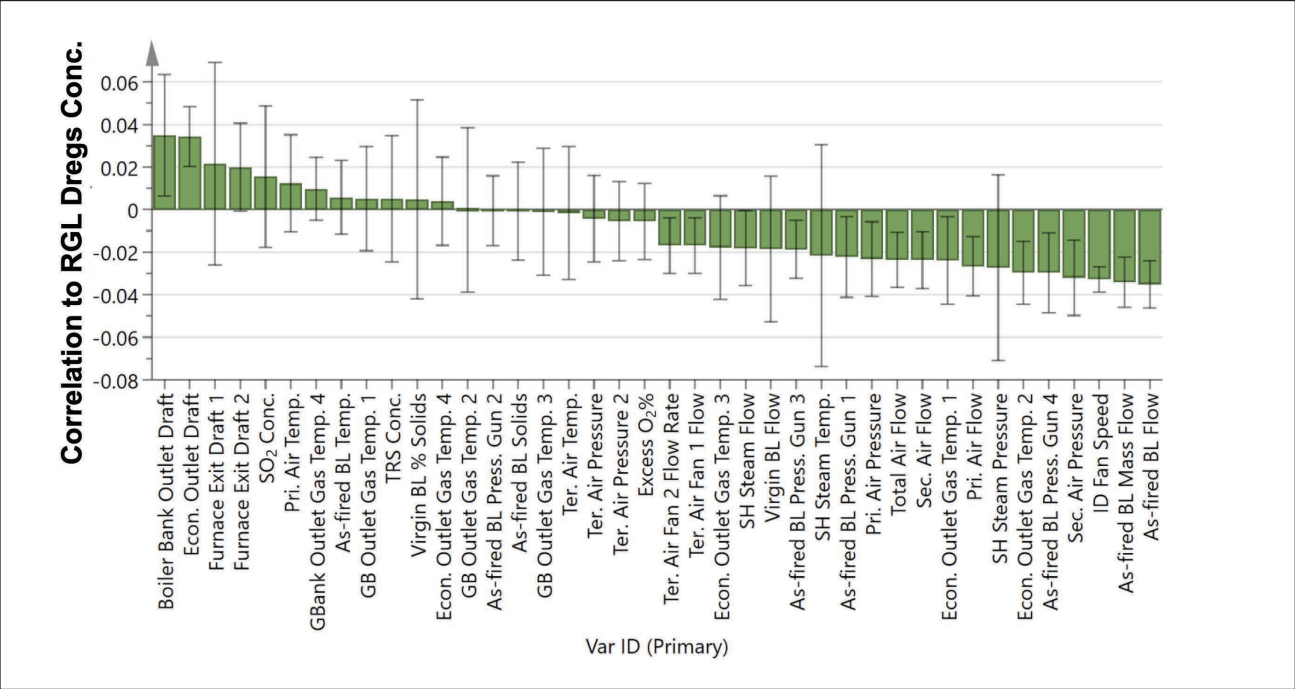
second component accounted for 10%. The scores plot is shown in **Fig. 9**.
The loadings plot for the model is shown in **Fig. 10**, and the correlations that are implied by the plot are listed in **Table IV**. The negative correlated variables suggest low firing load to the recovery boiler leads to high dregs concentrations at Mill B.
A PLS model was built using the data from Mill B with

RGL dregs concentration as the target parameter. The correlation plot for the model is shown in **Fig. 11**. Some positive correlations had high error bars and, thus, are inconclusive. The negative correlation of black liquor flow rate (As-fired BL Flow, As-fired BL Mass Flow) further suggests that high dregs concentrations occurs when the recovery boiler is at a low firing load. A low firing load to the recovery boiler can lead to low green liquor reduction efficiency.

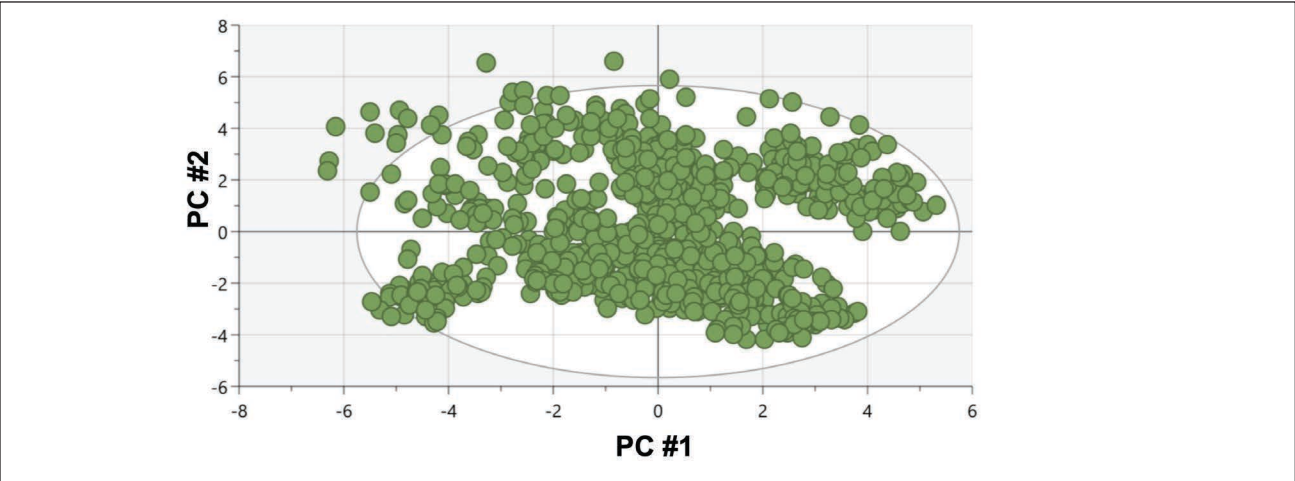
Positive Correlations	Negative Correlations
Boiler Bank Outlet Draft	Economizer Outlet Gas Temperature 4
GB Outlet Gas Temperature 4	As-fired Black Liquor Pressure Gun 1
Tertiary Air Pressure	As-fired Black Liquor Pressure Gun 2
Primary Air Temperature	As-fired Black Liquor Pressure Gun 3
Economizer Outlet Draft	As-fired Black Liquor Pressure Gun 4
	SH Steam Pressure
	ID Fan Speed

GB = generating bank; SH = superheater; ID = induced draft.

IV. Mill B PCA model loadings plot correlations.



11. Mill B PLS model coefficient plot. See Table II for acronyms.



12. Mill C PCA model scores plot.

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13. Mill C PCA model loadings plot. See Table II for acronyms.

Positive Correlations	Negative Correlations
Excess O ₂ East	TRS Concentration at 8% O ₂
Excess O ₂ West	Primary Air Flow
Tertiary Air Flow Rate	Boiler Bank Inlet Draft West
Tertiary Air Temperature	CO Concentration at 8% O ₂
SO ₂ Concentration at 8% O ₂	

O₂ = oxygen; TRS = total reduced sulfur; CO = carbon monoxide; SO₂ = sulfur dioxide.

V. Mill C PCA model loadings plot correlations.

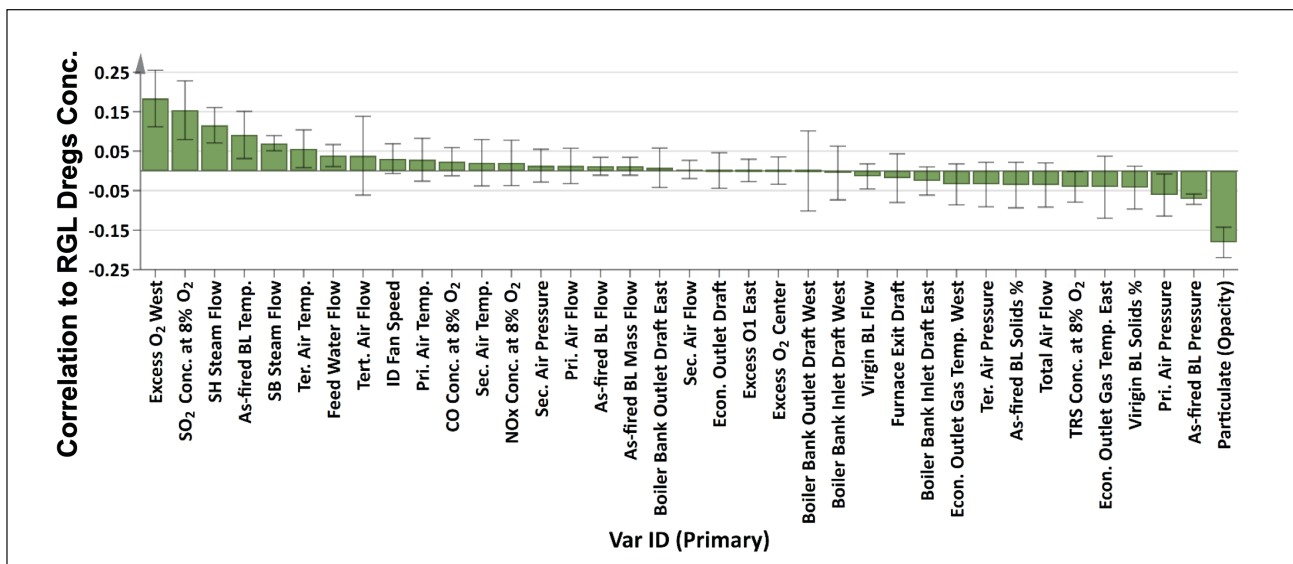
This means green liquor has a higher sulfate content, and as a result, a higher density. An increase in liquor density can make dregs more difficult to settle.

Mill C results

The data compiled from Mill C was used to build PLS and PCA models that contained 1006 observations and 38 variables. For the PCA model, seven components explained 62% of the total variability in the data. **Figure 12** shows the scores plot for PC #1 and PC #2, which accounted for 19% and 12% of the total variability, respectively.

The loadings plot for the PCA model is shown in

Fig. 13, and the implied correlations are listed in **Table V**. Excess oxygen (Excess O₂ East and Excess O₂ West) were positively correlated to RGL dregs concentration. High excess oxygen can be an indicator of low load operation, suggesting low firing load to the recovery boiler leads to high dregs concentrations at Mill C. This finding is further supported by the positive correlations of tertiary air flow rate (Tert. Air Flow) and temperature (Tert. Air Temp.) and the negative correlation of primary air flow (Pri. Air Flow). If less air is being used up or available at the primary and secondary air levels while total air flow rate remains constant, this can be an indicator of the recovery boiler operating at a low load.



14. Mill C PLS model coefficient plot. See Table II for acronyms.

Sulfur dioxide concentration (SO₂ Conc. at 8% O₂) is positively correlated to RGL dregs concentration. High SO₂ emissions can be indicative of char bed instability or low char bed temperature. This finding is further implied by the aforementioned correlations of air flow rate and temperature. Less air consumption at the primary and secondary air level can result in low char bed temperatures and hence more dregs.

A PLS model with RGL dregs concentration as the target parameter was constructed for the data from Mill C. The

resulting coefficient plot is shown in **Fig. 14**. Several of the same correlations obtained from the PCA model were also obtained from the PLS model, which further supports the implications of the PCA model. Furthermore, the negative correlation of as-fired black liquor pressure to RGL dregs concentration suggests the adverse effect of low firing load on dregs concentrations at the mill.

CONCLUSIONS

A systematic study was conducted to examine how recov-

ABOUT THE AUTHORS

We chose the topic of dregs to research because it has been a persistent problem for many mills. Dregs issues have not been well studied, and our research represents one of the first in-depth studies on dregs settling and filtering issues. This research specifically builds on research done previously within our research group at the University of Toronto.

The most challenging aspects of this research was selecting a target parameter measured at mills that is indicative of dregs settling and filtering issues. We addressed this by seeking advice from companies participating in our study.

This research allowed us to gain an understanding of how powerful and useful multivariate data analysis (MVDA) can be in identifying correlations in datasets and identifying root causes of issues. The most interesting finding was that low recovery boiler load at some mills seems to lead to higher amounts of dregs in raw green liquor.

Mills can use this information to identify operating conditions that may lead to issues with dregs



Maggs



Jones



Tran

settling and filterability. Our next step is to summarize all the key results obtained from this research program into a technical article and present it at a future TAPPI Conference.

Maggs is a graduate student and Tran is professor emeritus in the Department of Chemical Engineering & Applied Chemistry at the University of Toronto in Toronto, ON, Canada. Jones is a research fellow at International Paper in Loveland, OH, USA. Email Tran at honghi.tran@utoronto.ca.

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ery boiler operation may affect the concentration of dregs in raw green liquor using SIMCA, a multivariate data analysis (MVDA) program. The results suggest that a low liquor firing load, insufficient time for char to burn in the boiler, and an unstable or “cold” char bed are the main contributing factors.

Since operating conditions vary from mill to mill and boiler to boiler, an MVDA study needs to be carried out for each mill and boiler individually. Key boiler operating parameters that are helpful for identifying the potential causes of high dregs concentrations include low black liquor flow rate, low as-fired black liquor pressure, high SO₂ emissions, and high excess oxygen. **TJ**

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