Alternate Models of Centrifugal Cleaners for the Paper Industry

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Western Michigan University

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ABSTRACT

Clean pulp is essential to the optimum operation of any paper machine. The hydrocyclone is the most space, energy and cost efficient method to remove both heavy and light contaminants from a papermaking slurry. The efficiency of a hydrocyclone cleaner increases as the amount of removed contaminants increases. An efficient hydrocyclone allows the least amount of usable fiber to be lost in the cleaning process. Bradley devised a mathematical model to measure the efficiency of a hydrocyclone, and it is still the accepted model today. Several problems may exist with the Bradley Model as it applies to paper making slurries. A term for the consistency of the slurry is non-existent. This may or may not be an issue; but further examination is necessary. Ferguson has proposed a model, which does include a term related to consistency. This project evaluated the Bradley Model and Ferguson Model. The results showed that the Ferguson model better predicted the efficiency of the hydrocyclone at the consistency levels of 1%, 0.5% and 0.25% and fiber lengths of 0.89mm and 1.17 mm used in the projects. The Bradley Model was found to be reasonably accurate for longer fiber and higher consistencies. Viscosity of the suspension was found to be the major driver in both the value of the model parameters and the actual efficiency of the cleaner.
ACKNOWLEDGEMENTS

I would like to begin by thanking the Carl and Winfred Lee Honors College at Western Michigan University for their generous financial award to allow this work to be performed. Without the benefit of this award, the resources for this research would not have been available to me.

Secondly, I wish to thank the staff of the Paper Pilot Plant at Western Michigan University for their generous donation of machine time, knowledgeable staff, and facilities in which to perform the numerous hours of work involved in this project. I also wish to thank Dr. Raja Aravamuthan for his all the guidance and assistance he has lent to this project. There is no doubt that without his dedication to the students, this project and many others would not have been possible.

Finally I would like thank my fiancée, Heather, for the countless times she read a paper that was poorly written, the many hours she listened to me babble about topics she had no interest in, and all the support that she showed to me.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>iv</td>
</tr>
<tr>
<td>STATEMENT OF PROBLEM</td>
<td>1</td>
</tr>
<tr>
<td>LITERATURE SURVEY</td>
<td>4</td>
</tr>
<tr>
<td>EXPERIMENTAL PLAN</td>
<td>7</td>
</tr>
<tr>
<td>Discussion of Experimental Plan</td>
<td>8</td>
</tr>
<tr>
<td>BUDGET &amp; FACILITIES</td>
<td>11</td>
</tr>
<tr>
<td>RESULTS &amp; DISCUSSION</td>
<td>12</td>
</tr>
<tr>
<td>CONCLUSION</td>
<td>17</td>
</tr>
<tr>
<td>RECOMMENDATIONS</td>
<td>18</td>
</tr>
<tr>
<td>APPENDICES</td>
<td></td>
</tr>
<tr>
<td>I. Variables in the cleaner runs</td>
<td>19</td>
</tr>
<tr>
<td>II. Experimental data &amp; results</td>
<td>20</td>
</tr>
<tr>
<td>III. Calculations</td>
<td>21</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>23</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Effect of consistency and fiber length on cleaner efficiency</td>
<td>12</td>
</tr>
<tr>
<td>2. Effect of consistency and fiber length on Bradley Model parameter $d_{50}$</td>
<td>13</td>
</tr>
<tr>
<td>3. Effect of consistency and fiber length on Ferguson Model Parameter M</td>
<td>14</td>
</tr>
<tr>
<td>4. Viscosity of all long fiber (1.17 mm) feed, accept and reject samples at various consistencies (1%, 0.5%, 0.25 %)</td>
<td>15</td>
</tr>
<tr>
<td>5. Viscosity of all short (0.89 mm) feed, accept and reject samples at various consistencies (1%, 0.5%, 0.25 %)</td>
<td>16</td>
</tr>
</tbody>
</table>
STATEMENT OF PROBLEM

The accepted model applied to centrifugal cleaners today is the Bradley Model. The model was first developed for the mining industry to remove solid particles from a water suspension. This same theory was applied to the paper industry in the 20th century. However, it is not certain if this model can be applied effectively to a suspension of paper fibers, water and unwanted contaminants.

Centrifugal cleaners are used to separate undesirable material from a suspension or slurry in the industrial process. Accelerating the suspension within a small, enclosed cone and allows the heavier particles to be separated from the bulk solution. The specific gravity of the particles is usually the criterion for separation. This is good for paper slurries because paper fibers have a specific gravity close to that of water. Particles that have a significantly larger specific gravity are pushed to the outer edge of the cleaner, fall to the bottom, and are pushed upward to the reject stream by the inner vortex. The main advantage of this system is that it is quick, efficient, and requires very little maintenance.

A previous thesis (Vought, 1999) applied the Bradley Model to paper solutions using an electronic process simulation tool. This simulation was found to be unsuccessful. The model did not hold true for a paper fiber solution, but did give accurate results for a mixture of sand in water. This leads to the following questions. Why did the Bradley Model give erroneous results for the pulp solution? If the Bradley Model is not applicable to the paper industry, does a model exist that is applicable? These questions need to be answered to give a clear picture of what happens to pulp solutions within centrifugal cleaners. Does fiber-to-fiber bonding within the cleaner play
a role? Do the operating parameters of the cleaners have a significant effect? The answers to these questions are the goals of this project.

The objectives of this project are to evaluate the Bradley Model of centrifugal cleaners, understand why the model does or does not apply to slurries of cellulose fibers, and examine other models in this regard.
The Bradley Model is the most accepted model for centrifugal cleaners. However, this model may not fully explain the interaction as particles are removed from paper pulp. Paper pulp is a slurry of fibrous cellulose particles that have the potential to interact with each other. The Bradley Model is not specific to fibrous cellulose material; leaving the possibility that all factors may not have been considered when the Bradley Model was used to simulate the actual conditions of separating unwanted particles from a paper pulp slurry in a hydrocyclone.

The Bradley Model (Bradley 1965) states that:

$$d_{50} = \frac{3 \times 0.28^n}{\alpha} \left[ \frac{\eta D_c (1 - R_f) \times \tan \Theta}{Q (\sigma - \rho)} \right]^{0.5} \frac{x D_i}{D_C}$$

Where:

- $\alpha = 0.45$
- $\eta = \text{absolute viscosity of the suspending fluid (kg/m}\cdot\text{s})$
- $\rho = \text{fluid density (kg/m}^3\text{)}$
- $\sigma = \text{particle density (kg/m}^3\text{)}$
- $D_c = \text{hydrocyclone primary diameter (m)}$
- $D_i = \text{inlet diameter (m)}$
- $Q = \text{feed flow rate (L/sec)}$
- $R_f = \text{flow split ratio}$
- $\Theta = \text{cone included angle (°)}$
- $d_{50} = \text{particle diameter at which 50% of the particles are removed}$
The Bradley Model analyzes the hydrocyclone by $d_{50}$, the particle diameter at which 50% of the unwanted particles are removed. This is a standard way to measure the efficiency of a centrifugal cleaner. However, several factors may not be accurate when the Bradley Model is applied to paper pulp slurries. Bliss (1997) points out that the most obvious problem is that there is no term in the Bradley Model for the consistency of the slurry. However, Bliss (1997) also says that consistency appears to have some effect on the efficiency of the cleaner. Even though a term for viscosity does exist in the Bradley Model, Ferguson (1988) claims that this does not accurately describe the interaction between fibers. Ferguson (1988) has developed a model which takes into account the properties of the paper pulp slurry.

Ferguson’s model introduces the parameter $M$, which is defined as:

$$M = \frac{\rho B R^{n+3/2} V_0^{n-1}}{\mu_p L^2 |\gamma_p|^{1-n}}$$

Where:

- $\rho$ = the fluid density (kg/m$^3$)
- $B$ = constant of the volume flux of the cleaner
- $R$ = radial coordinates
- $V_0$ = spin velocity (m/s)
- $\mu_p = \eta_p L^2$ (centipoise/m$^2$)
- $n$ = flow index (unitless)
- $\eta$ = viscosity (centipoise)
- $\gamma_p$ = shear rate coefficient (unitless)
This parameter is a property of the fluid and can be used to help predict the efficiency of a cleaner. The fiber slurries observed by Ferguson (1988) demonstrated properties of Newtonian fluids, non-Newtonian fluids, and the characteristics of solid-liquid flow. This makes the viscosity of the slurry hard to predict once it is in the hydrocyclone. Ferguson (1988) also claims that fibers may form networks and act like viscoelastic solids. Bliss (1994) also believes that cellulose fibers may be extreme macro polymers and form networks. This explains Ferguson’s (1988) belief that the networks formed by fibrous slurries suppress turbulence when many fibers are present. It also stands to reason that when fewer fibers are present, there will be less suppression of turbulence. As a result, Ferguson (1988) believes that if the consistency is low, the suppression of turbulence will be low, and thereby the cleaner will be more efficient the. In fact, Ferguson’s (1988) model proved experimentally that cleaners were more efficient when the feed consistency was below 0.5%. One possible reason according to Paul (2000) is that higher viscosity decreases the amount of flocs in the slurry (Paul). With less fibers there will be less flocs and contaminants have less chance of being trapped with a floc and therefore accepted. Paul and others (2000) showed that the passage ratio of a pressure screen increased with higher viscosity. The same principle can be applied to hydrocyclone cleaners. With increased viscosity, the fibers have less chance to entangle, allowing fewer good fibers to be rejected because they are entangled with other fibers.

According to Kerr (1983) the bottom line in any evaluation of the cleaner design is the efficiency of the cleaner. Ferguson (1988) found that the efficiency of the cleaner decreased as the consistency of the feed stream increased. In addition, the efficiency increased as the particle size increased.
Centrifugal cleaners are important tools in the paper making process. Modeling has significantly affected the way hydrocyclones are produced and operated (Bliss, 1988). Still, the interactions within the system are not yet fully understood. Many possible explanations are currently available to the paper industry. Only experimentation will tell if any of these will become significant in the future.
EXPERIMENTAL PLAN

There are several theories as to how a cellulose fiber slurry reacts in a hydrocyclone. The objective of this project is to evaluate two models and determine which, if any is applicable to a papermaking slurry. The basic questions that must be answered are: Is the Bradley model useful for slurries of cellulose fibers? Is the paper industry using parameters outside of those limits applicable to the Bradley Model?

If the properties of the slurry itself are found to be outside the parameters of the model, the next logical step is to determine which properties of the cellulose slurry do not allow the Bradley Model to work. Particle size is the first factor that may contribute to the problems with cellulose fiber slurries. Another possibility is the interaction between the particles. In order to completely answer the questions, several simple experiments can be performed.

In all experimental runs, a single cone of the Beloit Posiflow Hydrocyclone cleaner located in the Western Michigan University Paper Pilot Plant was used. Two different fiber slurries were made up. The first was heavily refined to a particle size of 0.89 mm and the second furnish, not refined in any way, and had a particle size of 1.17 mm. With both furnishes, experiments began with one hundred pounds of the same softwood kraft pulp. To each slurry, ten pounds of "black sand" was added as a contaminant. This sand was obtained from the Construction Engineering Department at Western Michigan University. It is also known as “Foundry Sand”. It was chosen because it was believed that the dark color would show easily in optical analysis and was
found to have a specific gravity of 1.422, which is significantly different from water leading to high rejection in the cleaner.

The cleaner was then run under normal operating conditions. The inlet feed rate was kept nearly constant at ninety gallons per minute. Each sample was allowed to run through the hydrocyclone for several minutes before samples of the feed, accept, and reject streams were taken in five-gallon buckets. The original slurry was then diluted from 1% consistency to 0.5% consistency and the same procedure was followed. Samples were taken from the feed, accept and reject streams in buckets. The slurry was then diluted to 0.25% consistency and run through the cleaner again.

The second part of the experiment involved the slurry of unrefined fiber. Another ten pounds of "black sand" was added and the same procedure was followed again. The consistency was varied from 1% to 0.5% to 0.25% and samples were taken from the feed, accept, and reject streams.

With all samples in hand, tests were performed for viscosity, consistency and density before three hand sheets were made from each bucket on British hand sheet makers according to TAPPI standard T205 om-88. These sheets were then taken and analyzed optically by scanning for dirt count. This was done with Spec\*Scan 2000 - V.1.2.18 software in the Western Michigan University Paper Testing Labs. The PPM/m² was used as the measurement for all sheets. The data from the dirt counts were then used to calculate both the reject rate and the efficiency of the cleaner. Additional measurements were also made on the cleaner cone itself to determine diameter, cone angle, inlet diameter and distance to the vortex finder. These data were used to calculate the mathematical model for each trial run.
Discussion of Experimental Plan

To determine whether or not the particle size is the issue it was necessary to obtain fibers of an extremely small particle size. This was easily accomplished by refining a slurry of known fiber characteristics, wood species and fiber length. The refining was harsh enough to cut the fiber to a particle size of 0.89 mm. These fiber particles can then be used, along with an easily removed known contaminant to evaluate the Bradley Model by attempting to recreate particles of the size of the coal dust used in Bradley’s original experiments.

The $d_{50}$ of the hydrocyclone was found for each run using Bradley’s equations. The $d_{50}$ particle can be calculated once the parameters of the hydrocyclone and the papermaking slurry have been established. The cone angle, cone diameter, inlet diameter, and reject diameter are properties of the Beloit Posiflow Hydrocyclone being used. These did not change the outcome from trial to trial as they will be held constant throughout the project. This left the size of the cellulose fibers as the only variable.

The next issue is to evaluate the Ferguson Model to observe if it can describe the interaction with cellulose fibers in the hydrocyclone more accurately. The parameter “$M$” was calculated using measured values for several different furnishes and consistencies to discern the validity of this model. The “$M$” parameter is believed to be a function of the consistency of the slurry. Therefore, the slurry consistency was varied from $1\%$ to $0.5\%$ to $0.25\%$ to observe if this change had any effect on the efficiency or the reject rate of the slurry. With all parameters of the hydrocyclone kept constant, the parameter $M$ was varied in both directions from Ferguson’s suggested value of less than 45.
With these data in hand, a judgement can be made on the Ferguson Model. If the $M$ value correlates well with the consistency, then an optimum fiber concentration can be established for future use. This will determine if the model has practical application. If consistency does in fact play a role in the hydrocyclone, then Ferguson’s model can be incorporated to different contaminant sizes and types within different furnishes.
BUDGET & FACILITIES

A grant from the Undergraduate Research Award Program was obtained in order to cover the expenses of this project. The Paper Pilot Plant at Western Michigan University donated the machine time and manpower necessary to run the hydrocyclone cleaner. The student was able to operate the equipment with the help of the pilot plant staff and collect all the required data. The time required was one day of pilot plant operation and several days of lab time to generate the test results. A Kajaani FS-100 fiber length analyzer located at Western Michigan University was used for fiber length analysis.
RESULTS & DISCUSSION

This project showed that the Ferguson Model of hydrocyclone cleaners was more effective at predicting the cleaner efficiency than the Bradley model. The results showed that the Ferguson parameter “M” more closely followed the trend set by the experimental data for both short and long fibers.

The cleaner was shown to be more efficient at a short fiber length as shown in Figure 1. It can also be see that in this experiment, the efficiency increases and approaches the same point for both short and long fibers as the consistency increases. This is in conflict with the original hypothesis by Ferguson that the efficiency will increase as the consistency decreased. In fact, in both reject rate and efficiency the value of the index increases as the consistency increases.

![Figure 1. Effect of consistency and fiber length on cleaner efficiency.](image-url)
As Figure 2 shows, the Bradley Model, while reasonably accurate for long fibers, shows very little change in $d_{50}$ value for short fibers. This is completely in opposition with the thought that the Bradley Model is inaccurate because it was originally designed for small dust particles.

It is important to note that neither model actually calculates the efficiency of the cleaner. Both model parameters are correlations to efficiency. The shape and slope of the following graphs was used to draw the conclusions in this project, not the actual values.

![Graph showing effect of fiber length and consistency on Bradley Model parameter $d_{50}$](image-url)

**Figure 2.** Effect of fiber length and consistency on Bradley Model parameter $d_{50}$.

For both short and long fibers, the increasing consistency does show an increasing efficiency. This increase is extremely small when the short fibers are considered.
The Ferguson Model, however, gave a reasonably accurate prediction for both short and long fibers as shown by Figure 3. Both curves follow the same general shape as the efficiency curves in Figure 1.

![Figure 3. Effect of consistency and fiber length on Ferguson Model parameter M.](image)

When short fibers are considered, the curve begins high, falls to a lower value around 0.5% consistency, and then rises again around 1%. This is the same basic pattern as the efficiency curve. When long fibers are considered, the curve stays basically the same from 0.25% to 0.5% consistency and then sharply increased after 0.5% to reach almost the same point as the short fiber curve. Again, this is basically the same as the efficiency curves.

Reject rate was not given as much credence as efficiency in this project because of the method of analysis. It is believed that the optical analysis was not able to pick out the correct amount of sand. This may be a result of sand buried with the fibers. This was
discovered when one set of sheets was fired to test this theory. The sheet, from the 0.5% 1.17 mm fiber trial, revealed an efficiency that closely correlated to the calculated efficiency from the optical analysis. However, the reject rate from this burn was significantly different leading to the rejection of the reject rate as a legitimate value.

Once all the results were in and calculations completed, a search began for a driving force, common in all models. It was discovered that the viscosity taken from the sample of each run could in fact be the deciding factor. When 1.17mm fibers are considered, the viscosity increased with higher consistency (see figure 4). This is similar to the trend seen in Figures 1 and 2 for long fibers.

![Figure 4. Viscosity (cp) for all long fiber (1.17mm) feed, accept and reject samples at various consistencies (1%, 0.5%, 0.25%).](image)

The same case can be made for short fibers. Figure 5 shows the same general trend as in figures 1 and 2 for 0.89mm fibers. This further suggests that the viscosity may be the deciding factor in the efficiency of the cleaner. Now the question becomes why does viscosity have such an impact on the efficiency of a hydrocyclone cleaner.
Figure 5. Viscosity for all short (0.89mm) feed, accepts and reject samples at various consistencies (1%, 0.5%, 0.25%).
CONCLUSIONS

This project showed that the Ferguson model of Hydrocyclone cleaners was more effective at predicting the overall efficiency of the hydrocyclone cleaner than the Bradley Model. The Ferguson model was reasonably accurate predicting efficiency for both short and long fibers, while the Bradley Model was somewhat accurate for only long fibers. This is the opposite of what was expected since the Bradley Model was developed for small dust particles. The major factor in efficiency was found to be viscosity. While the viscosity of the slurry is hard to determine, it does appear to play a significant role in the efficiency of the system. Higher viscosity leads to less flocs and fewer entangled fibers. The efficiency of a cleaner is also affected by the consistency of the slurry and fiber length to some degree. While both short and long fibers were found to approach the same efficiency as consistency increased, short fibers lead to higher efficiencies at lower consistencies.
RECOMENDATIONS

In this project, viscosity was found to be the driving factor in both the model parameters and the actual efficiencies of the cleaners. It is not fully understood what effect viscosity has on a pulp slurry in a hydrocyclone. This bears further investigation. In particular, why the viscosity of the 0.89 mm fibers did not follow the same general trend of the 1.17 mm fibers. It is suggested that more experimentation be performed with short, refined fibers and viscosity variations. In addition, slurries whose viscosities are modified by the addition of some chemical, such as carboxyl methylcellulose, could be run through the hydrocyclone. This would give an accurate picture of the effect of viscosity in a hydrocyclone cleaner.
## APPENDIX I

Variables in the cleaner runs

<table>
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<tr>
<th>Run #</th>
<th>Fiber Length</th>
<th>Feed Flow Rate</th>
<th>Feed Consistency</th>
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<tr>
<td>1</td>
<td>0.89 mm</td>
<td>85.8 gpm</td>
<td>1.01%</td>
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<tr>
<td>2</td>
<td>0.89 mm</td>
<td>91.6 gpm</td>
<td>.514%</td>
</tr>
<tr>
<td>3</td>
<td>0.89 mm</td>
<td>91.4 gpm</td>
<td>.266%</td>
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<td>4</td>
<td>1.17 mm</td>
<td>87.0 gpm</td>
<td>.886%</td>
</tr>
<tr>
<td>5</td>
<td>1.17 mm</td>
<td>91.6 gpm</td>
<td>.483%</td>
</tr>
<tr>
<td>6</td>
<td>1.17 mm</td>
<td>91.4 gpm</td>
<td>.269%</td>
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## Appendix II

### Experimental Data and Results

<table>
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<tr>
<th>Sample</th>
<th>PPM/m²</th>
<th>Viscosity (cp)</th>
<th>Reject Rate</th>
<th>Efficiency</th>
<th>d50</th>
<th>M</th>
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<tr>
<td>L-.25-acc</td>
<td>1652.733</td>
<td>51.6</td>
<td>44.08054031</td>
<td>0.37290365</td>
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APPENDIX III
Calculations

Bradley Model Calculation

\[
\begin{align*}
\alpha &= .45 & Dc &= 2 \text{ in} & Rf &= .5 & n &= .5 \\
\Theta &= .087 \text{ rad} & Di &= 1.5 \text{ in} & \rho &= .00097 \frac{\text{kg}}{\text{cm}^3} & \eta &= 39.1 \cdot 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}} & Q &= 91.4 \frac{\text{gal}}{\text{min}} \\
\end{align*}
\]

\[
\begin{align*}
d_{50} &= \frac{3 \cdot 28^n}{\alpha} \left[ \tan (\Theta) \cdot \eta \cdot Dc \cdot (1 - Rf) \right]^5 \frac{Di}{2 \cdot Q \cdot (\sigma - \rho)} \\
d_{50} &= 0.011
\end{align*}
\]

Ferguson Model Calculation

\[
\begin{align*}
B &= 5 & \rho &= .001422 \frac{\text{kg}}{\text{cm}^3} & \mu_p &= 10 \frac{\text{N} \cdot \text{m}}{\text{s}^2} & \eta &= 39.1 \cdot 10^{-3} & Vo &= 1.264 \\
R &= .508 & \gamma_p &= 100000000 & n &= \frac{1}{3} & \mu_p &= 10 \frac{\text{N} \cdot \text{m}}{\text{s}^2} \\
\gamma_p &= 10000000 & n &= \frac{1}{3} \quad \mu_p &= 10 \frac{\text{N} \cdot \text{m}}{\text{s}^2} & \eta &= 39.1 \cdot 10^{-3} & Vo &= 1.264 \\
y &= R \left[ \left( \frac{3}{2} \right) - \frac{1}{2} \right] \frac{\text{m}}{\text{m}} & x &= Vo \left( 1 - \eta \frac{m}{s} \right) \\
M &= \frac{(\rho \cdot B \cdot y \cdot (x))}{\mu_p \cdot L^2 \left[ \left( \gamma_p \right)^{1 - \eta} \right]} \\
M &= 5.287 \cdot m^{-7} \cdot s^3
\end{align*}
\]
APPENDIX III

Calculations

Reject Rate

\[ RR = \frac{116175.733}{1652.733} \]

RR = 44.0805

Efficiency

\[ E = \frac{(2635.533 - 1652.733)}{2635.533} \]

E = 0.3729
REFERENCES


9. TAPPI Standard Procedure 1988 Forming Handsheets for physical testing of pulp Pulp Properties Committee of the Process Quality Division of TAPPI