A Laboratory Simulation of a Rotary Vacuum Drum Brownstock Washer

Hugh E. Muller Jr.
Western Michigan University

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A LABORATORY SIMULATION OF A ROTARY VACUUM DRUM BROWNSTOCK WASHER

by

Hugh E. Muller Jr.

A Thesis
Submitted to the
Faculty of The Graduate College
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A LABORATORY SIMULATION OF A ROTARY VACUUM DRUM BROWNSTOCK WASHER

Hugh E. Muller Jr., M.S.
Western Michigan University, 1987

Mass balances can quantify the dilution and thickening of a liquor/fiber suspension on a brownstock washer. However, the complex displacement process necessitates an empirical approach. Given empirical data, washers can be optimized through use of efficiency factors with mass balances.

Because empirical data is difficult to obtain, a laboratory washing method was developed to empirically generate displacement efficiencies on pulp under mill washer conditions. Reproducible data generated by this method resulted in a displacement/dilution function as seen on mill washers. A laboratory simulation using mill samples, exclusive of problems for one vacuum drum, resulted in comparable efficiencies with less than 10% error.

The relationship between dilution and displacement was examined with a system constant. System constants, which account for the inaccessible dissolved solids portion in the exiting mat, were determined.
ACKNOWLEDGEMENTS

Much appreciation goes to S. D. Warren Paper Company, Muskegon, MI, for supplying samples and data from their brownstock washer.

I would like to particularly thank Reid Miner of the NCASI, National Council of The Paper Industry For Air and Stream Improvement, for his suggestions and contribution of insight into brownstock washing. In addition, sincere gratitude is due the entire staff of the NCASI, Central Lakes Region, for their timeless help with problems encountered along the way.

An expression much greater than "special recognition" goes to my wife, Susan, for her endurance and constant encouragement. Recognition also goes to my children, Alex and Erin, whom unknowingly brought things into perspective.

Hugh E. Muller Jr.
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CHAPTER I

INTRODUCTION

Problem

The universal objective of washing brownstock pulp is to remove the maximum amount of soluble inorganic and dissolved organic material by using the minimum quantity of fresh or process water. This removal results in: cleaner pulp that reduces bleaching costs, less pollutants carried to the sewer through subsequent operations, and recovery of costly pulping chemicals. A sacrifice for this must be made however, as cleaner pulp is the result of increased amounts of wash water. This results in greater quantities of steam needed to evaporate the wash water in the filtrate. An improved efficiency in a washing process is seen if the liquor dilution is minimized or kept constant while chemical recovery is increased.

The optimization of a washer's efficiency is an important cost incentive, however the resultant mill effluent quality may dictate additional operational parameters. A study by Wong, Wearing, and Uloth (1) illustrates a case where brownstock washer dilution factor correlates with toxicity, BOD, COD, sodium, lignin, and color of black liquor carry-over in the bleach plant effluent. Another
study at Paprican (2) indicated a similar correlation with recommendations that future studies be made in the laboratory with scaled down mill washing equipment. This recommendation was made because of the trouble they had in acquiring mill samples for their research.

Two processes described by Perkins (3) are involved in the washing of wood pulp fibers: dilution of stock in the vat and thickening on a filter drum, and a subsequent dilution or displacement of the liquor in the fiber mat with wash liquid. The fabrication of a washing system must be made with these mechanisms in mind. Mass balance approaches can quantify the mechanism of dilution and thickening a liquor/fiber suspension; however an empirical approach is needed to explain the complex displacement process.

A displacement efficiency rating can be determined with empirical data and used in conjunction with system balances to analyze the carry-over of a system and thus optimize within operating parameters. The displacement efficiency is a result of many independent and interdependent variables.

Lee (4) states that efficiency ratings have mostly been based on empirical data from existing systems. In addition, he explains that these ratings give only gross approximations of the behavior of similar washing systems. He states that the usefulness of an efficiency rating
would be enhanced if it could be accurately predicted for a particular washing system. Field studies that result in accurate efficiency ratings over a wide range of dilutions for different operating conditions and pulps are very difficult, if not impossible.

Objective

In this study, a laboratory washing method was developed to empirically generate displacement efficiencies on wood pulp fibers under actual mill washer conditions. Initially, an apparatus was constructed to simulate the displacement washing function as seen on a brownstock vacuum drum washer. The apparatus was then tested to see if it performed in the manner as expected by thickening, and displacement washing. A comparison study with mill samples run through the apparatus and mill results was completed to test for simulation feasibility. In addition, the relationship between displacement and dilution was examined. Ideally the displacement efficiency should behave as a function of dilution for specific pulps under different washing conditions.
CHAPTER II

REVIEW OF SELECTED LITERATURE

History

Development of the kraft industry began with its proposition by Dahl in Danzig in 1879, and the later construction of a mill in 1891. This was the first pulp industry to realize the necessity for recovering the expensive process chemicals. At that time, the sulfite industry was operating with less expensive chemicals that were drained to the sewer in the blow pits.

In addition to recovering expensive kraft chemicals, it was important to obtain a pulp that was essentially free of soluble impurities for the production of strong bleachable fibers. The oldest method of washing pulp began with the sulfite process by merely flooding the blow pit pulp with water and allowing it to drain. To solve its technical wash/recovery problems, the kraft industry borrowed the sugar industry’s diffuser method. This was similar to the present day technique of washing in the digester.

Later in the 1930’s, filter washing was introduced to alleviate problems that were occurring with bleaching. It was then found that minimal amounts of water could be used
in the production of cleaner pulp, resulting in higher efficiency chemical recovery operations. After World War II most of the new washing installations in America were of the filter type, while in Europe the diffusion method predominated.

Today there are many types of brownstock washers in use. They include the vacuum drum filter washer, the diffusion washer as more commonly seen in a continuous digester, the rotary pressure washer, the horizontal belt washer, the wash press, and the extraction press. It is intended here to focus on the vacuum drum filter washer, which is indicated by Rydholm (5) to be the major method of washing in North America.

**Rotary Vacuum Drum Washers**

The washing of pulp is most commonly accomplished through the use of rotary vacuum filters. A vacuum filter, or drum, is immersed in a vat and fed with low consistency pulp. As the drum turns, a vacuum pulls from the inside of the filter resulting in adherence of a pulp mat to the surface. This is known as the dilution/thickening phase, resulting from prior heavy dilution to obtain a low consistency slurry, followed by dewatering and mat formation. As the drum rotates further, a set of showers spray wash liquid onto the pulp mat. Displacement of the remaining liquid in the pulp mat by the shower liquid
occurs here as shown in Fig. 1. Rotation continues with vacuum applied and subsequent removal of the pulp mat.

The phases described for a vacuum filter washer are shown in Fig. 2. Extraction of liquid, as a result of the internal vacuum, occurs from the sheet formation zone to the discharge zone. During discharge the differential pressure must be removed so the sheet can break loose from the drum. Valve-type filters use a fixed valve in the cylinder to allow the application of vacuum in all zones except discharge. The pulp mat is formed on a plastic or metal face on the drum. This filter media is between 25 and 40 mesh. The inlet stock to the vat is at .75% to 2.5% o.d. (oven dry) consistency, and the exit mat is at 10% to 20% o.d. consistency.

Fig. 1 Displacement Principle (Smook)
The relation of a vacuum drum to an entire washing system is seen in Fig. 3. Although this illustration is for a three stage washer, washing systems can have more or less stages. Pulp from the digester is blown into the blow tank at about 10% fiber o.d., and there diluted to about 4% o.d. with filtrate from the first drum washer filtrate tank. This diluted pulp is then further diluted by the first filtrate tank in the knotters to about 1.25% o.d. fiber before washing. The low consistency pulp then enters the vat of the first washer drum. As previously described, the pulp is washed on the drum and exits to the next drum. However, prior to the next drum, a repulper
Fig. 3 Three Stage Brownstock Vacuum Drum Washing System
takes the higher mat consistency pulp and mixes it with filtrate from the subsequent drum filtrate tank. This thickening, displacement washing, and rediluting is repeated for the second and third drum, and then the pulp sheet is discharged from the system.

The washwater enters the system through the showers on the last drum. Because the pulp flow direction opposes the shower flow, the system is termed countercurrent. Shower liquid on the third stage is used in displacing the cleanest mat liquid. This displaced liquid or filtrate then travels to a filtrate tank and onto the next stage where the cycle is repeated for the first stage. Filtrate from the first stage is used for dilution, with the remainder sent to chemical recovery for evaporation. In addition to shower liquid, the filtrates from the second and third drums are used for dilution in the repulpers of the first and second stages. An approximate dissolved solids (DS) content of the shower liquid on the third stage and the filtrate from the first stage is respectively 0% and 16%.

Level indicators on the filtrate tanks maintain a constant dilution of the shower liquid to the pulp on all three stages. The vacuum drums are elevated from the filtrate or seal tanks. This elevation allows for development of a vacuum as the filtrate flows down the drop leg from the drum to the seal tank. Generally 20 to 30 ft
of vertical drop is required to draw the liquor and air through the valve-type filters into the drop leg.

Brownstock Washer Variables

The degree of removal of dissolved solids and soluble inorganics in kraft pulp is affected by several variables. These variables are described by Korhonen (6) as being fixed by washer design and controlled during washer operation. He classifies the controllable variables as independent and interdependent. Independent variables are classified as those which when manipulated do not have a significant impact on others. Interdependent variables are those which affect other variables when altered. A listing of these variables is shown in Table 1.

Table 1

<table>
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<th>Controllable Variables Affecting Drum Washers</th>
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<td>Defoamer Usage</td>
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<td>Sheet Removal System</td>
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Shower Flow

The amount of shower flow is the most important variable which affects losses. Dilution factor is
expressed as the pounds of excess shower liquid (i.e. over that required for complete mat liquid displacement) per pound of oven dry pulp. An increase in dilution factor results in recoverable chemical gains to a point, where the cost of increased evaporation must be weighed. Regulation of the shower flow is usually accomplished by measuring the dissolved solids in the last stage filtrate.

**Shower Distribution**

Distribution of the shower flow among the shower pipes and number of shower pipes, (or weir structure and location), all affect the quality of shower flow. Complete shower coverage of the pulp mat is important, as areas of excess or insufficient flows will either "waste" the fluid or result in poor localized washing. Placement of shower bars which allows the pulp mat to be flushed back into the vat, results in inefficient dilution washing. Also, plugging of shower pipes is common which can again decrease shower efficiency.

**Shower Temperature**

Temperature of the wash liquid also affects a washer's efficiency. Washing is poor at both cold temperatures and at those above the boiling point of the shower liquid. At temperatures less than 60°C the fiber structure is somewhat closed because the hemicellulose has not
softened. A high temperature will reduce efficiencies by promoting flashing in the vacuum leg. The likelihood of this occurring is in the first stage where the pulp is still at a high temperature from the previous cook.

Production Rate

The problem with production rate variations is that shower dilution cannot always follow the changes. This results in both over and under dilution during the production swings. A more reasonable dilution can be achieved if a feedback unit connecting pulp flow control to the washer, is installed. If this occurred, according to Korhonen (7), losses should increase linearly with increased pulp loading.

Defoamer Usage

Air entrainment occurs as a result of air entering the pulp mat on the washer face. This air allows the liquid to be driven from the mat, however it must be minimized to avoid the problem of foaming. Entrainment is present in both the filtrate and in the pulp mat. Surfactants in defoamers are used to reduce the entrained air and thus the foaming action, which results in improved drainage. Also, an increased residence time in the filtrate tanks allows for a reduction in foam.
Sheet Removal System

Sheet removal systems include steam and air doctors, and take-off rolls. The take-off roll does not always clean the drum's surface, however liquor blowback is not a problem. Steam doctors result in blowing some of the filter pocket liquor back into the sheet at high pressures. The blowback on the steam doctor increases with steam pressure. An increase in filtrate liquor temperature, resulting in flashing, can also occur on a steam doctor. Air doctors give sufficient cleaning and are more economical than steam doctors. Generally steam or air doctors should be operated at the lowest possible pressure that results in keeping the drum surface clean.

Drum Speed

Residence time and mat thickness are affected by drum speed. Poor washing is seen with either too thick or thin a mat, therefore an optimal drum speed exists. At low drum speeds, a high vacuum due to reduced dilution flow and increased flow resistance, results in low sheet consistency. Poor washing at low drum speeds can also be the result of easily occurring sheet plugging. At high drum speeds poor washing is the result of air entrainment, low sheet diffusion time, and high blowback. Drum speed must be optimized with the opposing factors, sheet diffusion

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time and vat consistency in mind. Diffusion washing in the vat is improved when drum speeds are increased, because the vat consistencies can be reduced.

**Vat Consistency**

Vat consistencies are changed by manipulating a dilution valve setting. As stated, low consistencies result in better diffusion washing, and in addition, sheet formation is improved, which results in better drainage. At higher consistencies poor formation and sheet plugging can occur. It is seen that the interrelation between vat consistency and drum speed must be considered when tuning a washer system.

**Vat Level**

Vat level depends on drum speed and dilution valve setting for a given rate of production. Ideally the vat level should be kept as high as possible to allow for low vat consistencies and relatively low drum speeds.

**Drum Vacuum**

Vacuum levels are set by system design. Variables which affect vacuum are shower flow, seal tank level, drop leg height, vat level, production rate, drum speed, and shower temperature. As vat consistency is increased, vacuum levels decrease. Washing problems can be detected by
monitoring vacuum levels. Decreased vacuum may indicate seal leakages or flashing. Increased vacuum may result from decreased drainage rates, or plugging.

**Black Liquor Characteristics**

Wood species, cook liquor quantity and content, and the degree of delignification are responsible for the characteristics of black liquor. Depending on the type of wood, the percentage of major components i.e. cellulose, hemicellulose, and lignin, may vary. This variation is carried on to the dissolved organics in the black liquor. Kappa numbers relate the degree of lignin removal from a cook, thus a low kappa relates to lower amounts of lignin left in the pulp. Less lignin left in the pulp results in more dissolved in the black liquor. Chemicals which go into a cook also end up as soluble inorganics in the black liquor. In a kraft process, cooking chemicals comprised of Na$_2$S and NaOH end up as the following major components in black liquor: Na$_2$CO$_3$, NaOH, and Na$_2$S.

Black liquor in the blow pit is roughly at 16% dissolved solids. According to Schlossnagle (8), of that, 28-40% is inorganic and 60-73% is organic. At lower dissolved solids content, black liquor is very foamy. As concentration increases, viscosity increases from 0.5-100 cP. A decrease in viscosity is seen with temperature elevation. Specific gravities generally increase with
greater percent solids. Temperature increases result in lower specific gravities for a given solids content. Different ratios of organic to inorganic matter at a defined concentration and temperature result in different specific gravities. Those with a higher organic content result in an increased specific gravity.

Drainage Rate

In a washing operation, a pulp's drainage rate, or freeness is dependent upon pulp consistency, viscosity of the liquid, the amount and size of suspended material in the liquid, the fiber itself, type of cook, pH, additives, and the force exerted on the mass. Freeness testing is used primarily for measuring pulp suspensions in regard to paper machine formation. This method of measuring the passage of liquid through a fibrous mat is not accurate when used with washing equipment. Perkins (9) states that the variables mentioned above have such an effect on drainage rate, that only empirical measurements on equipment which simulate and/or exactly duplicate mill conditions are reliable for a point in the system.

Entrained air present in the liquid portion of a suspension can result in a significant reduction in drainage. This is most evident when trying to displace a strong black liquor with a weaker black liquor having air in suspension. Air bubbles block flow and reduce drainage.
because they take on properties of a solid. Acting as solids, they are filtered out by the fiber mass.

Washer Losses

As previously stated, soluble inorganics and dissolved organics are washed out of the pulp on the washers. The soluble inorganics have traditionally been reported as soda losses (salt cake—\(\text{Na}_2\text{SO}_4\), or sodium). The dissolved organics consist mostly of lignin and acids.

Types of Sodium

Sodium losses are determined for a brownstock washer so that a complete mill balance for sodium can be made, and also for evaluation of that washer's efficiency. As explained by South and Gulley (10), total sodium from a washer sample consists of three parts: bound sodium, wash water sodium, and washable sodium. The total sodium from a sample can be measured fairly easily with a flame spectrophotometer; however care must be used in that a measure of only the sodium attributable from the pulping process is being measured and not that, for instance, from well water on a decker's shower. Bound sodium is the amount of sodium that is adsorbed onto the fibers. It is termed the amount of sodium that would remain with the pulp if there were an infinite number of conventional brownstock washing stages. Wash water sodium is that portion which is
introduced to the pulp through the shower fluid. Washable sodium can be arrived at by subtracting the bound and wash water sodium from the total sodium. It is a measure of the sodium portion which can be removed from the pulp on a washer. This is the portion that is used for washer evaluations.

A flame spectrophotometer test by South and Gulley on loblolly pine pulp at a kappa number of 65 resulted in the following breakdown. Washable salt cake accounted for 62.1%, wash water salt cake 8.6%, and bound salt cake 29.3%. As previously discussed, an approximate organic/inorganic dissolved solids ratio is 2:1. With that in mind, in the above example, the bound salt cake portion is significant.

Work by Grahs (11) indicates that adsorption by lignin on the pulp is negligible. His results also show a large difference between the washing of lignin and sodium in a laboratory displacement cell. Residence time of sodium in packed beds of pulp was longer than that of lignin. This is most easily explained by the larger size of the lignin molecules having smaller mass transport times between the flowing and stagnant liquors. It was also shown that the ratios of washed sodium and lignin varied. This was demonstrated by simulation, by decreasing bed length and increasing flow velocity, resulting in increased lignin yields and decreased sodium.
The ratio of sodium to organic matter washed out of the pulp may vary depending on wood species, cook conditions, and washing conditions. It is therefore important, recommends Perkins (12), to measure losses on a dry dissolved solids per unit of pulp basis. At different locations through the process, a determination of equivalent sodium contents could be then made for the black liquor dissolved solids concentration.

Solute Removal

Different mechanisms are responsible for the washing of a pulp suspension. These fundamental mechanisms are important to the understanding of washing in a vacuum drum. Several divisions between these washing mechanisms can be made.

Micro Washing

Ranhagen (13) classifies washing on two levels: micro or macro. On the micro level black liquor is being moved from the inside of the fiber to the outside. This movement is accomplished by three methods: diffusion, squeezing, and changes in swelling.

In a pulp suspension some liquid does not participate in physical flow. There is always some that is trapped between fibers and in fiber voids. The movement of this liquid into the flowing liquid occurs by diffusion. These
molecules of dissolved solids move from areas of higher to lower concentration. Although diffusion is slow, it significantly increases with a temperature increase. Bubbles of foam, as a result of air entrainment, can inhibit diffusion and decrease the washer's overall efficiency. Although the greatest degree of diffusion occurs in the dilution stage, diffusion is ongoing throughout the drum zones where there is a concentration gradient.

Trinh and Crotogino (14) worked on determining the rate of diffusion in the dilution stage. They did this by measuring solute concentrations of a stirring pulp slurry over time. The measurements were made after a pulp sample was introduced to a tank of deionized water. Their results were termed as three mass transfer processes: mixing, rapid diffusion, and slow leaching. Mixing of the wash fluid and the pulp within the lumens and between the pulp fibers occurred very quickly. An equilibrium value of solute removal from the fibers was reached in 3 to 8 seconds in pulps having consistencies less than 15%. A slow leaching phase occurred beyond the two day limit of their experiment.

Squeezing liquid out of the fiber cavity occurs above 18% fiber content. This phenomenon is seen in washer presses and in wash zones of continuous digesters. A change in pH values can result in fiber contraction due to variations in fiber wall thickness as the outside
dimensions remain constant. At high pH values the fiber wall is usually the thickest. Contraction begins at pH values less than 13.

**Macro Washing**

Macro washing is the removal of the black liquor from the pulp suspension. Extraction which consists of mixing and dewatering is one method of removing the liquor. The other method is displacement, where a solid is being separated from a solid with minimum dilution. Ideally with plug flow all of the liquid in a pulp mat would be replaced exactly by the shower liquid. Instead, the laminar flow results in a velocity gradient in the pore structures, i.e. flow rates may be less at the wall of a pore due to viscous drag. Mixing of shower and mat liquid, and channeling also contributes to a less than ideal plug flow.

**Channeling and Mixing**

Foam can channel the wash liquid through the mat so that all of the fibers are not washed properly. Lee (15) states that mixing can occur from diffusion, and channeling which is induced by local variations in permeability. When channeling exists, the amount of mixing attributable to diffusion is negligible. The primary control of channeling is a result of the differences in density between
the shower liquid and the mat liquid. Ideally the displaced liquid should have a higher density than the displacing liquid. Therefore, in a conventional drum washer, the shower liquid should have a lower specific gravity than the mat liquid.

He suggests a mobility ratio, which is the ratio of the displaced liquid's mobility to the displacing liquid's mobility. Mobility is defined as a ratio of the medium's permeability to the fluid's viscosity. Channeling is self perpetuating with mobility ratios greater than 1 and suppressed with ratios less than 1. He also found that traces of high molecular weight polymers in wash liquor can reduce channeling. Channeling can also be reduced by uniform pulp packing in the blow pit or diffuser.

**Solute Adsorption**

Dissolved substances in the liquor are adsorbed onto the fibers depending on the wood species and the type of solute and its concentration. The rate at which adsorption can occur is controlled by the particular sorption equilibrium. Work by Hartler and Rydin (16) has shown that the Langmuir isotherm can describe sodium adsorption. This isotherm is nonlinear; a limiting value of the substance adsorbed is approached as the liquor concentration increases. A schematic of a pulp suspension by Gullichsen and Ostman (17) showing the displacement action on fibers
is shown in Fig. 4. The immobile closed volume represents a portion on the fiber surface in which the sodium is sorbed (bound).

It was found by Rosen (18) that the degree of sodium adsorption is a function of pH, degree of cooking, and wood species. Fig. 5 shows that the amount of sorbed sodium decreases with a reduction in pH. The mechanism for this is described by two functional groups in the pulp: the first dissociating at a pH above 3, and the second at pH values above 9. The first functional group, which is influenced by wood species, is completely dissociated and has no further capacity for sorption of sodium ions at a pH of 6 or 7. This is a carbosilic group, which is

![Diagram of Pulp Suspension]

1 - Flow Channel, 2 - Immobile Closed Volume, 3 - Fiber Solid

Fig. 4 Schematic of Pulp Suspension

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present on both the carbohydrate and lignin fractions. The second functional group, attributable to phenolic hydroxyls on the lignin portion in the pulp, is not affected by kappa number or wood species. In contrast to Hartler and Rydin's work, Rosen indicates that dissolved sodium concentration has only a minor influence on the sorbed sodium in the washed pulp. This indicates that changes in wash water quantity should not have an effect on sorbed soda. Also, with higher kappa numbers and softwoods instead of hardwoods, an increase in sorbed sodium was seen. Wash temperature had no effect on the sorbed sodium losses in the pulp.

![Fig. 5 Effect of pH on Sorbed Sodium](image_url)
Washing Efficiency

Countercurrent Washing

The displacement of cooking liquor with water is the objective of washing. As explained by Tomiak and Lauzon (19), simple washing differs from countercurrent washing. Simple washing involves the percolation of a fixed bed of pulp with wash water. In contrast, countercurrent washing is the multiple exchange of solute from the pulp to the wash water. Here the pulp is getting progressively cleaner in the direction opposed to the shower liquid becoming dirtier. Mathematical explanations consisting of the theory of miscible fluid displacement from porous media used to explain simple filter cake washing cannot be used with complex countercurrent pulp washing. A uniform starting concentration in a fixed bed, which is not the case in pulp washing, was the basis of derivation for these equations. This fundamental theory can explain a washing stage, however problems arise in connecting stages and in introducing recycle streams. As of yet there is no universal notation system for the complex mathematical explanations of countercurrent pulp washers. In addition, terminology specific to the paper industry instead of that used in general filter cake washing, complicates matters.

Countercurrent washing can be analyzed by two approaches: the direct application of physical models
which describe the washing process, and the use of "black boxes" that split a washing process into blocks for system analysis by formal mathematical treatment. Fundamentally, physical models are preferred, however they are complex for stagewise operations.

Washing Models

Solute sorption can contribute significantly to a mill's overall salt cake losses. Recovery operations generally recover from 95-99% of the initial Na$_2$SO$_4$. The amount which is lost due to sorption varies between operations and therefore must be determined individually based on experimental extraction techniques. Hartler and Rydín (16) explained that at low concentrations a desorption of the solute can occur, necessitating efficiency models incorporating a Langmuir isotherm. Rosen (18) indicates that at higher concentrations desorption does not occur and subsequently Tomiak and Lauzon (19) state that only displacement washing occurs and volumetric wash ratios will apply. In addition, Phillips (20) states that near the 99% recovery rate, sorption can be neglected. According to Cullinan (21), models which have provision for solute sorption, are too complex for design use or efficiency determinations.

Physical washing models were grouped by Norden and Viljakainen (22) into three categories: microscopic,
P.M.C. (perfect mixing cells), and macroscopic. Microscopic models which generally entail adsorption isotherms, describe the axial dispersion in a fiber bed. P.M.C. models take into account the number of perfect mixing cells across the cake, and macroscopic models involve the efficiency of a washing system. The latter two models rely on empiricism based on concepts of perfect stages. In the very least, the nonuniversal treatment in developing methods to describe a washing process can lead to confusion.

**Displacement Ratio**

Macroscopic models are of a general concern in measuring a system's operating efficiency. Perkins, Welsh, and Mappus (23) introduced a method of measuring efficiency based on a displacement ratio. Perkins, et al. defined the displacement ratio as the actual reduction of soluble solids across the shower zone of each stage compared to the maximum possible reduction. Mathematically this can be stated:

\[
\text{Displacement Ratio (DR)} = \frac{C_v - C_m}{C_v - C_{sh}} \quad (1)
\]

The displacement ratio is calculated based on the dissolved solids portions of the vat liquid \(C_v\), the mat liquid through squeezings \(C_m\), and the shower liquid \(C_{sh}\). When all of the mat liquid in the sheet is replaced by shower liquid, a displacement ratio of 1 is
attained, i.e. there is a maximum reduction in dissolved solids.

DR can also be expressed as the fraction of liquid in the mat on any stage which is of the total shower origin. This is seen as:

\[ DR = \frac{W_s}{W_p} \]  

(2)

Ws equals the weight of shower liquid with the pulp leaving the washer and Wp equals the total weight of liquid with the pulp leaving the washer.

Perkins, et al. also arrived at a theoretical correlation between the displacement ratio and the shower flow, or dilution factor, based on the number of showers as a series of perfect mixings. It is stated:

\[ \frac{W_s}{W_p} = 1 - \left( \frac{nW_p}{n+1}(W_p+DF) \right)^n \]  

(3)

As explained Ws/Wp is equivalent to the displacement ratio and DF is the dilution factor which is dependent on the number of showers, n.

\[ DF = \frac{\text{lbs shower liquid} - \text{lbs mat liquid}}{\text{o.d. lbs fiber}} \]  

(4)

The dilution factor remains constant throughout a countercurrent washing system and therefore can be calculated at the end or at any intermediate step. From the definition it is seen that a dilution factor of 0 exists when the
shower liquid and the mat liquid weights are equal; therefore it is possible to have a negative dilution factor. Note that when operating a system at equilibrium, different drum discharge consistencies do not change a system's dilution factor. Figs. 6 and 7 illustrate the correlation and the effect of mat consistency and number of showers.

Empirical curves were generated resulting in the same form as the theoretical curves as shown in Fig. 8. This indicates that the shower's washing action or dilution factor is a function of the same form of the equation that was derived. Theoretical and empirical data do not fall exactly on the same curves because a washing operation is not perfect in regard to dilutions and extractions. Mixing, channeling, and entrainment create conditions other than ideal.

Because the displacement ratio appeared to be a function of the dilution factor, Perkins et al. expressed this relationship as a constant multiplied by the theoretical equivalent of the displacement ratio.

\[
\frac{Ws}{Wp} = K \left( 1 - \left( \frac{nWp}{n+1}(Wp+DF) \right)^n \right)
\]

K is an empirical displacement constant which is a function of the independent variables in a washer operation. K would be unique for a pulp specie in a given washer under specific operating conditions.
Fig. 6 Effect of Showers on DR

Fig. 7 Effect of Mat Consistency on DR

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Another macro approach to washer efficiency is the Norden Method. This method is defined by Norden (24,25,26) as the number of mixing stages in series with complete mixing of overflow and underflow as seen in Fig. 9, that is required to achieve the same overflow and underflow as that departing from an actual washing stage. The underflow would be the washer feed, (pulp slurry) and the overflow is the shower feed.
Fig. 9 Norden's Washing System

A derivation by Miner (27) of the Norden efficiency factor for a single stage, n, is as follows:

\[
E_n = \frac{E_1 \left( \frac{L_1 (X_i - Y_o)}{L_0 (X_o - Y_i)} \right)}{E_n} \cdot \frac{L_0 (X_i - Y_o)}{(V_i/L_0)} \tag{6}
\]

- \(L_1\) = flow rate of incoming liquid
- \(V_i\) = flow rate of shower liquid
- \(L_0\) = flow rate of liquid leaving with the mat
- \(X\) = concentration of material in \(L\)
- \(Y\) = concentration of material in \(V\)
- \(i\) = washer inputs of feed liquid and shower water
- \(o\) = washer outputs of excess filtrate and mat liquid

Wash liquor ratio is introduced by Norden in the denominator of equation 6:

\[
WLR = v = \frac{V_i}{L_0} \tag{7}
\]

This is a ratio of the wash liquid from the shower to the liquid remaining in the departing mat. In contrast to the dilution factor, the wash liquor ratio (WLR) has no
negative values. When the quantity of shower liquid equals the liquid in the mat, there is a WLR of 1 which would be a DF of 0. The WLR is simply a ratio of liquids, without taking the fiber fraction into account.

Normally a Norden number is generated for an entire washing system by simply adding up the efficiencies for each stage. For a given stage the displacement ratio is analogous to the Norden number. However, the Norden method does not segregate the operations of repulping, dilution or crosscurrent washing, (dilution and thickening), on each drum. Nierman (28) states that in estimating efficiencies for a system, the Norden efficiency was a futile effort. It appears that the Norden method without data adjustment is too sensitive to get realistic results from a reasonable number of samples. Although the Norden number is not as straightforward as the displacement ratio, it can be simpler to use especially when comparing equipment. Also, according to Baldus (29), the Norden number is not quite as dependent on wash liquor ratio as the displacement ratio is. He also states that under a constant wash liquor ratio the displacement ratio remains valid when the quality of wash liquid changes under reasonable conditions.

**Dimensionless Mass Transfer Coefficient**

Cullinan (30) explained where studies should be
targeted to avoid the ongoing confusion in different washer efficiency techniques. He defines three efficiencies that are interrelated: the local, stage, and overall. The local efficiency is directly related to the separation (displacement) process. A stage efficiency is most useful in characterizing the performance of a filter stage. An overall efficiency is a ratio of numbers of hypothetical to actual stages with no detail about the process. The Norden method is essentially an overall efficiency and the displacement ratio is at the level of a local efficiency.

Through his derivations he concludes with the following relationship of displacement ratio to a local efficiency, where \( E \) = local efficiency and \( N = WLR \):

\[
DR = 1 - e^{-EN}
\]  

His observation is that the local efficiency is governed by a dimensionless mass transfer coefficient. This value for a local efficiency then dictates the stage and overall efficiency. This relationship can be compared to Perkins' original theoretical equation if the number of showers is altered to a mixing parameter. Concurrent with Perkins' statement on finding a constant for a given pulp, Cullinan suggests studies be focused on a dimensionless mass transfer coefficient dependent on pulp mat structure, the Reynolds number in the wash zone, and the Schmidt number.
of the solute.

**Pore Model Concept**

Klein (31) developed a pore model linking the displacement ratio to the wash liquor ratio. He defined a pulp mat as having pores with equal resistance to liquid flow. As seen in Fig. 10, with complete plug flow a wash liquor ratio of 1 would give a displacement ratio of 1, i.e. all the liquid in the pulp mat is displaced when the volume of applied shower liquid is equivalent to that in the discharged mat. Because of viscous drag at the pore walls, laminar flow results which limits the displacement ratio from attaining 1. Therefore the shower liquid breaks through the pore structure before the wash liquor ratio equals 1. He calculated a break through point to be where WLR = 0.5. A relationship was then calculated:

\[
\text{DR} = \text{WLR} \quad \text{when WLR} < 0.5 \quad (9)
\]
\[
\text{DR} = (1 - 1/40) \quad \text{when WLR} > 0.5 \quad (10)
\]

He then went on to assign formation indexes (FI):

\[
\text{DR} = f(\text{FI, WLR}) \quad (11)
\]

When the quality of mat formation declines, the pulp washing efficiency becomes poor. A mat with poor formation has pores with varying radii and lengths. This variation results in preferential flow through the larger
Fig. 10 Klein's DR as a Function of WLR for Mat Formation

pores, and thus a decrease in efficiency. A formation index of 1 refers to a uniform pore structure in a mat, and those less than 1 refer to less uniform structures. An index of 1 then relates to a perfect formation resulting in a maximum DR for a given WLR. It is interesting to note that Klein's approach is similar in concept to Perkins' and Cullinan's. Klein is also working with a constant, in his case the formation index.

Laboratory Simulation

One way of determining a mass transfer coefficient or
constant is through the generation of empirical data with a laboratory apparatus. Unfortunately most of the laboratory studies have focused on solute adsorption. Grahs (32) constructed a displacement cell consisting of a cylinder and movable piston with the intent of understanding differences in the washing of different substances from the pulp. Rydin (33) also experimented with a piston and cylinder. He was interested in dissolved solids content on pressing. Pellett (34) worked with solute flow through an unconsolidated bed of porous particles (viscose yarns) using a cylinder, piston, and a photometric system to determine changes in solute concentration.

Most recently, Lee has worked with a laboratory apparatus to characterize the displacement process (35). A diagram of his apparatus consisting of a cylinder and piston is seen in Fig. 11. A water jacket was used to keep the samples at temperatures of those in a mill. The fiber pads were repeatedly compressed to a thickness of 2.54 cm to allow for reproducible results. Subsequently, distilled water was used under pressure from a piston to displace the liquid from the fiber pad, with collection of the displaced liquid from an outlet at the bottom of the pad. Washing was carried out under differing conditions of temperature, permeation rate, and fiber concentration.

It appears that his method of shower liquid application does not accurately simulate a mill drum washer.
Fig. 11  Lee's Laboratory Displacement Washer

Instead of showering followed by vacuum filtration, his apparatus forces liquid through the mat with a piston. The superficial shower velocities attained in his apparatus range from 0.0072 to 0.075 cm/s where those in mill conditions are 0.24 to 0.71 cm/s. Mill conditions are arrived at assuming a specific loading of 0.692 o.d. tpd/ft$^2$ or 0.157 g/cm$^2$. Velocity values were calculated with an average mat consistency similar to Lee's of 10% and a dilution factor of 0. Lee's apparatus, however, is useful in that it provides information about the effects of some washer operating variables.
CHAPTER III

DESIGN AND METHODOLOGY

Construction of Laboratory Washer

An apparatus was constructed to allow for the generation of empirical data in the laboratory under mill operating variables. This system simulates the washing of pulp through one revolution on the vacuum drum: i.e. mat formation, extraction, shower with extraction, extraction, and final discharge. In Fig. 12 a cross section of a drum operating at 3 rpm is shown. Residence times and the corresponding area for each zone are listed. The laboratory washer presented here is operated with similar zones as shown in Fig. 12, taking into account the times and areas and other necessary operating data. This apparatus can be set up differently to respond to zone changes seen in other washers at different loadings, dilutions, speeds, temperatures, and vacuum levels.

In general, the laboratory washer consists of a Buchner funnel, a shower head, and a 2 L vacuum flask. The pulp is washed on the Buchner by the shower head and the filtrate is collected in the flask (see Fig. 13).

A shower head capable of throwing a 5 in. diameter circular fan at a 6 in. distance from the pulp mat surface
Fig. 12 Cross Sectional Zones of a Vacuum Drum
Fig. 13 Laboratory Vacuum Drum Brownstock Washer

A - Battery    I - Buchner Funnel    Q - Laboratory Heater
B - Relays    J - Vacuum Flask    R - Vat Sample
C - Output Terminal    K - Ring Stand    S - Shower Circuit
D - Computer    L - Vacuum Solenoid    T - Vacuum Circuit
E - Vacuum Pump    M - Nitrogen Tank    U - Vacuum Line
F - Shower Solenoid    N - Pressure Gauge    V - Shower Line
G - Shower Head    O - Shower Cylinder    W - Nitrogen Line
H - Buchner Spacer    P - Water Bath    X - Pressure Line

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is switched by an electrically operated solenoid. Shower flow rate is altered by a pressure change on the shower liquid which is housed in an acrylic cylinder. The pressure gradient is regulated by a cylinder of nitrogen and monitored by an external pressure gauge.

The Buchner funnel, measuring 5-1/2 in. OD and 5 in. ID is used to simulate the vat and drum surface. A plastic insert can be placed inside the funnel to allow for increased volumes of vat sample. Inside the funnel a 5 in. diameter 10 x 10 metal wire mesh screen is placed followed by a 5 in. diameter 32 x 32 plastic mesh screen. The wire mesh is used to raise the plastic mesh off of the Buchner filter holes, thus decreasing the possibility of irregular flow patterns such as channeling. The plastic mesh serves as the filtering media, as seen on a vacuum drum washer.

A vacuum pump is connected to a vacuum flask through a similar solenoid which regulates the on/off function. Vacuum levels are changed by simply changing the pump's vacuum. A quick connect on the vacuum line allows easy removal of the flask and funnel for analysis after a run.

The shower head, Buchner funnel, vacuum flask, and solenoids are all mounted on a ring stand. The acrylic cylinder, (shower reservoir), and vat sample are maintained at operating temperatures in a 25 gallon galvanized tub by a circulating laboratory heater. Shower liquid is
pumped through a fill valve into the shower reservoir by a peristaltic pump. The water bath tub, and the shower line running from the reservoir to the shower head, are insulated with bubble pack.

A 12 V battery is used to supply the current in the circuits between the solenoids and the electromagnetic relays. The relays operate the solenoids in response to output from the computer. A computer is used as a timer in conjunction with an internal data translation board and an external input/output terminal board which sends the signal to the relays. The computer's software consists of a file creator and a laboratory input/output data manager.

The shower flow rate is controlled by regulating the gas pressure on the wash fluid. Flow rates must be calibrated over several ranges of pressure for different systems, because different liquids have different flow properties. In turn, the shower remains on for a length of time, by the computer controlled solenoid, to simulate the zone time the pulp is washed on a vacuum drum. Likewise, a vacuum is pulled through the pulp mat for the zone times necessary to simulate a drum vacuum. The vacuum and reservoir pressure are always on, however the inline solenoids allow for designated open and closure of the line flows. Solenoid operation may be controlled for all practical purposes to 0.10 s, however possible lag times such as evacuation of the Buchner and filling of the shower

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head must be considered.

Initially an industrial shower head was used as a showering device. Flow problems were encountered with the head until a drilled aluminum plate was inserted in the head followed by a packing of teflon boiling beads. Prior to actual testing of the apparatus, the shower head was calibrated with approximately 0% dissolved solids water. This worked fine for the NaCl tracer run operating at near 0% dissolved solids in the shower liquid. However, the introduction of 6% dissolved solids black liquor shower liquid in the mock mill run, resulted in an uneven flow distribution and a delay in start-up, and drainage after the head was shut off. In response, a small lawn sprinkler head, which gave the required flow distributions, was acquired and calibrated for approximately 0% water and 6% black liquor dissolved solids. Calibration curves for both shower heads are in Appendix 1.

Setting up the Laboratory Washer

Software files particular to a specific drum are created for control of the vacuum and shower solenoids. These files are created with regard to the operating zones shown in Fig. 12. For example, the drum in Fig. 12 operating at 3 rpm would have two files created, one for the shower and one for the vacuum, both 20 s long. The shower file would be set up to trigger the shower solenoid to
open after a 10 s delay. The solenoid would then remain open for 3.8 s, and then close for the remaining 6.2 s. The vacuum file would be constructed so that the vacuum solenoid would open for the first 17.5 s and shut off for the last 2.5 s.

Once a loading for a mill washer has been selected, the correct loading for the apparatus can be determined. For example, a mill operating at a specific loading of 400 o.d. tpd/578 ft$^2$ or 0.692 o.d. tpd/ft$^2$, similar to Fig. 12, would have 0.3204 lbs/ft$^2$ of oven dry pulp. In comparison, the Buchner with a 5 in. ID has an area of 0.1364 ft$^2$. At a similar loading to the mill drum, the Buchner would need 0.3204 lbs/ft$^2$ x 0.1364 ft$^2$ or 0.0437 lbs or 19.82 g of o.d. pulp. Operating at a desired vat consistency of 2%, this translates to 991 g of a pulp slurry needed for one run at conditions noted.

Shower flows are set up based on an estimate of expected mat discharge consistency. For example, a mat having a consistency of 18.25% with a similar loading of 19.82 o.d. g of pulp would consist of 108.6 g (19.82 o.d. g/18.25%) of fiber, dissolved solids, and water. If the shower was operating at a dilution factor of 2, a back calculation would give the amount of wash liquid needed, X. Following is an example which shows the calculation of X to be equal to 128.42 g.
DF = \frac{X \text{ g wash liquid} - (108.6 \text{ g fiber, dissolved solids, and water} - 19.82 \text{ g o.d. fiber})}{19.82 \text{ g o.d. fiber}}

The shower reservoir's pressure and computer file would then be set up to supply 128.42 g of shower liquid over a designated zone time. If the shower zone time was 3.8 s, then \( \frac{128.42 \text{ g}}{3.8 \text{ s}} = \text{approximately } 33.8 \text{ ml/s} \). Therefore, the pressure would be adjusted to the amount necessary to supply this flow. Note that the amount calculated for dilution is a weight and that calibrated with the shower is a volume. In the testing of the apparatus with the NaCl tracer run, a direct g to ml conversion was made because tap water was used as the shower liquid. However, in the mock mill and mill simulation runs, specific gravities were considered and a correction was made.

**Operating Procedure**

The cylinder filled with shower liquid is placed into the water bath. A 20 L bucket containing the vat sample is also placed in the bath and they are both brought to the desired operating temperature.

Both the shower and vacuum files are set up according to particular run specifications. The shower is tested at the desired pressure to see if the correct dilution factor has been obtained based on the approximated mat discharge consistency. The amount of vat pulp needed has been
determined for a given loading, and a tared 1 L beaker and triple beam balance have been prepared for that weight.

The vacuum pump is turned on and adjusted for the correct vacuum. Next, the computer program is brought to a point where the "enter" key will trigger the washing cycle. A spatula is used to stir the vat pulp thoroughly to achieve a representative sample. Using a plastic beaker, approximately 1 L of vat pulp is scooped out of the container and poured into the tared glass beaker until the desired weight is obtained.

By triggering the shower solenoid, 10 to 20 ml of shower liquid is wasted to a beaker to remove cooled fluid in the line. The flask and funnel with insert are quickly moved onto the ring stand and connected to the vacuum solenoid. The vat pulp is poured into the funnel and the computer is triggered to initiate the cycle. Note that the vat sample does not drain excessively out of the funnel prior to the start of the cycle because the flask is airtight.

When the cycle is finished the flask and beaker are disconnected, and the pulp pad is removed with a spatula from the Buchner. The plastic mesh screen is peeled off of the fiber pad, and then the pad is weighed on a top loading scale. The pad is then placed in a recloseable plastic bag and labeled for analysis. In addition, the
filtrate is thoroughly mixed and a 250 ml sample is obtained, covered, and labeled. Analyses of these samples are done when the rest of the runs have been completed. Samples are refrigerated if analysis is not completed the same day.

Sample Analysis

The pulp mats are squeezed to obtain a sample of the mat liquor in a beaker. This squeezing is accomplished by hand with a vinyl medical glove. It is important to note that the washing efficiency obtained using the mat liquor dissolved solids amount, is a function of how one measures washer losses. For example, use of the squeezing technique is variable among and between operators, dependent on the hand pressure exerted in obtaining a liquor sample. In this study, all squeezings were performed by the same operator with maximum pressure exerted.

The squeezed mat is then diluted in a 2 L beaker with distilled water and mixed with a lab mixer for 15 min. The mixed pulp is then filtered on a filter paper in a 6 in. Buchner funnel and continually washed with distilled water until a conductance reading of less than 40 uv is obtained. This value is comparable to approximately 0.002% remaining dissolved solids in the pulp. The washed pulp mat is then dried with the filter paper on a tin for
24 h in a drying oven at 105°C and then removed and weighed. Subtracting the weight of the filter paper and tin results in the weight of pulp only.

The mat liquor sample is filtered at 12 in. Hg vacuum through a Whatman 934-AH filter using a Millipore to remove suspended solids. Any fiber that accumulates on the filter is returned to the stirring pulp sample. Also, the filtrate sample is filtered to remove suspended solids. A dissolved solids analysis on the filtered mat liquor and filtrate samples are run separately. Two dissolved solids tests were performed on all samples except in the case of the mill washer simulation where 3 dissolved solids were run when possible. These samples were dried in tins for 24 h and then weighed. An average of the dissolved solids run for a particular sample was used in further calculations.

Pipeted 20 ml liquid samples were used for dissolved solids analysis of the NaCl tracer runs and drums 2 and 3 of the mock mill runs. These samples resulted in a g/L figure which was directly converted into a percent. It was determined that this direct conversion did not make a significant difference in the displacement ratio. However, a weight basis yielding a direct percent was used for drum 1 of the mock mill run, and all of the mill washer simulations. This is accomplished by weighing a sample of filtered liquor in a tin, drying it, and weighing it again.
to determine content. This method was employed for ease, and also to avoid any future discrepancy problems that might occur with high dissolved solids liquor content, in converting g/L to percent.

Testing the Laboratory Washer

Two sets of tests were performed to analyze the washer's operation: a NaCl tracer run and a mock mill simulation run. The NaCl run was performed to see if the apparatus was workable and could produce reproducible results, i.e. did the results indicate expected displacements as a function of dilution changes. A mock mill simulation was run to determine if the washer could produce expected results under varying conditions as those seen on a three stage washer system in a mill.

The NaCl tracer run was set up based on a 11.5 ft x 16 ft washer operating with a load of 400 o.d. tpd at 3 rpm. An 8 L diluted blow pit pulp sample from an integrated kraft mill was obtained and analyzed by the above methods which resulted in the following contents: 4.27% fiber, 1.59% dissolved solids, and 94.14% water. This sample was then diluted with sufficient amounts of distilled water and NaCl, acting as a dissolved solids tracer, to arrive at the following approximate contents: 2% fiber, and 10% dissolved solids. The sample was prepared in this manner so that washability of the apparatus at
different dilutions on a high dissolved solids sample could be examined.

Vacuum levels were set at 12 in. Hg, and vat and shower temperatures were set at 66°C. Tap water with 0.023% dissolved solids was used as shower liquid at three target dilution factors; -1, 2, and 5. According to Steel and Torrie's (36) statistical procedures for randomization, four runs for each dilution factor were randomly performed. Dilutions were based on an approximate mat fiber content of 18.25% determined from previous testing on pulp at 12 in. Hg vacuum levels.

The mock mill simulation was also based on 11.5 ft x 16 ft washer with a 400 o.d. tpd load operating at 3 rpm. Samples were obtained from an integrated kraft mill operating with a pulp feed of hardwoods, 40% dense (oak) and the remainder poplar, to a continuous digester. A 40 L sample of diluted blow pit pulp and a 40 L sample of black liquor evaporator feed were analyzed and mixed as required to give representative samples of vat pulp and shower liquid for three stages of a mill vacuum drum system. Initial analysis of the blow pit pulp contained approximately 4.7% fiber, 4.0% dissolved solids, and 91.3% water. The heavy dissolved solids evaporator feed contained approximately 17% dissolved solids.

Three runs were randomly performed for each stage at the following dilution factors: -1, 3, and 7. In
addition, where supplies allowed, extra runs were performed. Dilution factors for drums 1 and 2 were based on a mat consistency of 16.4% and drum 3 was based on 18.0%. Because of the higher specific gravity of high dissolved solids shower liquid over water, a correction for volume to weight was made for drums 1 and 2. This is necessary because the shower flows are recorded as ml's and the displacement ratio is obtained from g's. Therefore, more error occurs in a direct conversion from ml to g in higher specific gravity shower liquids. A volumetric weight correction of the shower liquid was determined for drum 1 to be 1.024 g/ml and for drum 2, 1.008g/ml. No correction for drum 3 was necessary, as tap water was used as the shower liquid. Approximate run conditions for each drum are in Table 2.

Table 2
Run Conditions--Mock Mill Run

<table>
<thead>
<tr>
<th></th>
<th>Drum 1</th>
<th>Drum 2</th>
<th>Drum 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vat Fiber (%)</td>
<td>2.23</td>
<td>2.37</td>
<td>1.95</td>
</tr>
<tr>
<td>Vat Dissolved Solids (%)</td>
<td>11.19</td>
<td>5.07</td>
<td>1.75</td>
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<td>Shower Dissolved Solids (%)</td>
<td>5.81</td>
<td>2.06</td>
<td>0.024</td>
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<tr>
<td>Vacuum (in. Hg)</td>
<td>12</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Shower Liquid pH</td>
<td>12.4</td>
<td>11.8</td>
<td>--</td>
</tr>
<tr>
<td>Vat Pulp pH</td>
<td>12.9</td>
<td>12.3</td>
<td>--</td>
</tr>
<tr>
<td>Shower Liquid °C</td>
<td>70</td>
<td>71</td>
<td>72</td>
</tr>
<tr>
<td>Vat Pulp °C</td>
<td>62</td>
<td>67</td>
<td>65</td>
</tr>
</tbody>
</table>
Mill Washer Simulation

The intent of this simulation was to determine if the lab washer could generate similar results as seen on a full scale washer. Inputs for the lab washer were actual vat and shower samples off of a mill washer. The lab washer outputs, mat and filtrate samples, could then be compared to samples of mat and filtrate from the mill washer taken at times coinciding with the vat and shower sampling.

Sampling for this was done at the same mill that donated the samples for the mock mill runs. Each drum in the three drum Impco washer system measured 9-1/2 ft in diameter by 16 ft wide, and was operating at a loading of 318.6 o.d. tpd and a dilution of 560 gpm. Operating conditions at the time of sampling are shown in Table 3.

The samples were taken continuously over a 1-1/2 h period. For each stage, 4 sets of 20 L samples were collected resulting in 12 sets of samples to be run through the simulator.

Table 3

<table>
<thead>
<tr>
<th>Impco Vacuum Drum Operating Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum (in. Hg)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Drum 1</td>
</tr>
<tr>
<td>Drum 2</td>
</tr>
<tr>
<td>Drum 3</td>
</tr>
</tbody>
</table>

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One sampling time consisted of initially getting vat samples in the order of drum 1 through 3. These samples were pumped into large sample buckets by using a Guzzler pump immersed in the vat. Next, the mat samples were taken about 1/3 of the way in on the discharge side of each drum with a large wooden paddle. This was also done in the order of drum 1 to drum 3. These samples were double bagged in recloseable plastic bags. Although, indicated by Service and Seymour (37), it is desirable to obtain a mat sample across the drum surface to rule out problems with nonuniform sampling; in this application it was physically impossible. A third stage shower sample was then put in a sample bucket. Filtrate from each drum's filtrate tank in the order of drum 1 to 3 was also sampled and put in plastic buckets. Samples of shower liquid from drum 1 and 2 could not be obtained, therefore filtrates from filtrate tanks 2 and 3 were substituted. Sampling immediately restarted using the same technique after completion of one sampling time.

A preliminary analysis of the sampled vats, mats, filtrates, and drum 3 shower liquid was then completed. According to the sample analysis procedures, one set of tests was performed for each of the samples. Run conditions of the mill drums became the conditions that were used for each lab run. For example, a lab dilution factor was calculated based on mill loadings and shower flow, and
mat fiber concentration in the mill for that drum and
time. The software for vacuum and shower operation was
set up for each drum based on rpm and the washing zones as
seen in Fig. 12. A volumetric weight correction for lab
shower flows for each drum was calculated similarly as in
the mock mill run. They are 1.011 g/ml, 0.995 g/ml, and
0.980 g/ml for drums 1, 2, and 3 respectively.

Three laboratory runs were performed for each mill
sample time and drum. This amounts to 36 runs in total,
3 each for the 4 times seen on each of the 3 drums. Addi­tional specific conditions for each set of runs are in Ta­
ble 4.

Table 4
Lab Washer Conditions for Simulation

<table>
<thead>
<tr>
<th>Drum/Time</th>
<th>Vat °C</th>
<th>Shower °C</th>
<th>Vat pH</th>
<th>Shower pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>62</td>
<td>62</td>
<td>13.3</td>
<td>12.8</td>
</tr>
<tr>
<td>1/3</td>
<td>62</td>
<td>62</td>
<td>13.4</td>
<td>12.8</td>
</tr>
<tr>
<td>1/4</td>
<td>61</td>
<td>62</td>
<td>13.6</td>
<td>13.1</td>
</tr>
<tr>
<td>2/1</td>
<td>58</td>
<td>46</td>
<td>13.7</td>
<td>13.1</td>
</tr>
<tr>
<td>2/2</td>
<td>52</td>
<td>52</td>
<td>12.8</td>
<td>11.8</td>
</tr>
<tr>
<td>2/3</td>
<td>50</td>
<td>52</td>
<td>13.0</td>
<td>12.0</td>
</tr>
<tr>
<td>2/4</td>
<td>48</td>
<td>52</td>
<td>13.0</td>
<td>12.0</td>
</tr>
<tr>
<td>3/1</td>
<td>62</td>
<td>62</td>
<td>11.8</td>
<td>7.4</td>
</tr>
<tr>
<td>3/2</td>
<td>62</td>
<td>62</td>
<td>11.8</td>
<td>7.4</td>
</tr>
<tr>
<td>3/3</td>
<td>60</td>
<td>63</td>
<td>12.0</td>
<td>6.8</td>
</tr>
<tr>
<td>3/4</td>
<td>57</td>
<td>63</td>
<td>11.9</td>
<td>7.4</td>
</tr>
</tbody>
</table>
The significant data, (DR, DF, and WLR), obtained for
the three runs for each time was then averaged so a resul-
tant comparison over 4 times for each drum could be made.
The averaging was done only on data that passed an ASTM
(38) outlier test at a 95% confidence level. This permits
the removal of any gross deviations in lab data points
that should not be used in comparison against mill data in
the assessment of the laboratory washer.
CHAPTER IV

PRESENTATION OF RESULTS

Introduction

A dissolved solids analysis was chosen as an indicator of both dissolved organic and inorganic material in a fraction of liquid. This method was chosen because it is a measure of the total material in solution. Other methods, such as measuring the conductivity of sodium ions, necessitate a correlation to the total dissolved solids.

A material balance was completed for all tests run through the lab washer. The following components were known: mat weight and content, shower weight and content, filtrate content, and vat weight. Using this information, a back calculation was made to give the actual initial conditions of the vat for a particular run. This was done because the assumption that vat samples from one container over a set of runs are uniform, is erroneous. During the course of a run evaporation occurs in the container, which results in different consistencies. Also, each vat sample scooped from the container does not result in the same proportions of contents. The actual dilution factors were calculated based on the actual fiber mat contents.

A displacement efficiency rating, displacement ratio,
and a measure of dilution, wash liquor ratio, were calculated so that a comparison of results could be made. The displacement ratio was chosen because it gives a straightforward indication of the physical processes occurring during vacuum drum washing. Wash liquor ratio is used because it works well with displacement ratio in describing their relationship. As explained, with complete plug flow in a displacement process, a wash liquor ratio of 1 would yield a displacement ratio of 1.

Note that when calculating a displacement ratio, it is based on the dissolved solids of the liquid fraction only and not the total fraction. Basing dissolved solids on the total fraction, inclusive of fiber, decreases the dissolved solids content, and is not permitted with Perkins' definition of displacement ratio.

In addition to determining the workability of the lab washer, the likelihood of generating system constants from the relationship of displacement ratio and wash liquor ratio was examined. As previously discussed, Cullinan's relationship is as follows:

\[
DR = 1 - e^{-EN} \quad \text{or} \quad DR = 1 - e^{-k(WLR)}
\]

(12)

A system constant governing the local efficiency, \(\varepsilon\), is represented by \(k\). \(N\) simply represents the wash liquor ratio.

Rearrangement of equation 12 yields the following
expression:

\[
\text{LN} (1 - \text{DR}) = -k \text{ (WLR)}
\]  \hfill (13)

This equation can be compared to the more familiar equation for a line, \(Y = MX + B\). In this case \(\text{LN} (1 - \text{DR})\) would be equivalent to \(Y\), the \(y\)-coordinate. \(\text{WLR}\) compared to \(X\), would be the \(x\)-coordinate. \(M\), or the slope of the line is comparable to the constant, \(-k\). In this case, there is no \(B\) term, or \(y\)-intercept, because in the case of \(\text{DR}\) approaching 0, the normalized expression of \(\text{DR}\) would be 0.

Therefore, equation 13 can be used as an attempt to evaluate a system's relationship between displacement ratio and wash liquor ratio. The slope of the line, \(-k\) would become a system constant dependent on the variables discussed by Perkins and Cullinan. This constant could explain how a displacement ratio behaves as a function of wash liquor ratio for a specific pulp under specific washing conditions.

Dissolved solids analyses of all runs, i.e., the NaCl tracer run, the mock mill run, and the mill washer simulation are in Appendix B. A material balance summary for the NaCl tracer runs is in Appendix C. Appendix D includes material balance summaries for drums 1, 2, and 3 of the mock mill runs. Material balance summaries of both mill and lab data for drums 1, 2, and 3 of the mill washer
simulation are included in Appendix E.

**NaCl Tracer Run**

The results for the NaCl tracer run are in Figs. 14 and 15. Fig. 14 is a plot of the relationship, displacement ratio as a function of wash liquor ratio, and Fig. 15 is an attempt to explain their relationship with a system constant. The least squares linear regression is \( Y = -0.038 -1.2 X \). This equation has an \( F \)-value of 473.3 and a critical value of 4.93 at 95% confidence.

**Mock Mill Run**

Figs. 16-18 illustrate the relationship between displacement ratio and wash liquor ratio for drums 1, 2, and 3 of the mock mill run. Equations of the lines for drums 1, 2, and 3 were obtained as a result of the plots in Figs. 19-21. A summary of all drums indicating displacement ratio as a function of wash liquor ratio is in Fig. 22. Fig. 23 is an attempt to explain their relationship with a system constant. A summarized system constant for those WLR's less than 2.0 is shown in Fig. 24. The equations for these lines and their level of significance at a 95% confidence level are in Table 5.
NaCl TRACER RUN

Displacement Ratio vs Wash Liquor Ratio

Fig. 14 NaCl Tracer Run DR as a Function of WLR
**NaCl TRACER RUN**

**LN(1-DR) vs Wash Liquor Ratio**

\[ y = -0.038 - 1.2x \]

![Graph showing LN(1-DR) vs Wash Liquor Ratio with a linear fit line and data points.]

**Fig. 15 NaCl Tracer Run LN(1-DR) as a Function of WLR**

62
Fig. 16 Mock Mill Run, Drum 1 DR as a Function of WLR
MOCK MILL RUN — DRUM 2
Displacement Ratio vs Wash Liquor Ratio

Fig. 17 Mock Mill Run, Drum 2 DR as a Function of WLR
Fig. 18 Mock Mill Run, Drum 3  DR as a Function of WLR
Fig. 19 Mock Mill Run, Drum 1 \( \text{LN}(1-\text{DR}) \) as a Function of WLR

\[ y = -0.698 - 0.256x \]
Fig. 21 Mock Mill Run, Drum 3 LN(1-DR) as a Function of WLR
MOCK MILL RUN - ALL DRUMS

Displacement Ratio vs Wash Liquor Ratio

Fig. 22 Mock Mill Run, All Drums DR as a Function of WLR
Fig. 23 Mock Mill Run, All Drums LN(1-DR) as a Function of WLR
 MOCK MILL RUN - ALL DRUMS

$Y = -0.275 - 0.656X$

For WLR's Less Than 2.0

$\ln(1-DR)$ vs Wash Liquor Ratio

Fig. 24 Mock Mill Run, All Drums $\ln(1-DR)$ as a Function of WLR's Less Than 2.0
Table 5
Regression Equations for Mock Mill Run

<table>
<thead>
<tr>
<th>Drum</th>
<th>Equation</th>
<th>F-Value</th>
<th>Critical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Y = -0.698 - 0.256 X</td>
<td>10.2</td>
<td>5.12</td>
</tr>
<tr>
<td>2</td>
<td>Y = -0.665 - 0.386 X</td>
<td>24.9</td>
<td>4.96</td>
</tr>
<tr>
<td>3</td>
<td>Y = -0.416 - 0.552 X</td>
<td>213.4</td>
<td>5.59</td>
</tr>
<tr>
<td>SUM</td>
<td>Y = -0.620 - 0.367 X</td>
<td>61.6</td>
<td>4.17</td>
</tr>
<tr>
<td>*SUM</td>
<td>Y = -0.275 - 0.656 X</td>
<td>144.2</td>
<td>4.38</td>
</tr>
</tbody>
</table>

* For WLR's less than 2.0.

Mill Washer Simulation

All data that was generated from the laboratory washer was used in the results. None of the data had to be rejected as a result of the outlier test previously mentioned. There were no tests of the displacement ratio, wash liquor ratio relationship in forming system constants for this simulation, because the mill wash liquor ratios encompassed only a small range.

A comparison of the lab displacement ratios and the mill displacement ratios and a corrected version are seen in Figs. 25 and 26. In Table 6, a t-test at a 95% confidence level compares lab and mill displacement ratios. Those tests which are significant, indicate the means are not equal at this level. Therefore, the nonsignificant tests suggest that the means may not be different.
Fig. 25  Mill Washer Simulation Comparison of Lab and Mill DR's
MILL WASHER SIMULATION

Corrected Lab DR vs Mill DR

Equivalence Line

Fig. 26  Mill Washer Simulation  Comparison of Corrected Lab and Mill DR's
Table 6
Results of Mean Lab and Mean Mill DR t-Tests

<table>
<thead>
<tr>
<th>Drum</th>
<th>Uncorrected Lab DR</th>
<th>Corrected Lab DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>significant</td>
<td>significant</td>
</tr>
<tr>
<td>2</td>
<td>nonsignificant</td>
<td>significant</td>
</tr>
<tr>
<td>3</td>
<td>significant</td>
<td>nonsignificant</td>
</tr>
</tbody>
</table>

Inaccessible Dissolved Solids Portion

Cullinan's relationship (equation 12) did not give a satisfactory system constant for the plots for the mock mill run. Apparently there is an inaccessible portion of the dissolved solids content on washing. Subsequently when a mat sample is squeezed, this portion adds to the concentration of the mat liquor. The inaccessible portion might be attributable to diffusion rates and that sodium which is bound.

It appears that the inaccessible dissolved solids prohibits the displacement ratio from ever attaining 1.0. Instead, an asymptotic value less than one is reached for a particular system. A modification of equation 12 to include an asymptotic value, DRa, is as follows:

\[ DR = DRa \left[ 1 - e^{-k(WLR)} \right] \]  

(14)

Rearrangement of equation 14 yields an expression similar to equation 13:

\[ \ln \left( 1 - \frac{DR}{DRa} \right) = -k(WLR) \]  

(15)
This equation again represents the more familiar equation for a line, $Y = MX + B$. Likewise a system constant, or slope is obtained, and there is no $y$-intercept.

In Figs. 27-30, an estimate of an equation of the line for DR as a function of WLR is given. This appears for the NaCl tracer run, and drums 1-3 of the mock mill run respectively. In addition, both the lab and the mill displacement ratios for the mill washer simulation are included in the plots for the mock mill runs. Note that samples for the mock mill run and the mill washer simulation were obtained from the same mill. System constant plots using equation 15, for the NaCl tracer run and drums 1-3 of the mock mill run, are respectively in Figs. 31-34.
**NaCl TRACER RUN**

Displacement Ratio vs Wash Liquor Ratio

**Fig. 27 NaCl Tracer Run DR as a Function of WLR**

Estimate of Equation

\[ DR = 0.97(1 - e^{-1.33WLR}) \]
LAB + MILL WASHER COMPARISON - DRUM 1

Displacement Ratio vs Wash Liquor Ratio

Displacement Ratio

Ideal Plug Flow

Mock Mill Run

Washer Simulation/Lab Data

Washer Simulation/Mill Data

DR = 0.77(1 - e^{-1.44WLR})

Fig. 28 Mock and Simulation Run Comparison, Drum 1

Estimate of Mock Equation DR as a Function of WLR
LAB + MILL WASHER COMPARISON - DRUM 2

Displacement Ratio vs Wash Liquor Ratio

DR = 0.86(1 - e^{-1.27WLR})

Fig. 29 Mock and Simulation Run Comparison, Drum 2
Estimate of Mock Equation DR as a Function of WLR
LAB + MILL WASHER COMPARISON - DRUM 3

Displacement Ratio vs Wash Liquor Ratio

DR = 0.82 \left(1 - e^{-1.52WLR}\right)

Fig. 30 Mock and Simulation Run Comparison, Drum 3

Estimate of Mock Equation DR as a Function of WLR
Fig. 31 NaCl Tracer Run \( \text{LN}(1-(DR/0.97)) \) as a Function of WLR.
MOCK MILL RUN — DRUM 1

\[ \text{LN}(1-(\text{DR}/0.77)) \text{ vs Wash Liquor Ratio} \]

*Note - One data point is missing here, because DR exceeds .77

Fig. 32 Mock Mill Run, Drum 1 \( \text{LN}(1-(\text{DR}/0.77)) \) as a Function of WLR
MOCK MILL RUN — DRUM 2

$\text{LN}(1 - (\text{DR}/0.86))$ vs Wash Liquor Ratio

$Y = -1.27X$

*Note — Three data points are missing here, because each DR exceeds 0.86

Fig. 33 Mock Mill Run, Drum 2 $\text{LN}(1 - (\text{DR}/0.86))$ as a Function of WLR
MOCK MILL RUN – DRUM 3

\[ \text{LN}(1-(\text{DR}/0.82)) \text{ vs Wash Liquor Ratio} \]

\[ Y = -1.52X \]

Fig. 34 Mock Mill Run, Drum 3 LN(1-(DR/0.82)) as a Function of WLR
CHAPTER V

DISCUSSION OF RESULTS

NaCl Tracer Run

Results from this run appear to indicate that the lab washer is functioning similarly to a full scale vacuum drum washer. As seen in Fig. 14, plotting DR as a function of WLR, minimal scatter occurs as the curve tapers off to the right. This is in agreement with the theoretical curve in Fig. 8 developed by Perkins. If perfect plug flow occurred, the data points would follow the solid line up to a DR and a WLR of 1. Instead a laminar flow exists due to mixing, channeling, and viscous drag at the walls of the pore structure resulting in a nonlinear increase of DR as dilution (WLR) increases.

In Fig. 10, Klein illustrates that at a formation index of 1, the relationship will deviate from linearity at a WLR of 0.5. He terms this as a break through point, where plug flow no longer exists due to shower liquid passing through the mat prior to complete displacement. The tapering action in Fig. 14 begins at an approximate WLR of 0.5 which is in agreement with Klein's proposed model.

The development of a system constant was examined in Fig. 15. A highly significant equation indicative of the
slope not equal to 0 for that line was determined to be:

\[ Y = -0.038 - 1.2 X. \]

Reiterating what was previously discussed, \( Y \) or \( \ln(1-DR) \), would be a function of \( X \), the WLR, and the system constant, -1.2 (the slope). For this theory the \( y \)-intercept should be 0 as explained. In this case a regression analysis of the data points results in an agreement of the \( y \)-intercept, -0.038 nearing 0. Therefore the examination of this relationship for the NaCl tracer run, yields a system constant of -1.2 for the pulp that was washed, under the specific operating conditions of this run. This system constant would be comparable to a formation index value in Klein's pore model theory or a mass transfer coefficient describing Cullinan's local efficiency.

An examination of mass balances in Appendix C for this run indicates reproducible results as dilutions are manipulated. For example, as target dilutions changed, the respective groupings for dissolved solids in the filtrate and mat liquor deviated as a whole. In addition, at a constant vacuum, the fiber concentrations in the mats were between 12% and 13% for all of the runs. However, target dilution factors based on expected mat consistencies were higher than actual dilution factors. This resulted from mat fiber concentrations being lower than what was used in the setup calculations.

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Mock Mill Run

Once the lab washer proved operable with reproducible results, a study involving different conditions as seen on a multiple stage washer was undertaken. Initially it was found that the shower head used in the NaCl tracer run had to be substituted for one that could operate with high dissolved solids liquids. With the correction of this problem, the apparatus operated in the same manner as for the NaCl tracer run.

In Fig. 16, a plot of DR as a function of WLR for simulated drum 1 shows the general trend that is expected from this relationship. At approximately a WLR of 0.5 the trend away from plug flow exists. Likewise in Fig. 17 and 18 for simulated drums 2 and 3, the same general trend exists. It should be noted that the range of wash liquor ratios for these runs extends approximately to 4.0, while the NaCl tracer run stopped at 1.5.

Above a WLR of 2.0 in all three simulated drums, the DR begins to level off. It is beyond this point that a further increase in dilution does not result in a vast improvement in washer efficiency. Dilution factors in mills are usually less than 3 or 4, or under a WLR of 2.0, as unnecessary dilution translates to unnecessary evaporation costs.

It appears there is more scatter in the results.
obtained when washing dirtier (higher dissolved solids) pulp with dirtier wash liquid. This is especially apparent in comparing simulated drums 1 and 3, as there is very little scatter in drum 3. Higher liquid viscosities in drum 1 could cause irregular flow patterns such as channeling and mixing, resulting in variations in the degree of washing.

A comparison of the relationships of all three simulated drums in Fig. 22 indicates much similarity. However, it is quickly noticed that overall efficiencies in drum 1 are lower than the fairly equivalent drums 2 and 3. This might be explained again by the higher dissolved solids liquids interacting in drum 1. According to Macdonald (39), in a mill vacuum drum washer the first drum has the highest efficiencies, because the pulp and liquid are relatively free of air, and the second and third drums are approximately equal. This is a result of subsequent entrained air that decreases efficiencies in the following drums. In the laboratory washer air entrainment was not simulated, therefore simulated drums 2 and 3 do not have an efficiency reduction.

In Fig. 8, a comparison of empirical data to Perkins' theoretical equation was made. Similarities are seen in comparing his plot to the summary in Fig. 22. In his plot, drum 1 is higher than drums 2 and 3 for the reason mentioned above. Drum 3 has higher efficiencies than drum
2 because there is a higher concentration of dissolved solids entering drum 2 from the preceding drum. When comparing efficiencies for wash liquor ratios less than 2.0 in the lab washer summary, the following occurs: efficiencies for a given WLR decrease from simulated drum 3 to 1. This is what occurs with Perkins' data, except for drum 1. However, if air entrainment was not considered in Perkins' plot, the two plots would be similar, as drum 1 efficiencies would be less than drum 2, for the same reason that drum 2 was less than drum 3. It may therefore be hypothesized that as washing stages become cleaner, the DR/WLR relationship approaches theoretical.

It was also noticed that scatter is reduced from simulated drum 1 to 3 with the washing of cleaner pulp in the system constant plots. This reduction is seen as the significance of the equations increase in Table 5 from simulated drum 1 to 3. In all cases the y-intercept did not pass through 0, as in the NaCl tracer run. However, as the washing system became cleaner, and subsequently scatter reduced, the y-intercept came closer to 0.

In the system constant plot for the NaCl tracer run, the WLR values did not exceed 1.5. The system constant plots for the mock mill runs in Figs. 19, 20, and 21 have maximum WLR's near 4.0. As previously discussed, above a WLR of 2.0 the DR does not tend to increase. In examining the system constant plots in only the range
of increasing DR, i.e. less than a WLR of 2.0 (most mill drum washers operate less than 2.0), new regression lines would put the y-intercepts much closer to 0.

A summary in Fig. 23 of system constant plots for simulated drums 1, 2, and 3 shows a regression line for all of the WLR's. In Fig. 24 a regression line is shown for only WLR values less than 2.0. It is noted that the y-intercepts for all the values and for those WLR values less than 2.0 are respectively -0.620 and -0.275.

It is seen from these intercepts, in addition to significance levels (Table 5), that in areas of increasing DR and WLR, (WLR < 2.0) the use of Cullinan's system constant equation improves. Perhaps the equation does not describe the entire relationship adequately, i.e. the deviation from theoretical at WLR's greater than 2.0, and with dirtier washing systems. It might also be that the laboratory washer does not have an effective displacement action at high wash liquor ratios.

The results of the NaCl tracer run might come closer to a theoretical relationship than the mock mill run because it is an easier system to wash. The NaCl tracer run did not contain the amount of black liquor dissolved solids as seen in the mock mill run. These black liquor solids containing organics and inorganics are a highly viscous difficult to wash system. The systems with higher concentrations of black liquor might promote increased
viscous drag at the pore walls, resulting in a further departure from ideal plug flow. Interesting evidence is seen when comparing similar WLR's of 1.5 between the runs. Respectively, WLR's in the NaCl tracer run and the mock mill run resulted in approximate DR's of 0.80 and 0.70. This may go back to the hypothesis that cleaner washing stages achieve closer to theoretical results.

A comparison of dissolved solids for mat liquor, filtrate and vat in Appendix D indicate reproducible data for a given range of dilutions. The system is responding to changes between drums as would be expected in a mill washer. Input concentration changes between drums resulted in expected output concentrations. Actual dilution factors fell closer to the targeted values than with the NaCl tracer run.

Mill Washer Simulation

The averaging of data from the three runs per time per drum encompassed all points with no outliers. This is indicative of the lab washer's reproducibility for a set of conditions. Four replications per drum were then compared between the lab and mill for displacement ratio and wash liquor ratio.

In Figs. 25 and 26 an uncorrected and corrected comparison of displacement ratios is shown. If the ratios were identical, the data points would fall on the diagonal.
line. In the case of the uncorrected DR's, one time for drum 2 is similar, with the rest of the points in groupings approximately 10% from the equivalence line. Drum 3 in the corrected figure (see below for explanation of correction) falls approximately on the line. The grouping for drum 1 has moved closer to the line, and drum 2 is actually further away.

A t-test of the drum means for lab and mill data in Table 6 indicates that for the uncorrected displacement ratios, drum 2 means may not be different, while the others are significantly different at a 5% error. T-tests for the corrected displacement ratios indicate a significant difference for drums 1 and 2, and an indication that the mean may not be different for drum 3.

A theoretical correction for the difference between the lab and mill displacement ratios was developed based on the fact that the lab washer was dewatering the mats to a higher degree than the mill washer. The difference between lab and mill fiber concentrations can be seen in Table 7. Although the vacuum levels in the lab were set in accordance with the mill drop leg vacuum level, it is possible that the actual vacuum under the wire in the mill was less than what the drop leg gauge recorded. A gauge is recording a vacuum level in the drop leg only, and not that which occurs under the cylinder wire.

According to plug flow, all of the vat dissolved
Table 7
Theoretical Laboratory Displacement Ratio Correction

<table>
<thead>
<tr>
<th>Drum/Time</th>
<th>Mill Mat Fiber %</th>
<th>Lab Mat Fiber %</th>
<th>Mill DR</th>
<th>Lab DR</th>
<th>Uncorr DR</th>
<th>Corr DR</th>
<th>Corr DR</th>
<th>%Diff Lab DR</th>
<th>%Diff Corr DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1</td>
<td>13.37</td>
<td>15.35</td>
<td>0.83</td>
<td>0.72</td>
<td>-13.3</td>
<td>0.76</td>
<td>-8.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2</td>
<td>14.09</td>
<td>15.58</td>
<td>0.85</td>
<td>0.70</td>
<td>-17.6</td>
<td>0.74</td>
<td>-12.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/3</td>
<td>14.91</td>
<td>16.40</td>
<td>0.85</td>
<td>0.77</td>
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Solids in a pulp mat should be removed and replaced with shower dissolved solids in the shower zone. Following the shower zone, the reextraction zone further removes some of the shower liquid from the pad. The hypothesis for this correction is that the lab washer is removing more of the shower liquid than what occurs in the mill samples. The resultant mat squeezing then shows a higher dissolved solids content in the lab, because the entrained liquid is being squeezed into a lower external mat liquid volume, resulting in higher concentrations. Subsequently, higher mat dissolved solids concentrations result in lower
displacement ratios, even though weights of the dissolved solids for comparable mill and lab sample sizes may be the same. The entrained liquid that is removed on squeezing may be that which was not completely diffused out of the fiber. This liquid might also be attributable to desorbing bound sodium.

A corrected laboratory displacement ratio is a result of answering the question: how much extra water and dissolved solids in the lab mat is needed to equal the respective components in the mill mat? It must be kept in mind that this makeup liquid contains the shower liquid components of the mill sample. An example of how this correction was calculated is in Appendix F.

In Table 7, no apparent trends between the lab and mill fiber concentrations exist, except for the fact that fiber concentrations are higher in the lab. This is especially true for drum 2, comparing an average of 19.16% in the lab to 12.84% in the mill. Fiber deviations between times for the drums are fairly small, more so in the lab. Due to sample times in the mill scattered only over a 1-1/2 h period, there appears to be no system fluctuations as evidenced by the mill displacement ratios for drum 1 and 3. In drum 2, the deviation rises to 0.06, in sharp contrast to the other drums. Exclusive of drum 2, the displacement ratio deviations for the laboratory runs are approximately equal.
There appears to be a couple of explanations for the deviations in mill displacement ratios for drum 2. The fluctuations in these displacement ratios are a direct result of the dissolved solids in the mill mat samples for drum 2, as seen in Appendix E. Sampling technique might have resulted in inaccuracies, as the mat was sampled in only one area. However, one would expect similar deviations for drum 1 and 3. The other explanation would be that the data obtained is representative, and problems within that drum are occurring.

One obvious question to ask is, why is drum 2 operating at a vacuum of 16 in. Hg, while drum 1 and 3 are respectively 4 in. and 8 in.? Perkins (40) explains that generally vacuum levels run 7 in., 9 in., and 12 in. Hg for drums 1, 2, and 3. Vacuums are lowest on the first drum because drainage rates are the highest due to a lack of air entrainment. Subsequent drums then have higher vacuum levels because of entrainment of air in the sheet on the first drum which is detrimental to formation, and thus reduces drainage. Because vacuum levels are left unadjusted, readings other than ordinary can be used to detect system problems. In this case, a high vacuum on drum 2 may indicate operational problems with the internals, plugging or mat sealing, or severe entrainment problems. Plugging can occur as a result of high vat consistencies, as seen for drum 2 in Appendix E, in combination
with slow drum speeds. Drum 2's speed of 5 rpm was the slowest of all the drums. Internal problems might also explain the variation in dissolved solids found in sampling the mat, as there could be regions on the drum operating with different vacuum and hence drainage levels. Note that all three drums were operating with similar internals and identical service dates.

For whatever reason it appears that drainage rates are lowest in drum 2. Evidence for this appears in the average mat fiber consistency for drum 2 being lower than drum 1 and 3. However drum 2 has only a 0.35% lower average mat fiber consistency than drum 3, and a resultant large vacuum difference, 16 in. – drum 2 versus 8 in. – drum 3. This might suggest there are other problems occurring.

As noted before, displacement ratios are highest for the first drum and approximately equal for the second and third drum. The mill data is in agreement with this, with the exception of drum 2 fluctuating. The higher two values in drum 2, (time 2 and 4), are similar to values for drum 3.

Displacement ratios should be comparable between the lab washer and the mill for drum 1 because entrainment is not occurring in the mill. In drum 2 the laboratory washer has no provision for simulating the entrainment which is occurring in the mill. Entrainment is greater for drum
2 than drum 3 because the pulp suspension from drum 1 still has approximately 4.5% dissolved solids and the shower liquid at approximately 1% has air in it from the drum 3 filtrate tank. As Perkins (41) points out, the amount and size of air bubbles as a result of air entrainment, has a controlling effect on drainage, especially when trying to displace a strong black liquor with a weaker black liquor having air in suspension. Approximately 1% dissolved solids are in drum 3's vat, and virtually un-aerated shower liquid at near 0% dissolved solids is used. Therefore, displacement ratio differences should be negligible for drum 3 between the mill and lab.

It is seen in Table 7 that displacement ratios are less for the lab than the mill in drum 1 and 3, and just the opposite for drum 2. As stated, a correction factor attempting to equate lab and mill mat fiber concentrations because of greater dewatering in the lab was calculated. This resulted in an increase for all of the lab displacement ratios. An uncorrected and corrected percent difference of lab displacement ratios in comparison to mill displacement ratios is shown in Table 7. A correction for lab DR's in drum 1 resulted in an overall improvement from 14.1% to 9.4% when compared to the mill DR's. Error went from 8% to 17.3% in drum 2. This over correction may be a result of two factors: an increase in drainage rate in the lab over the mill due to entrainment effects in the
mill, and hypothesized unreliable mill data as indicated by a high level of vacuum on drum 2. When considering only the higher two mill DR values in drum 2 that are similar to drum 3, the corrected error is reduced from 17.3% to 9.6%. The correction for drum 3 improved the average difference from 8.9% to 0%.

Because mat dewatering was different between the mill and lab, it was necessary to determine if the lab washer could achieve the same mat consistencies as seen on the mill washer. An attempt at controlling mat fiber consistencies in the lab was made by vacuum and time adjustments. A mill sample from drum 2, time 2, was run under the same parameters used for the simulation run. Besides vacuum level, two vacuum durations after the shower zone ends, were examined, i.e. 2.25 s, and 0.8 s. The results are shown in Table 8.

It is seen that the extent of mat dewatering can be controlled as a function of vacuum level, and duration following the end of the showering zone. In addition to

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<th>Lab Mat Fiber %</th>
<th>Mill Mat Fiber %</th>
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<td>4.5 in. Hg/0.8 s</td>
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<td>7.0 in. Hg/0.8 s</td>
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these test runs, other runs were performed at higher vacuum levels also indicating that the degree of mat dewatering can be manipulated.

Apparently in this mill washer simulation, the lab vacuum levels did not correspond to levels seen under the wire in the mill. For example, 16 in. Hg was recorded at the drop leg for drum 2 in the mill resulting in a 12.68% mat fiber consistency. A comparable vacuum level for that fiber consistency in the lab as seen in Table 8 is between 2.5 in. and 4.5 in. Hg. However, one must keep in mind that entrainment effects for drum 2 not simulated on the lab washer, might raise this vacuum level range somewhat.

It seems that a direct approach to this problem would be to measure vacuum levels under the wire. This approach does not seem feasible for the reasons of time, money and technology involved in formulating a method. The next best method would appear to perform test runs on mill samples so that a correlation between lab vacuum levels and mill mat consistencies could be obtained.

Although the laboratory apparatus was set up according to the mill operating conditions, conditions in simulation are not always duplicated. For example, after the mill samples were procured, a period of one month passed before all the tests were complete. In that period further fiber degradation, sorption, and diffusion phenomenon occur. At high pH's (>13), fiber walls swell and force
liquid out, and at lower pH's the walls contract and draw liquid in. In a dynamic mill operation, where vat pH's in the second and third drum may be below pH 13, the fibers do not have a chance to contract. However, during the time the samples were obtained, and run through the lab washer, fiber contraction could have occurred. This would have resulted in an uptake of liquid for drums 2 and 3, that would have to diffuse out during washing.

Vat and shower temperatures that were controlled in the lab did not exactly duplicate those seen in the mill. The shower temperatures for drum 1 and the vat temperatures for drum 3 were both higher in the lab than the mill. Although these differences were noted, according to Perkins (42), between 43°C and 88°C there is a negligible change in viscosity. It is this change in viscosity, especially for temperatures less than 40°C, that higher viscosity wash liquids reduce diffusion in the sheet, resulting in a decline in washing efficiency.

Inaccessible Dissolved Solids Portion

As previously explained, the equation developed by Cullinan (equation 12) did not satisfactorily explain the DR/WLR relationship for the mock mill run. In Cullinan's equation, the DR values are asymptotic to 1.0 with increasing WLR. However, in the mock mill run, especially with the higher dissolved solids washing systems, the DR's
are asymptotic to a value less than 1.0. There appears to be an inaccessible dissolved solids portion in the mat, which is not washed out. However, when the mat sample is squeezed for a dissolved solids analysis, this portion is removed. This inaccessible portion increases the dissolved solids concentration, and decreases the washer's efficiency.

An attempt to explain the DR/WLR relationship with the inaccessible dissolved solids portion in mind was made. A modification of equation 12 to incorporate the asymptotic value, DRa, resulted in equation 14, which is an equation for the line. Rearrangement of this equation results in an equation describing the system constant (equation 15).

In Fig. 27 there is an equation for the line for DR versus WLR for the NaCl tracer run. The asymptotic value, 0.97, is very near the DR value of 1.0. Likewise, in Fig. 31, the system constant is equal to -1.33 in comparison to -1.20 as seen in Fig. 15. The asymptotic value obtained here, and the system constant are close to the values obtained with Cullinan's original equation 12.

However, examination of the highest dissolved solids system (drum 1) in the mock mill run, indicates an asymptotic value of only 0.77 and a system constant of -1.44. These values are seen in the plots for drum 1 in Figs. 28 and 32. In Fig. 28 the lab and mill data from the mill
washer simulation is included. The results from the lab data for the mill washer simulation coincide with the mock mill run data. Mill data from the mill washer simulation again fell somewhat higher than the other data. The system constant plot in Fig. 32 is forced through 0 with a slope, or constant, of -1.44. This is compared to a previously determined plot which did not go through 0. That plot, in Fig. 19, had a slope of -0.256.

In Fig. 29 an equation for drum 2 for the mock mill run is shown. In this system, the asymptotic value has increased to 0.86 in comparison to 0.77 seen in drum 1. Both the lab and mill data for drum 2 from the mill washer simulation fell close to the mock mill run's equation of the line. A system constant of -1.27 in Fig. 33 is again different than that previously obtained (-0.386) in Fig. 20.

The asymptotic value for drum 3 in Fig. 30 in the mock mill run is 0.82. In this plot the mill data from the mill washer simulation fell higher than the equation for the line, and the lab data fell lower. A constant for drum 3 in Fig. 34 is -1.52, compared to -0.552 in Fig. 21.

It appears that the higher dissolved solids systems have asymptotic values further from 1.0. This would suggest that in these systems there is a larger inaccessible dissolved solids portion. The NaCl tracer run was the cleanest system, and was indicated as such with an
asymptotic value of 0.97. Perhaps the absence of the large organic and inorganic portions attributable to black liquor allowed for a near theoretical occurrence.

Envelope confidence intervals are shown in Appendix G for those equations in Figs. 27-30. The confidence interval for the NaCl tracer run does include the asymptotic value of 1.0. However, in the mock mill runs for all of the simulated drums, the confidence intervals did not include 1.0. This is indicative of an inaccessible dissolved solids portion that must be accounted for by a method other than Cullinan's equation. In examining the confidence intervals of the slope, or system constant, note that the scales are not identical. Respectively, the intervals of the slopes for simulated drums 1-3 are approximately 1.5, 0.8, and 0.55. In the cleaner washing systems for the mock mill run, a reduction in scatter is evidenced by smaller intervals. The interval for the slope in the NaCl tracer run is approximately 0.65.

The lab data generated in the mill washer simulation appears to fit the same curves that were generated for the mock mill run. This is especially apparent in Figs. 28 and 29. However in Fig. 30 the mill washer simulation lab data falls lower than the equation of the line for drum 3 of the mock mill run. This may be explained by the fact that in the mock mill run the average vat liquor percent dissolved solids was 1.8%, while in the mill washer
simulation the average vat dissolved solids was approximately 1.0%. Perhaps the larger amount of dissolved solids available for washing in the mock mill run resulted in a higher washing efficiency.
CHAPTER VI

SUMMARY OF RESULTS

In the NaCl tracer run the results indicate the laboratory washer is functioning in agreement with a mill washer, i.e. as dilution is increased, the washing efficiency also increases. In agreement with theoretical models, with further increases in dilution the washing efficiency responds nonlinearly: as laminar, not plug flow exists in the displacement zone. Changes in dilution resulted in reproducible changes in data. Expected dilution levels were not obtained because the actual mat fiber concentrations differed from what was used as setup data.

Reproducible results and trends that characterize a vacuum drum washer were seen in the mock mill run. However, as the washing system became dirtier, i.e. higher dissolved solids in the pulp and shower liquid, more data scatter was seen. Also, it was noticed that at a given dilution, displacement ratios decreased in order from drum 3 to 1. Drum 1 efficiencies in a mill washer are usually the highest, due to entrainment effects on the other drums. Because the lab washer is not capable of simulating entrainment, there were no efficiency reductions seen in drums 2 and 3.
Increased scatter and efficiency reductions may be a result of mixing and channeling seen in those higher viscosity systems having the higher dissolved solids content. It was hypothesized in a comparison with Perkin's data that, as the washing system becomes cleaner, the relationship between displacement ratio and dilution approaches theoretical.

Data was very reproducible for the mill washer simulation, as all data points passed an outlier test. T-tests indicated that there may be no significant difference between the lab and mill displacement ratios for drum 2. When a correction was made to the lab data, the test indicated there may be no significant difference between the lab and mill displacement ratios on drum 3.

The lab mat fiber consistencies, especially on drum 2, were being dewatered to a greater degree than on the mill vacuum drum washer. A correction was made based on equivalent fiber consistencies between the mill and lab. Apparently, the greater dewatering occurring in the lab, was a result of differences in vacuum levels between the vacuum drum washer and the lab washer.

Relatively small deviations were seen between mill displacement ratios for drums 1 and 3, however on drum 2 the results were quite variable. This deviation on drum 2 was a result of problems occurring within that drum, or an error in sampling. A check of laboratory vacuum levels
and respective mat dewatering indicated that to achieve the fiber consistency of the mill mat, between 2.5 in. and 4.5 in. Hg was necessary, not 16 in. Hg, as recorded on the washer's drop leg.

The corrected lab displacement ratios for drum 1 were less than 10% from the mill displacement ratios, while on drum 3 they were approximately equal. The lab correction for drum 2 increased the error to over 17% from the mill’s displacement ratio. Although, when only the mill DR’s on drum 2 that were similar to drum 3 were considered, the corrected error was reduced to 9.6%. The over correction in drum 2 may be a result of the lab washer’s inability to simulate entrainment and/or inaccurate mill data, or a flaw in the correction technique.

A highly significant equation resulting in a system constant for the NaCl tracer run was determined. In this equation the slope of the line is the system constant, which is descriptive of how the displacement ratio changes as a function of dilution. This system constant is specific for a specific pulp under specific operating conditions.

The equations for the system constant plots for the mock mill simulation were not as significant as with the NaCl tracer run. Although as scatter was reduced, or on the cleaner drums, the equations became more significant. It was noticed in a summary plot that when wash liquor
ratios only under 2.0 were considered, (the NaCl tracer run's maximum WLR was 1.5), the significance of the equation improved. Either the lab washer was not operating properly at higher dilutions, or Cullinan's system constant equation does not explain the deviation from theoretical at wash liquor ratios greater than 2. Higher displacement ratios were seen for a wash liquor ratio in the NaCl tracer run when compared to the mock mill run, again perhaps cleaner washing stages function closer to a theoretical level.

As discussed, the use of Cullinan's system constant equation may not be an accurate method for describing deviation from theoretical. It was hypothesized that an inaccessible dissolved solids portion in the mat liquor limits the displacement ratio from being asymptotic to 1.0. A modification to Cullinan's theoretical equation, resulted in a new equation that better explained the DR/WLR relationship.

It appears that the lower dissolved solids (cleaner) stages have asymptotic values which are closer to 1.0. This is suggestive of larger inaccessible dissolved solids portions in the dirtier washing stages. Confidence intervals for all of the simulated stages in the mock mill run did not encompass the displacement ratio of 1.0. This indicates that in the work presented here, Cullinan's equation does not account for the inaccessible dissolved solids.
solids portion. The confidence intervals for the slopes, or system constants, are indicative of a reduction in scatter with cleaner stages, as evidenced by smaller intervals.

The lab data from the mill washer simulation fit well (exclusive of one stage) on the lines determined by the equations in the mock mill run. The one stage was hypothesized to not fit as well due to vat liquor concentration differences. The fit of this data between two different sets of similar samples exemplifies the reproducible results attainable with this laboratory washer.
CHAPTER VII

CONCLUSIONS

The laboratory apparatus that was constructed to simulate the displacement function as seen on a brownstock vacuum drum washer, generated reproducible data for a given set of runs. In addition, the laboratory washer appears to be capable of characterizing a displacement efficiency as a function of dilution for a pulp. Therefore in its present state, the apparatus could be used to optimize an existing brownstock vacuum drum washer. The effect of changes to both pulp characteristics, and wash water quality and quantity, could be analyzed using the laboratory washer.

It was not the sole intent in examining the relationship between wash liquor ratio and displacement ratio, to determine a system constant for those test conditions. The exercise was initiated so that one could see how data from an apparatus such as this, could be used in describing a relationship that occurs in a mill washer. Once a relationship is defined for a pulp at particular operating conditions, efficiencies and therefore carryover can be optimized for a dilution with mass balances.

An inaccessible dissolved solids portion in the mat
liquor was identified. This portion limits the displacement ratio from attaining a value of 1.0. The higher dissolved solids washing stages appeared to have larger inaccessible fractions, evidenced by their maximum attainable displacement ratios being furthest from 1.0.

Set up parameters for this apparatus are dependent on the desired mat fiber consistency. If the desired mat fiber content is not achieved, predetermined dilution is deviated from and hence an unrepresentative system efficiency results. It is therefore important to perform test runs to determine vacuum levels which are necessary to arrive at similar mat fiber consistencies as seen in the mill.

Due to the number of variables responsible for the operation of a brownstock washer, it is evident that dynamic simulation is difficult. Specific problems were seen with drum 2 in the mill washer simulation. In addition the general problem of mat consistency difference between the mill and the lab for the mill washer simulation exists. It appears that further research is needed, so that the present identifiable problems with the laboratory washer can be corrected. With further evolvement of the apparatus, and generation of data bases for specific pulps under specific operating conditions, the guesswork in designing a washing system for a particular end use may be eliminated.
CHAPTER VIII

RECOMMENDATIONS

The next simulation study should focus around a mill washer that allows for more representative sampling. Although the mill samples in this study were fairly consistent, except for drum 2, variations in fiber content and dissolved solids can occur across the discharge area of a mat. In addition, variations also occur across shower zones. Composite sampling in these areas might provide more reliable data.

Prior to mill simulation, a development of a correlation table between lab mat dewatering and lab vacuum is necessary. This would permit an approximate mat fiber consistency to occur in the lab washer as it did in the mill, thus allowing for more comparative results.

The shower head on the lab washer appeared to be functioning satisfactorily, however the spray pattern was not entirely full, i.e. the pattern resembled that of a shower, and not a shower bar. Also towards the end of several runs, with high alkalinity shower liquid, the holes in the head's face became eroded. It appears that a showering device that can give a 5 in. diameter, 0 to 100 ml/s full flow, at a 6 in. distance from the mat.
surface is required: a difficult engineering problem.

Although conductivity measurements can be misleading as to a combination of organic and inorganic content in a liquid sample, it might be useful in this application. The proper correlation between conductivity and dissolved solids could reduce tedious lab analysis and thus increase the usefulness of this apparatus.

A provision for simulating air entrainment in the pulp and/or shower liquid should be investigated. Injection of air into the samples prior to a run might be useful. Perhaps dissolved oxygen measurements taken from a mill's drum could be correlated to an amount to inject in lab samples.

Hand squeezings provided a reproducible dissolved solids content for a mat sample. However, different squeezing techniques between operators result in varying contents. Therefore, to help eliminate the dependency of a washer's efficiency on the way dissolved solids is measured, a method which minimizes error within and between operators should be adopted.
REFERENCES


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**Appendix B**

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**SHOWER FLUID (g/20ml)**  
*Boil Over - sample loss*  

| SAMPLE 1 | SAMPLE 2 | 118 |
| Sample 1 | Sample 2 | |
| .0045 | .0047 |  |

**Mock Mill Run - Drum 2 - Dissolved Solids Analysis**

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**Mock Mill Run - Drum 3 - Dissolved Solids Analysis**

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<td>8.24</td>
<td>8.34</td>
<td>8.36</td>
</tr>
</tbody>
</table>

**APPENDIX D**
### APPENDIX E

**Table: Milk Water Distribution - Daily Data Summary**

<table>
<thead>
<tr>
<th>Time</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>10.02</td>
</tr>
<tr>
<td>0.15</td>
<td>10.03</td>
</tr>
<tr>
<td>0.20</td>
<td>10.04</td>
</tr>
<tr>
<td>0.25</td>
<td>10.05</td>
</tr>
<tr>
<td>0.30</td>
<td>10.06</td>
</tr>
<tr>
<td>0.35</td>
<td>10.07</td>
</tr>
<tr>
<td>0.40</td>
<td>10.08</td>
</tr>
<tr>
<td>0.45</td>
<td>10.09</td>
</tr>
<tr>
<td>0.50</td>
<td>10.10</td>
</tr>
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</table>

**Figure: Milk Water Distribution - Daily Data Summary**

![Milk Water Distribution Diagram](image-url)
<table>
<thead>
<tr>
<th>MILL WASHER SIMULATION - DRUM 2 DATA SUMMARY</th>
<th>MILL WASHER SIMULATION - DRUM 2 DATA SUMMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN</td>
<td>RUN</td>
</tr>
<tr>
<td>10:17 I 10:17 I</td>
<td>11:11 I 11:11 I</td>
</tr>
<tr>
<td>TARGET DF</td>
<td>TARGET DF</td>
</tr>
<tr>
<td>4.61 I</td>
<td>3.67 I</td>
</tr>
<tr>
<td>ACTUAL DF</td>
<td>6.01 I</td>
</tr>
<tr>
<td>3.99 I</td>
<td>4.08 I</td>
</tr>
<tr>
<td>DR</td>
<td>DR</td>
</tr>
<tr>
<td>7.2 I</td>
<td>.68 I</td>
</tr>
<tr>
<td>WLR</td>
<td>3.78 I</td>
</tr>
<tr>
<td>1.65 I</td>
<td>.80 I</td>
</tr>
<tr>
<td>SHOWERTOTAL I/m</td>
<td>SHOWERTOTAL I/m</td>
</tr>
<tr>
<td>5262 I</td>
<td>4881 I</td>
</tr>
<tr>
<td>134 g</td>
<td>117 g</td>
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<tr>
<td>SHOWERTOTAL g</td>
<td>SHOWERTOTAL g</td>
</tr>
<tr>
<td>132.73 I</td>
<td>116.83 I</td>
</tr>
<tr>
<td>SHOWERTOTAL %</td>
<td>SHOWERTOTAL %</td>
</tr>
<tr>
<td>99.05 I</td>
<td>99.01 I</td>
</tr>
<tr>
<td>VAT TOTAL I/m</td>
<td>VAT TOTAL I/m</td>
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<tr>
<td>37821 I</td>
<td>39509 I</td>
</tr>
<tr>
<td>980 g</td>
<td>1024 g</td>
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<td>VAT FIBER g</td>
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<tr>
<td>11.20 I</td>
<td>11.62 I</td>
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<td>VAT FIBER %</td>
<td>VAT FIBER %</td>
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<tr>
<td>4.05 I</td>
<td>4.38 I</td>
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<tr>
<td>VAT LIQUOR DS %</td>
<td>VAT LIQUOR DS %</td>
</tr>
<tr>
<td>4.42 I</td>
<td>4.89 I</td>
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<tr>
<td>VAT WATER %</td>
<td>VAT WATER %</td>
</tr>
<tr>
<td>94.48 I</td>
<td>94.01 I</td>
</tr>
<tr>
<td>VAT WATER g</td>
<td>VAT WATER g</td>
</tr>
<tr>
<td>3196 I</td>
<td>1064 I</td>
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<tr>
<td>VAT FIBER g</td>
<td>VAT FIBER g</td>
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<tr>
<td>1.47 I</td>
<td>1.78 I</td>
</tr>
<tr>
<td>VAT WATER %</td>
<td>VAT WATER %</td>
</tr>
<tr>
<td>84.25 I</td>
<td>97.93 I</td>
</tr>
<tr>
<td>RUN</td>
<td>TARTER DF</td>
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<tr>
<td>-------</td>
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</tr>
<tr>
<td></td>
<td>5.79</td>
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<tr>
<td></td>
<td>7.92</td>
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<tr>
<td></td>
<td>8.22</td>
</tr>
</tbody>
</table>

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Theoretical Laboratory Displacement Ratio Correction

<table>
<thead>
<tr>
<th>LAB MAT</th>
<th>MILL MAT</th>
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</thead>
<tbody>
<tr>
<td>Make-up</td>
<td>Shower Water</td>
</tr>
<tr>
<td>Shower Water + DS</td>
<td>Shower Water</td>
</tr>
<tr>
<td>Shower Water</td>
<td>Shower Water</td>
</tr>
<tr>
<td></td>
<td>79.45% 85.90%</td>
</tr>
<tr>
<td>Shower DS</td>
<td>Shower DS</td>
</tr>
<tr>
<td>Vat Water</td>
<td>Vat Water</td>
</tr>
<tr>
<td></td>
<td>.759g 1.515g</td>
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<tr>
<td>Vat DS</td>
<td>Vat DS</td>
</tr>
<tr>
<td></td>
<td>1.30% 1.68%</td>
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<tr>
<td>Fiber</td>
<td>Fiber</td>
</tr>
<tr>
<td></td>
<td>11.20g 12.42%</td>
</tr>
<tr>
<td>DR = .82</td>
<td>DR = .72</td>
</tr>
</tbody>
</table>

The total mill mat components equal 90.18 g. The components of the lab mat equal 58.21 g, thus giving a make-up quantity of: 90.18 g - 58.21 g = 31.97 g of dissolved solids and water from the shower liquid. By using equation 2, a new DR for the lab mat can be calculated. DR = Ws/Wp

The shower water and dissolved solids, and vat water and dissolved solids are calculated by subtracting the fiber (11.20 g) from the total quantity (58.21 g) which equals 47.01 g. From the above definition of DR, the contributing shower water and dissolved solids can be calculated: 47.01 g (.82) = 38.5 g.

Therefore: DR=(38.5g+31.97g)/(47.01g+31.97g)= .89
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