PART II

POWER CONSUMPTION
CHAPTER I

MEASUREMENT OF THE POWER CONSUMPTION

HITHERTO we have dealt with the mode of operation of the beater, its output, and the character imparted to the stuff, without taking any account of the power consumption. The question of power consumption, however, is of equally great importance in any thorough investigation of the beating problem. The beaters are frequently the largest power-consuming aggregates in the mill, so that a few per cent. of saving may be of considerable economic importance. Moreover, the beaters absorb a large number of horse power which are wasted in the sense that they do not contribute to the actual beating of the stuff. The power which is consumed in the actual beating of the stuff is often only 25 to 50 per cent. of that required to drive the beater. It is, therefore, important to investigate not only the power used for beating but also the losses which occur.

Let \( N_M \) be the number of horse power required for the actual beating of the roll against the bedplate. (Power consumption of beating tackle.)

" \( N_R \) be the power required merely to rotate the roll in the stuff (circulation and friction).

And let \( N_{LP} \) be the balance of the power consumption which represents chiefly friction losses in the bearings.
THE ACTION OF THE BEATER

The value of $N_{1,p}$ can be calculated from the bearing pressures, which vary with $P$, the roll pressure.

If $N$ is the total number of horse power consumed by the beater, we then have

$$N = N_M + N_R + N_{1,p} \quad \ldots \quad (17)$$

Let $N_{1,o}$ be the power consumption when the beater is empty and the roll lifted clear. This is the no-load power consumption and represents bearing losses and a little air resistance.

If now the beater is filled and the roll rotates in the stuff without beating, the power consumption will be

$$N_i = N_R + N_{1,o} \quad \ldots \quad (18)$$

The values of $N$, $N_C$, and $N_{1,o}$ can be directly measured where direct electric drive is available. The value of $N_{1,p}$ can be calculated with fair accuracy, as will be shown later, and we then have from equations (17) and (18)

$$N_M = N - N_i + (N_{1,o} - N_{1,p}) \quad \ldots \quad (19)$$

Several authors\(^1\) have laid down for the value of $P$ the following expression:

$$N_M = \frac{\mu P_n}{75} \quad \ldots \quad (20)$$

where $\mu$ is termed the beating coefficient.

From equation (18) we have

$$N_R = N_C - N_{1,o} \quad \ldots \quad (18a)$$

This portion of the power consumption is absorbed in the following two ways: for the whipping of the flybars against the stuff (in the cells) and for overcoming the friction between the rotating bars and the stuff in the cells on the one hand and the stuff in the trough.

\(^1\) Kirchner, "Das Papier." IV., p. 39; Pfarr, "Hollaender," p. 10.
### BEATER TEST SHEET

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<td>87</td>
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<td>0</td>
<td>227</td>
<td>88</td>
<td>20.6</td>
<td>40.9</td>
<td>20.4</td>
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<td>88</td>
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**Diameter of Roll, D = 3,800 mm.**
**Length of Roll, L = 1,180 mm.**
**Fly Bars, 94 x 17 mm.**
**Bedplate Bars, 19 x 14 mm.**

**L = 3,880 m/sec for n = 127 r.p.m.**
**K = 13-4 m.**
**a = 23.6 m/sec when n = 127 r.p.m.**

**Filling, from 2 P.M. to 3.20 P.M.**
**Beating, from 3.20 P.M. to 6 P.M. = 5-35 hours, 15-8 H.P., 104-5 H.P. hours.**
**Washing, from 2 P.M. to 8 P.M. = 6 hours, 19-6 H.P., 117-6 H.P. hours.**
**No. Load, from 3 P.M. to 8.5 P.M. = 6-5 hours, 1-8 H.P., 10-9 H.P. hours.**

**Time to Empty and Wash Out = 40-5 H.P. hours.**

**Furrow, 19 Sulphate.**
2 Broke.
365 kg. Dry Stuf.
Consistency, 7-7 per cent.
Sheet,.............

**Total = 40-5 H.P., 233-0 H.P. hours.**

*By Schopper-Kingley Beating Tester.*
on the other hand. These two sources of loss of power can be allowed for separately as will be shown later.

The tests described below were carried out with two direct electric-driven beaters, allowing speed variations of 1 : 1.7.

The no-load losses, armature resistance, and field currents were very carefully measured. Millivolt and ammeters were installed and the efficiencies of the motors determined at all loads and all speeds, so that for any given kilowatt input the horse power output to the belt was always known. The belt pull was practically horizontal and the motor mounted on slide rails.

The no-load power consumption of the beater \((N_{LO})\) was measured before and after each test and the mean value taken into account in the calculations. \(N\) and \(N_c\) were frequently measured during the beating process. The value of \(N_{LP}\) had to be calculated, as it was not possible to measure it directly.

The subjoined specimen beater test sheet indicates how the values of \(N\) and \(N_c\) were determined during the tests. Each time \(N\) was determined from the voltmeter and ammeter readings, the roll was immediately raised and the value of \(N_c\) also measured. This naturally eased the load on the motor, causing it to speed up a little, and in determining the value of \(N_c\) allowance had to be made for the altered motor speed.

By way of example we shall now proceed to calculate the value of \(N_{LP}\) for experimental beater No. MIII3. The roll was fitted with steel flybars 17 mm. thick and weighed 3,115 kilos. The weight \((T)\) of the shaft was 600 kilos, and the weight \((U)\) of the pulley was 640 kilos. The pressure on the bedplate will as usual be denoted by \(P\). \(R\) is the pull in the slack side of the belt and \((R + r)\) the pull in the tight side. \(r\) is therefore the
effective tension. Figs. 22 and 23 indicate the forces which are in equilibrium during the rotation of the roll,

![Diagram showing forces acting on a roll](image)

Fig. 22 showing the vertically acting forces, while Fig. 23 shows the horizontally acting forces.

The vertical bearing pressures $A_L$ and $B_L$ can be found from the following equations:

\[
A_L + B_L = V + T + U - P,
\]

\[
A_L (a + b) = Vb + Tb_1 - Uc - Pb,
\]
and substituting in these equations the values shown in Fig. 22 we have

\[ A_L = 2263 - 0.073 \, \text{P} \]
\[ B_L = 2092 - 0.327 \, \text{P} \]
The values of $A_L$ and $B_L$ as well as those of $(A_L)^2$ and $(B_L)^2$ corresponding to various values of $P$ are shown in Table IV.

<table>
<thead>
<tr>
<th>P (kg.)</th>
<th>$A_L$</th>
<th>$B_L$</th>
<th>$A_L^2$</th>
<th>$B_L^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2,263</td>
<td>2,092</td>
<td>5,120,000</td>
<td>4,360,000</td>
</tr>
<tr>
<td>925</td>
<td>1,640</td>
<td>1,790</td>
<td>2,700,000</td>
<td>3,310,000</td>
</tr>
<tr>
<td>1,645</td>
<td>1,156</td>
<td>1,554</td>
<td>1,340,000</td>
<td>2,420,000</td>
</tr>
<tr>
<td>2,400</td>
<td>648</td>
<td>1,304</td>
<td>420,000</td>
<td>1,710,000</td>
</tr>
<tr>
<td>3,155</td>
<td>138</td>
<td>1,062</td>
<td>19,000</td>
<td>1,130,000</td>
</tr>
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Referring now to Fig. 23 and taking moments, the following equations are obtained for the horizontal bearing pressures, the friction in the bearings being neglected:

\[
A_v(a + b) + c(2R + r) = br \frac{D_1}{D_1'}
\]

\[
B_v(a + b) = (a + b + c)(2R + r) + ar \frac{D_1}{D_1'}
\]

where $D_1$ is the diameter of the pulley, and $D_1 = 1,350$ mm.

The effective tension ($r$) in the belt is:

\[
r = \frac{75 \times 60}{\pi} \text{ N} = \frac{1430}{D_1'} \text{ N}
\]

where $N$ is the number of horse power transmitted by the belt.

The diameter of the pulley was 2.3 m. and the speed $n = 125$ revs. per minute, so that

\[
r = \frac{1430}{2.3} \text{ N} \approx 5N.
\]

Taking the tension in the slack side of the belt to be 200 kilos ($R$) and substituting in the above equations, we get:

\[
A_v = 5N - 58
\]

and

\[
B_v = 8.5N + 458.
\]
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The values of $A_V$ and $B_V$ so obtained, as well as those of $(A_V^2)$ and $(B_V^2)$ corresponding to various horse powers, are given in Table V.

**Table V**

<table>
<thead>
<tr>
<th>N.</th>
<th>$A_V$</th>
<th>$B_V$</th>
<th>$A_V^2$</th>
<th>$B_V^2$</th>
</tr>
</thead>
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<td>H.P.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2.7</td>
<td>-45</td>
<td>481</td>
<td>2,000</td>
<td>232,000</td>
</tr>
<tr>
<td>10</td>
<td>-8</td>
<td>543</td>
<td>64</td>
<td>296,000</td>
</tr>
<tr>
<td>15</td>
<td>17</td>
<td>585</td>
<td>289</td>
<td>342,000</td>
</tr>
<tr>
<td>20</td>
<td>42</td>
<td>628</td>
<td>1,760</td>
<td>395,000</td>
</tr>
<tr>
<td>30</td>
<td>92</td>
<td>713</td>
<td>8,400</td>
<td>510,000</td>
</tr>
<tr>
<td>40</td>
<td>142</td>
<td>798</td>
<td>20,000</td>
<td>640,000</td>
</tr>
<tr>
<td>50</td>
<td>192</td>
<td>883</td>
<td>37,000</td>
<td>785,000</td>
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<td>60</td>
<td>242</td>
<td>968</td>
<td>58,600</td>
<td>940,000</td>
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Tables VI. and VII. give the values of the bearing pressures $A$ and $B$ calculated from their components $A_L$, $A_V$, and $B_L$, $B_V$ for various roll pressures $(P)$ and various horse powers transmitted by the belt.

**Table VI**

Bearing Pressure, $A = \sqrt{A_L^2 + A_V^2}$.

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<tr>
<th>P.</th>
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</thead>
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<tr>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td>kg.</td>
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</tr>
<tr>
<td>0</td>
<td>2,263</td>
</tr>
<tr>
<td>625</td>
<td>...</td>
</tr>
<tr>
<td>1,645</td>
<td>...</td>
</tr>
<tr>
<td>2,400</td>
<td>...</td>
</tr>
<tr>
<td>3,155</td>
<td>...</td>
</tr>
</tbody>
</table>
THE ACTION OF THE BEATER

TABLE VII

Bearing Pressure, \( B = \sqrt{B_L^2 + B_i^2} \).

<table>
<thead>
<tr>
<th>P. (kg.)</th>
<th>2.7</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60 H.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2,140</td>
<td>2,155</td>
<td>2,165</td>
<td>2,180</td>
<td>2,200</td>
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<td></td>
</tr>
<tr>
<td>625</td>
<td></td>
<td>1,870</td>
<td>1,885</td>
<td>1,900</td>
<td>1,930</td>
<td>1,960</td>
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<td></td>
</tr>
<tr>
<td>1,645</td>
<td></td>
<td>1,650</td>
<td>1,660</td>
<td>1,680</td>
<td>1,710</td>
<td>1,750</td>
<td>1,790</td>
<td></td>
</tr>
<tr>
<td>2,400</td>
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<td>1,430</td>
<td>1,450</td>
<td>1,490</td>
<td>1,530</td>
<td>1,575</td>
<td>1,625</td>
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</tr>
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<td>3,155</td>
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<td>1,210</td>
<td>1,235</td>
<td>1,280</td>
<td>1,330</td>
<td>1,380</td>
<td>1,440</td>
<td></td>
</tr>
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</table>

The coefficient of friction, \( \mu_L \), for the journal friction is calculated from the following equation:

\[
\mu_L (A + B) \cdot \frac{\pi d_L n}{60 \times 75} = N_{L_n}
\]

where \( A \) and \( B \) are the bearing pressures corresponding to the power consumption at no-load. In the present case \( n = 125 \) revs. per minute. The diameter of the journal \( d_L \) is 130 mm. and \( N_{LO} = 2.7 \) H.P. Therefore

\[
\mu_L = \frac{230}{A + B} = 0.053
\]

(the value of \((A + B)\), according to the tables, being 4,403 kilos for \( P = 0 \) and \( N_{LO} = 2.7 \)).

With a roll pressure \( P \), horse power transmitted by the belt \( N \), and at \((n)\) revs. per minute we get

\[
N_{L_P} = 0.053 (A + B) \frac{\pi d_L n}{60 \times 75}
\]

or with \( d_L = 130 \) mm. and \( n = 125 \) revs. per minute,

\[
N_{L_P} = 0.0006 (A + B).
\]

*The values for \( N_{L_P} \) (friction losses in the bearings) at 125 revs. per minute are shown in Table IX. as
calculated from this equation taken in conjunction with Table VIII.

**Table VIII.—Sum of the Bearing Pressures (A + B)**

<table>
<thead>
<tr>
<th>P.</th>
<th>2.7</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60 H.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg.</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>4.400</td>
<td>4.410</td>
<td>4.430</td>
<td>4.440</td>
<td>4.465</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>925</td>
<td>...</td>
<td>3.510</td>
<td>3.525</td>
<td>3.540</td>
<td>3.570</td>
<td>3.610</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>1,645</td>
<td>...</td>
<td>2.800</td>
<td>2.820</td>
<td>2.830</td>
<td>2.870</td>
<td>2.915</td>
<td>2.960</td>
<td>...</td>
</tr>
<tr>
<td>2,400</td>
<td>...</td>
<td>...</td>
<td>2.080</td>
<td>2.100</td>
<td>2.145</td>
<td>2.190</td>
<td>2.250</td>
<td>2.315</td>
</tr>
<tr>
<td>3,155</td>
<td>...</td>
<td>...</td>
<td>1.350</td>
<td>1.380</td>
<td>1.445</td>
<td>1.510</td>
<td>1.620</td>
<td>1.720</td>
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</table>

**Table IX.—Friction Loss, N_{LP}, in the Bearings**

Calculated for 125 Revs. per Minute

<table>
<thead>
<tr>
<th>P.</th>
<th>2.7</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60 H.P.</th>
</tr>
</thead>
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<tr>
<td>kg.</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.70</td>
<td>2.70</td>
<td>2.72</td>
<td>2.72</td>
<td>2.74</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>925</td>
<td>...</td>
<td>2.11</td>
<td>2.12</td>
<td>2.12</td>
<td>2.14</td>
<td>2.16</td>
<td>...</td>
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</tr>
<tr>
<td>1,645</td>
<td>...</td>
<td>1.68</td>
<td>1.69</td>
<td>1.70</td>
<td>1.72</td>
<td>1.75</td>
<td>1.78</td>
<td>...</td>
</tr>
<tr>
<td>2,400</td>
<td>...</td>
<td>...</td>
<td>1.25</td>
<td>1.26</td>
<td>1.29</td>
<td>1.31</td>
<td>1.35</td>
<td>1.39</td>
</tr>
<tr>
<td>3,155</td>
<td>...</td>
<td>...</td>
<td>0.81</td>
<td>0.83</td>
<td>0.87</td>
<td>0.92</td>
<td>0.97</td>
<td>1.03</td>
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</tbody>
</table>

The friction loss, N_{LP}, at other speeds with the roll raised can be found by assuming that the loss is directly proportional to the speed. Table X. gives the values calculated in this manner from the figures in the top row of Table IX. This method of calculation is not
strictly correct, as the belt tension will vary at different speeds; but for all practical purposes the error involved may be safely neglected.

Table X

<table>
<thead>
<tr>
<th>$n$</th>
<th>$N_{1,5}$</th>
<th>20</th>
<th>40 H.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>1.81</td>
<td>1.84</td>
<td>1.87</td>
</tr>
<tr>
<td>94</td>
<td>2.00</td>
<td>2.03</td>
<td>2.07</td>
</tr>
<tr>
<td>103</td>
<td>2.16</td>
<td>2.19</td>
<td>2.26</td>
</tr>
<tr>
<td>115</td>
<td>2.44</td>
<td>2.48</td>
<td>2.52</td>
</tr>
<tr>
<td>129</td>
<td>2.70</td>
<td>2.80</td>
<td>2.80</td>
</tr>
<tr>
<td>134</td>
<td>2.85</td>
<td>2.90</td>
<td>2.95</td>
</tr>
<tr>
<td>143</td>
<td>3.04</td>
<td>3.08</td>
<td>3.15</td>
</tr>
</tbody>
</table>
CHAPTER II

THE POWER CONSUMPTION OF THE BEATING TACKLE. SPECIFIC POWER CONSUMPTION

In the previous chapter the work done in beating between the roll and the bedplate was shown to be expressed by \( \mu P.v. \). The coefficient \( \mu \) is termed the beating coefficient, and we have seen how it is possible to measure the power consumption \( N_M \) of the beating tackle and so to determine the value of the beating coefficient.

In the literature on beating there are still evidences of uncertainty as to the nature of the beating coefficient. In the majority of cases it is regarded simply as a coefficient of friction. Some assume that the stuff is present between the roll and bedplate in a similar manner to the oil between a journal and bearing,\(^1\) while others appear to believe that there is direct friction between the roll and the bedplate.\(^2\) Again, there are those who regard the resistance to the rotation of the roll as being caused simply by friction between the surfaces of the bars and the stuff, looking upon both these as solid elements; while yet others \(^3\) consider that friction and shearing effects also occur in the interior of the thin layer of stuff between the bars, which effects

\(^{1}\) Pfarr, "Hollaender und deren Kraftverbrauch," pp. 10-11.
\(^{2}\) Clayton Beadle and Stevens, "Theory and Practice of Beating."
\(^{3}\) Kirchner writes in this sense, "Das Papier. IV.," p. 41.
contribute towards the beating of the stuff. In addition to all these factors there is yet another source of resistance to the movement of the flybars, namely the cutting resistance which originates from the cutting action of the bars. When a shearing machine is in operation, a resistance to the shearing action of the blades is set up at the exact point at which the blades intersect one another. Referring back to Fig. 4 on p. 25 it will be seen that there are two different sources of resistance to the movement of the top shear blade, viz.: (1) the actual shearing resistance of the material being worked, and (2) a frictional resistance due to the lateral pressure which holds the two blades close up together and prevents the material from being "jammed" between the blades. If it be assumed that the material to be cut is the same length as the lower shear blade (L) then the work done in cutting can be expressed as \( eL \), where \( e \) is the amount of work (measured in metre-kilograms) which is required to effect a cut 1 m. long. Even if the lateral pressure should be insufficient to keep the blades tightly pressed together, so that jamming occurs and the material instead of being severed is abraded on both sides, then the expression \( eL \) will still represent the work done by the upper blade during its downward movement in passing the lower blade; for \( e \) represents the work required to move the blades past one another over a cutting length of 1 m. The frictional work due to the lateral pressure also has to be taken into consideration in addition to the work \( e \).

Everything that has been said above of the shearing machine can be applied directly to the beater bars, having regard to the analogy which was developed in the earlier part of this book. The friction in question between the surfaces of the bars may under some conditions be simply ordinary friction between the bars.
and the stuff; but it may also arise from a tearing of the layer of stuff between the bars (as Kirchner has envisaged): in either case the effect is to produce a resistance to the rotation of the roll. If $f$ denote the coefficient of resistance, and $P$ is the pressure of the roll, then $fP$ will be the total resistance. In the first case $f$ would be termed a coefficient of friction; whereas in the second case it would be more in the nature of a coefficient of tearing; but at the moment very little is known regarding it.

Employing the same symbols as before, the work done per second by the roll in passing over the bedplate may be expressed in the following way:—

$$75N_m = f.P.v + eI.$$  

In the previous chapter this work was expressed by $\mu Pv$, so that we now have

$$\mu Pv = f.P.v + eI,$$  

or

$$\mu = f + e\frac{I}{Pv}.$$  

(21)  

(22)

If the beating coefficient $\mu$ is measured in the manner indicated in the last chapter it will soon be noticed that its magnitude depends on the working conditions which prevail in the beater, and it appears to be affected by so many factors that analysis seems at first sight to be hopeless. But a knowledge of these factors will tend to throw so much light on what occurs during beating between the bars, that they are well worthy of investigation. All records of the variation of power consumption during beating show that when beating rags the value of $\mu$ varies very considerably over the beating period and is much lower at the end than at the beginning.\(^1\)

On the other hand, when beating chemical wood pulp, the value of the beating coefficient remains practically constant throughout the whole of the beating period. In a number of cases the author has investigated the behaviour of the beating coefficient and particularly the relation between the beating coefficient and the peripheral speed of the roll and the roll pressure (P). Below are given the results of investigations on the

![Graph](image)

**Fig. 24.**

relation between the beating coefficient and the peripheral speed of the roll.

The curves in Fig. 24 show the values found for $\mu$ at various peripheral speeds ($\nu$). The data for curves A to E were obtained by beating sulphite in beater S3 at roll pressures of 302 to 448 kg. Although considerable errors occurred in taking the observations, the results of the tests clearly show that in the main the beating coefficient is independent of the peripheral speed. In the next chapter it will be shown that the value of the coefficient $f$ is also independent of the
peripheral speed, and it is thus possible to prove that the power consumption for cutting \( e \) is also independent of the peripheral speed of the roll. This can be demonstrated quite simply as follows:

Substituting \( \frac{v}{\pi D} \) for \( \frac{n}{60} \) in equation (1) we have

\[
L_z = m_v m_s L_1 \frac{v}{\pi L}
\]

and substituting this value for \( L_z \) in equation (22) we then get

\[
\mu = f + \frac{m_v m_s L_1}{\pi D p}
\]

It is thus clear that the power required for cutting \( e \) must be independent of the peripheral speed \( v \) of the roll, because \( \mu \) and \( f \) are independent of \( v \).

A large number of experiments has been made with the object of determining the relationship between the beating coefficient and the roll pressure, from which it appears that as the pressure increases so the value of the beating coefficient decreases. In the beaters employed for these experiments, chemical wood pulp was beaten mostly with \( \mu = 0.09 \) to 0.12 and rag half-stuffs with somewhat higher values for \( \mu \) (0.12 to 0.20).

In the graphical representation of the results, the values of \( p_k \) are shown as abscissæ. In the course of the numerous investigations it has appeared that the diagrams are much easier to read if the values for \( \mu p_k \) instead of those for \( \mu \) are taken as ordinates. This method of illustration affords a clearer survey over the effect of the individual factors on the power consumption.

The expression \( \mu p_k \) will be denoted by the symbol \( \bar{\mu} \).

Now \( p_k = \frac{P}{100 K} \) and from equation (21) we therefore get

\[
100 \mu p_k K v = 100 f p_k K v + q L_c
\]
and dividing both sides by $100Kv$:

$$
\mu = \mu_0 + \frac{eL}{100Kv}
$$

(23)

Putting $Kv = L_s(s_r + s_r)$ (see p. 29) we then have

$$
\mu = \frac{e}{100(s_r + s_r)}
$$

(23a)
From the equations $75 N_M = \mu P v = 100 \mu K v$ it is seen that $\mu$ is the power consumption of the beating tackle per square decimetre of beating surface per second, measured in metre-kilograms. $\mu$ is, therefore, termed the specific power consumption.

Figs. 25A and 25B show curves for $\bar{\mu}$ expressed as a function of $\dot{\rho}_k$. These curves are based on the mean
value of $\bar{\mu}$ (averaged over the whole beating process and calculated on the basis of the momentary values of $\mu$ determined during the course of the beating process) at various roll pressures.

This method of procedure is applicable in the case of beating chemical wood pulp because the specific power consumption only changes slightly during this beating process.

![Graph](image.png)

**Fig. 25D.**

It was not possible to carry out the beating process at a higher pressure than approximately 2.5 kg. per square centimetre, and for this reason the curves cannot be taken beyond this pressure.

A few $\mu$-$p_k$ curves were, therefore, obtained by varying the weight on the roll counterbalancing gear for short periods, and so obtaining readings of the power consumption at different loads. In this manner it was found possible to take readings at edge pressures up to 5 to 6 kg. per centimetre. If, however, it had been attempted to carry on beating for any appreciable
FIG. 25E.
length of time at such high pressures, the stuff would have been rendered useless.

![Graphs of different materials](image)

*Fig. 26A-E.*

All these curves indicate that different raw materials and different beaters give very varying values for $\bar{\mu}$. 
While some curves are practically straight lines, others, such as in Fig. 25A, are S-shaped for the reason that the specific power consumption only increases slightly within a certain zone. The variety in the shapes of the curves is probably closely related to the size of the abrasions on the bar edges; to the relation between the coefficients \( f \) and \( e \), and the roll pressure; and to the condition and nature of the surface of the bedplate.

![Graph showing data](image)

**Fig. 27.**

The coefficient \( f \) exercises most influence on the specific power consumption. It will be shown later how from the \( \mu - p_k \) curves important conclusions may be deduced regarding the working conditions between roll and bedplate, when the factors are known which govern the magnitude of the coefficient \( f \).

Schubert has carried out some similar experiments in connection with the power consumed for beating. The author has calculated the specific power consumptions corresponding to the results of these experi-
ments and they are illustrated in Fig. 26A-E in the same manner as those in Fig. 25.

It is of special interest to note that the experiments have shown that in order to beat chemical wood pulp (in these cases, sulphite and sulphate) a certain definite number of horse-power hours are required, irrespective of whether the beating is carried out under heavy or slight beating pressure. As has been pointed out, in beating these pulps, the power consumption ($N_M$) of the beating tackle only varies very slightly during the beating time. The total power consumption (horse-power hours) will, therefore, be:

$$N_M T = \frac{100\bar{\mu}L_0(s_r + s_s)T}{75}$$

where $\bar{\mu}$ is the mean value of $\mu$ during the process. Furthermore,

$$Q = kL_0 T.$$

Dividing the former equation by the latter, we get the number of horse-power hours required to beat 1 kg. of stuff:

$$\frac{N_M T}{Q} = \frac{100\bar{\mu}L_0(s_r + s_s)T}{75kL_0 T} = 1.33(s_r + s_s)\bar{\mu}.$$  

The values of $\frac{\bar{\mu}}{k}$ are depicted in Fig. 27, in which the values of $\bar{\mu}$ and $k$ are taken from the curves in Figs. 26 and 13 which apply to the same experiments. It will be seen from Fig. 27 that the number of horse-power hours required to beat 1 kg. of chemical wood pulp remains approximately constant irrespective of whether the beating pressure is high or low.
CHAPTER III

EXPERIMENTS ON FRICTION AND TEARING

A long series of experiments was carried out with the object of investigating the conditions which determine the value of the coefficient $f$. Their original aim was to examine the relation between this coefficient and the pressure; but the experiments were soon extended so as also to cover the investigation of other factors. At the commencement the coefficient $f$ was regarded merely as a coefficient of friction, and the first experiments were accordingly carried out as friction tests.

The investigations will be described in the sequence in which they were carried out, in order to enable the stages of development to be followed clearly.
The following materials were employed in the first experiments (friction tests):—

(1) A steel bed with machined transverse grooves (Fig. 28).

(2) A smooth steel bed.

(3) A smooth phosphor-bronze bed.

All three beds were planed and showed coarse tool marks running along their length directions.

(4) A steel friction block with a sliding surface 19.2 sq. cm. in area (Fig. 29).

(5) A steel friction block (Fig. 30) with a sliding surface 9.6 sq. cm. in area.

Both friction blocks had their sliding surfaces rough planed similarly to the beds with the tool marks running in the direction of motion of the blocks.

(6) A steel friction block (Fig. 31) with a sliding surface 4 sq. cm. in area.
(7) Two friction blocks (steel and bronze) (Fig. 32) with a sliding surface 2 sq. cm. in area.

(8) A steel friction block (Fig. 33) with a sliding surface 1 sq. cm. in area.

These friction blocks had their sliding surfaces filed smooth.

The bed was erected as shown in Fig. 34, and before commencing the tests, was adjusted so as to be exactly horizontal. A screw-threaded spindle was employed to draw the friction block over the bed, the spindle being connected to a spring balance which indicated the force required to move the block. Fig. 34 also shows the yoke which with its attached weights enabled the friction blocks to be loaded to any desired extent.

First of all the coefficient of friction for steel on steel was determined, during which time water was poured over the bed. For the smooth bed the value for $f$ was found to be 0.17, and for the grooved bed $f = 0.24$. Sulphite pulp of beater consistency was then poured on to bed No. 2.

A little water ran off and the stuff remained as a pulpy mass on which the friction block was placed and then weighted down. In this manner, using the friction blocks shown in Figs. 29 and 30, coefficients of friction between 0.65 and 0.82 were found corresponding to
THE ACTION OF THE BEATER
loads of $p = 0.75-1.50$ kg. per square centimetre. Similar values were found for the grooved bed.

As stated in the previous chapter, the value of the beating coefficient $\mu$ was determined under the most varied conditions; but in no case was its maximum value found to exceed $0.22$. It is obvious that the coefficient of friction $f$ for the stuff rubbing against the working surfaces of the bars must be less than the beating coefficient $\mu$ (cf. equation (22)); and it therefore follows that the above described method for the determination of the coefficient of friction is unsuitable for the purposes here in view.

It appeared likely that the surfaces of the beds and blocks were so uneven as to offer in reality far more resistance to the motion of the stuff than would generally be offered by the working surfaces of beater bars. All the beds were, therefore, ground with emery and then filed accurately flat with the file marks running in the same direction as the planer tool marks had previously been. The intention was to produce a surface corresponding as closely as possible to the working surface of a beater bar. The latter is also not quite smooth, but usually has grooves worn into it in the direction of rotation of the roll.

After making these alterations the tests were resumed, the coefficient of friction for steel on steel and bronze on bronze being again determined as a preliminary step. In order to saponify any fats possibly present, the surfaces of the beds were washed with caustic soda and then flushed with cold water and a dilute solution of alum. The results of the friction tests then carried out are shown in Tables XI. and XII.
TABLE XI.—Friction Tests with Bronze on Bronze. Smooth Bed. Friction Block as shown in Fig. 32

*Lubricant Consisted of Water Containing a Slight Quantity of Alum*

<table>
<thead>
<tr>
<th>Load on Friction Block (kg.)</th>
<th>Surface Pressure in kilos/sq. cm.</th>
<th>Coefficient of Friction after Washing Surface with Solution of Alum</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>4.1</td>
<td>0.18</td>
</tr>
<tr>
<td>13.2</td>
<td>6.6</td>
<td>0.19-0.23</td>
</tr>
<tr>
<td>18.2</td>
<td>9.1</td>
<td>0.25</td>
</tr>
<tr>
<td>23.2</td>
<td>11.6</td>
<td>0.26</td>
</tr>
<tr>
<td>28.2</td>
<td>14.1</td>
<td>0.28</td>
</tr>
<tr>
<td>33.2</td>
<td>16.6</td>
<td>0.27-0.33</td>
</tr>
<tr>
<td>38.2</td>
<td>19.1</td>
<td>0.31-0.36</td>
</tr>
</tbody>
</table>

TABLE XII.—Friction Tests with Steel on Steel. Smooth Bed. Friction Block as shown in Fig. 32

*Lubricant Consisted of Water Containing a Slight Quantity of Alum*

<table>
<thead>
<tr>
<th>Load on Friction Block (kg.)</th>
<th>Surface Pressure in kilos/sq. cm.</th>
<th>Coefficient of Friction after Washing Surface with Solution of Alum</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>4.1</td>
<td>0.18</td>
</tr>
<tr>
<td>13.2</td>
<td>6.6</td>
<td>0.23</td>
</tr>
<tr>
<td>18.2</td>
<td>9.1</td>
<td>0.22-0.27</td>
</tr>
<tr>
<td>23.2</td>
<td>11.6</td>
<td>0.26</td>
</tr>
<tr>
<td>28.2</td>
<td>14.1</td>
<td>0.28-0.32</td>
</tr>
<tr>
<td>33.2</td>
<td>16.6</td>
<td>0.30</td>
</tr>
<tr>
<td>38.2</td>
<td>19.1</td>
<td>0.29-0.31</td>
</tr>
</tbody>
</table>

With a view to determining the value of the friction in the presence of sulphite pulp it was attempted to
repeat the plain friction experiments described above; but it did not prove at all easy to maintain steady conditions by these means, the tendency being for only that pulp to follow the block which was actually carried along by the block edge. Moreover, it was difficult to form any estimate of the thickness of the layer of stuff between the block and the bed; although this thickness affects the value of the coefficient of friction.

<table>
<thead>
<tr>
<th>Area of Friction Block in sq. cm.</th>
<th>Surface Pressure in kg./sq. cm.</th>
<th>Crêped Serviette Paper in:—</th>
<th>1 Layer</th>
<th>2 Layers</th>
<th>4 Layers</th>
<th>16 Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.2 cm.²</td>
<td>0.75 0.40-0.43</td>
<td>0.50 0.50-0.53</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.25 0.38-0.42</td>
<td>0.50 0.52-0.54</td>
<td>0.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5 0.39</td>
<td>0.49 0.51-0.54</td>
<td>0.51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.4 0.44</td>
<td>0.48 0.56</td>
<td>0.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.6 cm.²</td>
<td>2.5 0.38-0.45</td>
<td>0.49 0.53</td>
<td>0.51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.0 0.39-0.42</td>
<td>0.42 0.47</td>
<td>0.51</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.1 0.36</td>
<td>0.49</td>
<td>0.49</td>
<td></td>
<td></td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>5.4 0.42</td>
<td>0.42</td>
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<td>...</td>
</tr>
<tr>
<td></td>
<td>6.6 0.40-0.49</td>
<td>0.45</td>
<td>0.45</td>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>7.9</td>
<td>0.45</td>
<td>...</td>
<td>...</td>
<td></td>
<td>...</td>
</tr>
<tr>
<td>2 cm.²</td>
<td>9.1</td>
<td>0.44</td>
<td>0.44</td>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>11.6</td>
<td>0.43</td>
<td>0.43</td>
<td></td>
<td></td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>14.1</td>
<td>0.44</td>
<td>0.39-0.43</td>
<td></td>
<td></td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>16.6</td>
<td>0.44</td>
<td>0.36-0.42</td>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>19.1</td>
<td>0.44</td>
<td>0.37-0.39</td>
<td>0.43-0.44</td>
<td></td>
<td>...</td>
</tr>
</tbody>
</table>

In order to obviate these uncertainties, the beater pulp was replaced by one or more layers of crêped serviette paper (crêped from unsized sulphite paper). The crêped paper was thoroughly softened in water containing a
<table>
<thead>
<tr>
<th>Total Pressure on Stuff (kg.)</th>
<th>Area of Friction Block in sq. cm.</th>
<th>Number of Layers of Créped Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 cm.²</td>
<td>2 cm.²</td>
</tr>
<tr>
<td>13·5</td>
<td>...</td>
<td>0·40-0·49</td>
</tr>
<tr>
<td>23·5</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>38·5</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>13·5</td>
<td>...</td>
<td>0·45</td>
</tr>
<tr>
<td>23·5</td>
<td>...</td>
<td>0·43</td>
</tr>
<tr>
<td>38·5</td>
<td>...</td>
<td>0·44</td>
</tr>
<tr>
<td>13·5</td>
<td>0·44-0·39</td>
<td>0·47-0·45</td>
</tr>
<tr>
<td>23·5</td>
<td>0·45-0·39</td>
<td>0·48-0·43</td>
</tr>
<tr>
<td>38·5</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>13·5</td>
<td>0·49-0·41</td>
<td>0·49</td>
</tr>
<tr>
<td>23·5</td>
<td>0·51-0·45</td>
<td>0·52</td>
</tr>
<tr>
<td>38·5</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Area of Friction Block in sq. cm.</td>
<td>Surface Pressure in kg./sq. cm.</td>
<td>Number of Layers of Creped Serviette Paper.</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>---------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Layer.</td>
</tr>
<tr>
<td>19.2 cm.$^2$</td>
<td>0.5</td>
<td>0.56$^1$</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.65$^1$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>0.57$^1$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>0.58$^1$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>0.49</td>
</tr>
<tr>
<td>4 cm.$^2$</td>
<td>4.5</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>7.0</td>
<td>0.53$^2$</td>
</tr>
<tr>
<td></td>
<td>9.5</td>
<td>0.50$^2$</td>
</tr>
<tr>
<td></td>
<td>8.2</td>
<td>0.36$^{12}$</td>
</tr>
<tr>
<td>1 cm.$^2$</td>
<td>18.2</td>
<td>0.44$^{12}$</td>
</tr>
<tr>
<td></td>
<td>28.2</td>
<td>0.41$^{12}$</td>
</tr>
<tr>
<td></td>
<td>38.2</td>
<td>...</td>
</tr>
</tbody>
</table>

$^1$ In these tests the block moved in short jumps instead of continuously.
small quantity of alum and then laid on the bed. The lubricant consisted of water with a slight addition of alum. In this way it was found to be comparatively easy to establish constant conditions. In the tests with the bronze bed and a movement of the block of 10 cm. the crêped paper only tore when a single layer was used, and the surface pressure reached or exceeded 6-7 kg. per square centimetre. With the steel bed the sheet tore at slightly lower pressures. The results of the tests are shown in Tables XIII., XIV., and XV.

It will at once be remarked that the grinding and filing of the surfaces did not have the anticipated effect; for the coefficients of friction are still considerably less than the values found for the beating coefficients. One must, therefore, conclude that the roughness of the surfaces is not a determining factor. Tests were carried out at various pressures (0.5 to 38 kg. per square centimetre) with friction blocks of contact areas varying from 1 to 19 sq. cm. and with 1 to 16 layers of crêped paper; but the values found for the coefficients of friction were all substantially higher than those of the beating coefficients. We find here the same lack of agreement as Haussner met with in carrying out similar experiments, and which led him to doubt the accuracy of his experimentally determined beating coefficients.

Since there can be no doubt as to the correctness of either the beating coefficients or the coefficients of friction determined in the experiments described above, it is probable that the method adopted for measuring the coefficient of friction was not properly suited to the objects in view and that at speeds of 6 to 10 m. per second

---

1 At the time of carrying out the above experiments, the author was unaware of Haussner's friction tests with woven materials between fluted blocks. Cf. W, 1909, pp. 1960-65.
the friction effects are totally different from those obtaining at a speed of a few millimetres per second on which the above experiments are based. In fact, in some of the tests with the steel surface, the block moved forward in jerks, so that the statical friction was measured instead of the friction of motion. It may be mentioned, however, that as a general rule the tests in which the block showed a tendency to jerk were disregarded; as it was not possible under such conditions to determine the actual coefficient of friction.

**Table XVI.—Coefficient of Friction of Sulphite Pulp against a Smooth Polished Brass Platf. Water as Lubricant**

<table>
<thead>
<tr>
<th>Pressure, kg.</th>
<th>Surface of Friction Block in sq. cm.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>13.25</td>
<td>0.15</td>
</tr>
<tr>
<td>23.25</td>
<td>0.13</td>
</tr>
</tbody>
</table>

In the tests with polished beds it was remarkable to note that the coefficient of friction rose rapidly with the speed at which the block was drawn over the bed. At the instant of ceasing to turn the actuating screw the spring balance continued to draw the block a short distance at a diminishing speed; and the reading was only taken when the block had come to rest completely. The coefficients of friction corresponding to these conditions are shown in Table XVI. and apply to statical friction: they are lower than the values found with even the slightest movement. Occasionally, as
a matter of experiment, the block was moved rapidly and the coefficient of friction then rose as high as 0.8; the block (the sliding surface of which was not polished) then commenced to slide on the stuff, which consisted

of four to eight layers of crèped paper. In these experiments it was also very difficult to obtain reliable results; trivial details being apt to exercise a very important effect on the values found for the coefficient of friction.
With a view to carrying out friction experiments under conditions approximating as closely as possible to those obtaining in the actual beater, the following arrangements were adopted: A cylindrical pulley 90 mm. in diameter was fitted to an electric motor of about \( \frac{1}{3} \)rd horse power at 2,400 revs. per minute. The cylindrical surface of the pulley was intended to take the place of the flat bed already described and was rough filed. After a few tests had been carried out, it appeared that this motor was too small and it was therefore replaced by a 1 horse-power motor with a speed of about 2,000 revs. per minute. The pulley was provided with a brake device, as shown in Fig. 35, consisting of a lever arm with a fitment for securing to it the friction blocks illustrated in Figs. 31, 32, and 33. A hook at the end of the lever arm carried the weights for varying the friction load on the pulley.

In the following equations the pressure exercised by the friction block will be denoted by \( p \), and the velocity of the pulley by \( v \). After the motor had been started up, the lever arm was placed in position and various layers of soaked unsized paper (made from the pulp under examination) were laid between the friction block and the pulley. During every test the power consumption was recorded from the readings of a combined millivoltmeter and ammeter. This instrument measured the armature current and the potential difference across the supply mains, \( i.e., \) between the points marked + and - . The armature resistance \( r_a \) and the amount of current \( (i_p) \) taken at no load were first measured. The potential difference was 220 volts. In this way the bearing and air resistance losses together with the iron and other losses (\( T \)) were determined.

\[
T = 220i_p - \beta r_a \text{ (measured in watts)}. 
\]
The armature current $i$ and the voltage $e$ were then measured with the motor loaded. The horse power developed was, therefore,

$$i.e - i^2r_a - T$$

$$\frac{736}{736}.$$ 

Considering now the brake, the horse power developed is given by

$$\frac{f.p.v}{75}.$$ 

So that we have

$$f = \frac{75}{736} \cdot \frac{i.e - i^2r_a - T}{p.u}.$$ 

In this calculation no attention is paid to the fact that the pressure of the friction block on the pulley will increase the friction loss in the adjacent motor bearing. If the coefficient of friction in the motor bearing is taken at 0.08, it will be found by calculation that the effect of neglecting this additional loss is to make the value of the coefficient $f$ appear higher than it should by 0.004.

It was possible to reduce the speed of the motor considerably, by means of the starting gear, thus also reducing the voltmeter reading. The observations obtained from the motor tests are recorded in Table XVII.

It will be seen from this table that at constant current the speed of the motor decreases in approximately the same ratio as the voltmeter reading. In other words, the work done by the motor at constant current consumption is approximately proportional to its speed. This fact was made use of in determining the value of the coefficient $f$ at the lower velocities; it having been previously ascertained by test that the flow of current was practically constant for any position of the starting
handle. From this it follows that, certainly within the limits of 7-11 m. per second velocity, the coefficient \( f \) must be regarded as being independent of the velocity.

<table>
<thead>
<tr>
<th>Starting Handle on Stop No.</th>
<th>For 1-00 Ampere.</th>
<th>For 1-30 Amperes.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Revs./min. ((n))</td>
<td>Voltage ((e))</td>
</tr>
<tr>
<td>5</td>
<td>2,350</td>
<td>224</td>
</tr>
<tr>
<td>4</td>
<td>2,200</td>
<td>212</td>
</tr>
<tr>
<td>3</td>
<td>2,050</td>
<td>196</td>
</tr>
<tr>
<td>2</td>
<td>1,750</td>
<td>168</td>
</tr>
</tbody>
</table>

During the tests the stuff was retained in position under the friction block solely owing to the edge of the block holding the sheet fast. This was proved by trying to retain a small piece of sheet under the block without any of it projecting beyond the edges of the block: at every such attempt the sheet was instantly torn away by the pulley. Where several sheets of crèped paper were used together at low pressures, the friction was very great at the moment of starting the test, but rapidly diminished as the load caused the layers to be pressed together to a thickness at which the friction
would remain constant for a fraction of a minute. At this point the reading was taken. The pulley naturally wore down the paper very rapidly and as soon as it got thin the power consumption would suddenly begin to rise and frequently only a few seconds elapsed before metal was running on metal. When working with only a few layers of paper or at high pressures, a diminution in power consumption in the early stage of the test could be observed.

The following tests were all carried out with block of 1 sq. cm. area which had previously been ground with emery exactly to fit the cylindrical surface of the pulley.

The friction experiments were carried out partly with unsized uncreped paper and partly with samples of the bleached sulphite pulp from which the paper had been prepared. These latter samples were in lap form, 0.85 mm. thick.

The results are shown in Tables XVIII., XIX., and XX., and it will be seen that the governing factor is the condition of the stuff. In the experiments with the sulphite lap and the uncreped paper, the test samples immediately became compressed into a compact mass of wooden or leathery consistency, not easily worn away and which gave a high value for the coefficient of friction throughout. Owing to the rapidly varying condition great difficulty was experienced in taking observations.

The creped paper, on the other hand, behaved quite differently and gave one the impression of being in a condition corresponding to that of stuff in the beater. Just as in the beater tests the beating coefficient fell to very low values as the pressure increased; so also in testing these samples of creped paper the coefficient fell to similarly low values. Even at very considerable pressures—up to 100 kg. per sq. cm.—the stuff did not
### EXPERIMENTS ON FRICTION AND TEARING

**Table XVIII** (Corresponding to Fig. 36). — *Unsized Crimped Serviette Paper*

<table>
<thead>
<tr>
<th>Pressure ( p ) in kg./sq. cm.</th>
<th>( f_p )</th>
<th>( f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Layers, Curve A.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.42</td>
<td>0.105</td>
</tr>
<tr>
<td>8</td>
<td>0.80</td>
<td>0.100</td>
</tr>
<tr>
<td>12</td>
<td>1.13</td>
<td>0.094</td>
</tr>
<tr>
<td>16</td>
<td>1.43</td>
<td>0.080</td>
</tr>
<tr>
<td>4 Layers, Curve B.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.31</td>
<td>0.077</td>
</tr>
<tr>
<td>8</td>
<td>0.43</td>
<td>0.054</td>
</tr>
<tr>
<td>12</td>
<td>0.60</td>
<td>0.050</td>
</tr>
<tr>
<td>16</td>
<td>0.75</td>
<td>0.047</td>
</tr>
<tr>
<td>20</td>
<td>0.79</td>
<td>0.040</td>
</tr>
<tr>
<td>24</td>
<td>0.91</td>
<td>0.038</td>
</tr>
<tr>
<td>8 Layers, Curve C.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.35</td>
<td>0.088</td>
</tr>
<tr>
<td>8</td>
<td>0.58</td>
<td>0.072</td>
</tr>
<tr>
<td>12</td>
<td>0.91</td>
<td>0.076</td>
</tr>
<tr>
<td>16</td>
<td>1.14</td>
<td>0.071</td>
</tr>
<tr>
<td>20</td>
<td>1.47</td>
<td>0.074</td>
</tr>
<tr>
<td>24</td>
<td>1.80</td>
<td>0.075</td>
</tr>
<tr>
<td>28</td>
<td>1.95</td>
<td>0.070</td>
</tr>
<tr>
<td>8 Layers, Curve D.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.33</td>
<td>0.083</td>
</tr>
<tr>
<td>8</td>
<td>0.42</td>
<td>0.052</td>
</tr>
<tr>
<td>12</td>
<td>0.58</td>
<td>0.048</td>
</tr>
<tr>
<td>16</td>
<td>0.67</td>
<td>0.042</td>
</tr>
<tr>
<td>20</td>
<td>0.80</td>
<td>0.040</td>
</tr>
<tr>
<td>24</td>
<td>1.00</td>
<td>0.042</td>
</tr>
<tr>
<td>28</td>
<td>1.18</td>
<td>0.042</td>
</tr>
<tr>
<td>32</td>
<td>1.15</td>
<td>0.036</td>
</tr>
<tr>
<td>36</td>
<td>1.29</td>
<td>0.036</td>
</tr>
<tr>
<td>40</td>
<td>1.33</td>
<td>0.033</td>
</tr>
<tr>
<td>44</td>
<td>1.44</td>
<td>0.033</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure ( p ) in kg./sq. cm.</th>
<th>( f_p )</th>
<th>( f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 Layers, Curve E.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.58</td>
<td>0.111</td>
</tr>
<tr>
<td>8</td>
<td>0.91</td>
<td>0.111</td>
</tr>
<tr>
<td>12</td>
<td>1.02</td>
<td>0.085</td>
</tr>
<tr>
<td>16</td>
<td>1.13</td>
<td>0.071</td>
</tr>
<tr>
<td>20</td>
<td>1.36</td>
<td>0.068</td>
</tr>
<tr>
<td>24</td>
<td>1.52</td>
<td>0.063</td>
</tr>
<tr>
<td>28</td>
<td>1.74</td>
<td>0.062</td>
</tr>
<tr>
<td>32</td>
<td>2.02</td>
<td>0.063</td>
</tr>
<tr>
<td>36</td>
<td>2.23</td>
<td>0.062</td>
</tr>
<tr>
<td>40</td>
<td>2.55</td>
<td>0.061</td>
</tr>
<tr>
<td>16 Layers, Curve F.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.46</td>
<td>0.115</td>
</tr>
<tr>
<td>8</td>
<td>0.80</td>
<td>0.100</td>
</tr>
<tr>
<td>12</td>
<td>1.07</td>
<td>0.089</td>
</tr>
<tr>
<td>16</td>
<td>1.25</td>
<td>0.078</td>
</tr>
<tr>
<td>20</td>
<td>1.55</td>
<td>0.079</td>
</tr>
<tr>
<td>24</td>
<td>1.80</td>
<td>0.075</td>
</tr>
<tr>
<td>28</td>
<td>2.02</td>
<td>0.072</td>
</tr>
<tr>
<td>32</td>
<td>2.09</td>
<td>0.065</td>
</tr>
<tr>
<td>36</td>
<td>2.29</td>
<td>0.063</td>
</tr>
<tr>
<td>40</td>
<td>2.38</td>
<td>0.060</td>
</tr>
<tr>
<td>44</td>
<td>2.50</td>
<td>0.057</td>
</tr>
<tr>
<td>48</td>
<td>2.45</td>
<td>0.051</td>
</tr>
<tr>
<td>52</td>
<td>2.50</td>
<td>0.048</td>
</tr>
<tr>
<td>56</td>
<td>2.50</td>
<td>0.045</td>
</tr>
<tr>
<td>60</td>
<td>2.83</td>
<td>0.047</td>
</tr>
<tr>
<td>64</td>
<td>2.62</td>
<td>0.041</td>
</tr>
<tr>
<td>68</td>
<td>2.86</td>
<td>0.042</td>
</tr>
<tr>
<td>72</td>
<td>3.05</td>
<td>0.042</td>
</tr>
<tr>
<td>76</td>
<td>3.11</td>
<td>0.041</td>
</tr>
<tr>
<td>80</td>
<td>3.33</td>
<td>0.042</td>
</tr>
</tbody>
</table>
Table XVIII.—continued

<table>
<thead>
<tr>
<th>Pressure $p$ in kg./sq. cm.</th>
<th>$fp$</th>
<th>$f$</th>
<th>Pressure $p$ in kg./sq. cm.</th>
<th>$fp$</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.69</td>
<td>0.172</td>
<td>56</td>
<td>3.25</td>
<td>0.058</td>
</tr>
<tr>
<td>8</td>
<td>0.91</td>
<td>0.114</td>
<td>60</td>
<td>3.20</td>
<td>0.053</td>
</tr>
<tr>
<td>12</td>
<td>1.09</td>
<td>0.091</td>
<td>64</td>
<td>3.27</td>
<td>0.051</td>
</tr>
<tr>
<td>16</td>
<td>1.58</td>
<td>0.099</td>
<td>68</td>
<td>3.45</td>
<td>0.051</td>
</tr>
<tr>
<td>20</td>
<td>2.02</td>
<td>0.101</td>
<td>72</td>
<td>3.55</td>
<td>0.049</td>
</tr>
<tr>
<td>24</td>
<td>2.11</td>
<td>0.088</td>
<td>76</td>
<td>3.80</td>
<td>0.050</td>
</tr>
<tr>
<td>28</td>
<td>2.19</td>
<td>0.078</td>
<td>80</td>
<td>4.28</td>
<td>0.053</td>
</tr>
<tr>
<td>32</td>
<td>2.17</td>
<td>0.068</td>
<td>84</td>
<td>4.50</td>
<td>0.053</td>
</tr>
<tr>
<td>36</td>
<td>2.34</td>
<td>0.065</td>
<td>88</td>
<td>4.45</td>
<td>0.051</td>
</tr>
<tr>
<td>40</td>
<td>2.34</td>
<td>0.059</td>
<td>92</td>
<td>4.80</td>
<td>0.052</td>
</tr>
<tr>
<td>44</td>
<td>2.47</td>
<td>0.056</td>
<td>96</td>
<td>4.90</td>
<td>0.051</td>
</tr>
<tr>
<td>48</td>
<td>2.76</td>
<td>0.057</td>
<td>100</td>
<td>4.95</td>
<td>0.050</td>
</tr>
<tr>
<td>52</td>
<td>2.96</td>
<td>0.057</td>
<td>56</td>
<td>3.25</td>
<td>0.058</td>
</tr>
</tbody>
</table>

32 Layers, Curve G.

become compacted, but retained its loose structure. The characteristic curves are illustrated in Fig. 36, and show the variation of the coefficient $f$ with increasing pressure as well as the variation of the force $fp$ with the pressure.

One would have expected to find that the higher the speed, the smaller would be the value of the coefficient $f$; but looking at Tables XVIII., XIX., and XX. it will be seen that this expectation is only realised fully in the case of loosely felted stuff. Even then at the lowest pressure (1-2 kg. per sq. cm.) the value of $f$ was often fairly high (0.17-0.20). For the purpose of friction tests which are intended to imitate as closely as possible the conditions in the beater, it is, therefore, essential to work only with loosely felted stuff; because the closely felted structure of a sheet of paper, even if
unsized, is not abraded and torn in a manner corresponding to beater stuff.

**Table XIX.**——**Uncrêped Serviette Paper**

<table>
<thead>
<tr>
<th>Pressure $p$ in kg./sq. cm.</th>
<th>$fp$</th>
<th>$f$</th>
<th>Pressure $p$ in kg./sq. cm.</th>
<th>$fp$</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Layers.</td>
<td></td>
<td></td>
<td>4 Layers.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0·85</td>
<td>0·212</td>
<td>4</td>
<td>0·97</td>
<td>0·260</td>
</tr>
<tr>
<td>8</td>
<td>1·09</td>
<td>0·139</td>
<td>8</td>
<td>2·76</td>
<td>0·350</td>
</tr>
<tr>
<td>12</td>
<td>1·13</td>
<td>0·091</td>
<td>12</td>
<td>3·85</td>
<td>4·500- 4·500-0·321-0·376</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td>16</td>
<td>1·28</td>
<td>5·760- 5·760-0·268-0·360</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>20</td>
<td>5·76</td>
<td>7·070- 7·070-0·288-0·353</td>
</tr>
<tr>
<td>8 Layers.</td>
<td></td>
<td></td>
<td>24</td>
<td>4·55</td>
<td>8·620- 8·620-0·190-0·359</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
<td>28</td>
<td>6·50</td>
<td>7·300- 7·300-0·232-0·262</td>
</tr>
<tr>
<td>32</td>
<td></td>
<td></td>
<td>32</td>
<td>4·95</td>
<td>10·410-10·410-0·155-0·325</td>
</tr>
</tbody>
</table>

**Table XX.**——**Bleached Sulphite Pulp in the Form of Board**

<table>
<thead>
<tr>
<th>Pressure $p$ in kg./sq. cm.</th>
<th>$fp$</th>
<th>$f$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0·80</td>
<td>0·200</td>
</tr>
<tr>
<td>14</td>
<td>3·25-3·67</td>
<td>0·032-0·262</td>
</tr>
<tr>
<td>24</td>
<td>2·60-5·76</td>
<td>0·108-0·240</td>
</tr>
<tr>
<td>34</td>
<td>5·36-9·20</td>
<td>0·158-0·272</td>
</tr>
<tr>
<td>44</td>
<td>5·16-10·20</td>
<td>0·117-0·232</td>
</tr>
</tbody>
</table>
The force \( fp \) which was measured in the experiments with the crèped serviette papers should, therefore, be characterised as a tearing force and not as a frictional force; and the coefficient \( f \) in this case becomes a tearing coefficient.

Fig. 36 shows that as the pressure rises so the tearing force also increases: the layer of stuff gets forced into the depressions in the surface of the pulley, thus causing the tearing effect to be increased and the power consumption to rise.

The same curves also show that the increase in power consumption does not take place steadily, but that it rises periodically. Thus, for example, in curves \( F \) and \( G \) the tearing force remains constant at 2-2.5 kg. over a fairly wide zone. It is only when the pressure exceeds about 40 kg. per sq. cm. that the layer of stuff begins to become compacted and to offer somewhat greater resistance. The curves for \( f \) and \( fp \) as functions of \( p \) are, therefore, discontinuous, and \( f \) always diminishes as the pressure increases. Seeing that the value of \( f \) is neither constant nor a simple function of the pressure, it is unreasonable to deal with it throughout as a coefficient for purposes of calculation. In future we shall, therefore, refer only to the tearing force per square centimetre and not to the tearing coefficient.

It was also found desirable to investigate whether other raw materials would yield similar results. A fresh series of experiments was, therefore, carried out with pieces of sulphate pulp board, cotton filter paper, and paper made from linen and cotton. None of these samples of paper, however, was in a sufficiently loosely felted condition to enable a tearing action to take place as in the beater. These experiments then had to be discontinued, and the author was only able to resume them after an interval of two years; but he
was then in a position to supplement the original somewhat primitive tests and to carry out the investigations with greater thoroughness. Means also became available for examining other raw materials with greater promise of success.

The apparatus illustrated in Fig. 35 was again employed, but this time the paper samples were specially prepared with hand-made moulds. Sulphite pulp was taken from the draining chests or beaters, beaten up by hand with a large quantity of water, and thick hand-made sheets prepared from it. The sheets were couched on a felt and then lightly pressed between two felts, as far as possible under the same pressure in every case. The wet sheets produced in this way possessed just sufficient cohesion to enable small pieces to be introduced on the under surface of the friction block of the test apparatus. For the purpose of investigating the effect of the thickness of the layer of stuff, two or more layers of samples from these sheets were employed. The sheets were of such thickness that ten layers under a pressure of

4 kg. per sq. cm. yielded a thickness of 2-3 mm.
44 „ „ „ „ 1-3-2 mm.; and
84 „ „ „ „ 1-1-7 mm.

Samples prepared in the manner just described were found to be in a suitable loosely felted condition for the work; and a long series of experiments was carried out with them. Sheets were hand-made from the following materials:—

Linen half-stuff.
Cotton half-stuff.
Cotton whole stuff.
Bleached sulphite pulp.
Finished beaten bleached sulphite (whole stuff).

The results are shown in Figs. 37 to 41.
Two pulleys were used in the experiments, both made of steel and revolving at a speed of about 9 m.

per second. One of the pulleys was gone over with a coarse file so as to give it a thoroughly rough surface and the experimental results for this pulley are indicated in the figures by continuous lines. The other pulley
was smooth polished, and the results which it gave are indicated by the dotted lines. Each series of tests was carried out with various numbers of layers (2, 4, 6, 8, and 10), and for each different number of layers a curve was drawn showing the relation between the tearing force and the pressure.

One of the first points to be observed during the experiments was that the rate at which tearing took place invariably increased with increase in tearing force. It is, therefore, possible to formulate the rule that the greater the tearing force in the beater the more intensive will its action be. The output will, therefore, rise steadily with the tearing force.

The torn stuff was flung freely off the pulley; and in some cases was caught on a glass plate for microscopic examination. It was found that in the case of eight layers of sulphite which had been subjected to a pressure of 4 kg. per sq. cm. the stuff had become very "wet," and some cellulose mucilage and lacerated fibres were observed in addition to a few pieces of fibre in a more or less well preserved condition. On the other hand, the same number of layers of sulphite (eight) tested under 84 kg. per sq. cm. pressure were transformed into a slimy mass from which every trace of the original fibrous structure had disappeared. The same experiments were attempted with two layers of sulphite, but presented considerable difficulty owing to the stuff being rapidly shredded into small pieces, so that no real beating took place.

The following further conclusions were drawn from the results of the experiments:

The rougher the surface of the pulley, the greater was the tearing force and the more rapidly the layer of stuff was abraded.

The tearing force is greater for half-stuff than for
The corresponding whole stuff, and greater for rags than for sulphite, using the same surface of pulley in every case.

The original moisture content of the sample affects the magnitude of the tearing force such that the latter is greater where the stuff is comparatively dry, and
diminishes somewhat if the stuff contains much water.

The tearing force is smallest with a thin layer of stuff and increases quickly with increase in the thickness up to eight to ten sheets. Beyond this point the effect of the thickness ceases.

This may be explained by the fact that great thickness results in a more uniform distribution of stuff on the pulley. This causes stuff to be forced into every minute depression in the surface of the pulley, thus producing a more intensive tearing action and increasing the force required to produce it. An exception to this rule was found in the case of cotton half-stuff in which the tearing force for two sheets in a layer was greater than that for four sheets.

It will be remarked that the discontinuity of the curves relating to the original experiments reappears in the case of most of the new curves. It is seen most clearly in the curves appertaining to cotton whole stuff and linen half-stuff. In the latter curves the tearing force becomes constant, or even diminishes with increasing pressure. In this connection the experiments have shown that the discontinuity is most marked with thin layers of stuff and particularly where for any reason the surface of the pulley has become slightly less rough. In the diagram (Fig. 39) for cotton whole stuff, the curves for three, four, and five layers diverge considerably from the approximately straight line which is the characteristic form of curve for greater thicknesses of stuff. The smoother the surface of the pulley, the earlier the curves will commence to diverge from the straight line characteristic; and a complete series of intermediate shapes can be plotted down to the limiting curve for the smooth polished pulley.

Each sheet of curves also contains two curves which
illustrate the variation of the coefficient $f$; and in which the curious discontinuity can be detected although it is not so marked as in the $fp$ curves. In the experiments with the smooth polished pulley practically no tearing off the stuff could be observed to take place, and the coefficient $f$ under these circumstances must be regarded
as a coefficient of friction. The dotted $fp$ curves for the smooth polished pulley only ascend slowly or not at all, and the coefficient of friction, therefore, diminishes rapidly with increasing pressure. This may be explained by the fact that even an increase in pressure cannot bring the fibres into more intimate contact with the smooth surface of the pulley; and it will be noted that the curves for unbeaten sulphite half-stuff practically do not ascend at all.

All the remaining stuffs contained a greater or less quantity of small fibrillæ, which with increasing pressure were caught and torn away by the minutely fine grooves in the surface of the polished pulley. For these materials slightly ascending curves were, therefore, obtained.

From experiments carried out with oil and dead-beaten stuff, Schubert has concluded that the minimum possible coefficient of friction between half-stuffs and the bar surfaces of beating tackle is 0.092. It will be seen from what has already been said that this conclusion must be erroneous. The coefficient of friction usually has a much lower value, being about 0.02 to 0.04 for the range of conditions with which we have been dealing. Even the tearing coefficient is less than 0.092 providing the pressure is not too low. Schubert has also produced curves showing the variation of the beating coefficient $\mu$ with different pressures, obtained by measuring the power consumptions (in beating various raw materials). He remarks in this connection that "the curves obtained from the values of $\mu$ tend to flatten off to a constant value at a beating pressure which depends on the nature of the half-stuff." This constant value Schubert terms the "specific beating coefficient" for the particular half-stuff. The experimental data now submitted by the author show that this process of thought cannot be correct: for any given
material there can neither be a characteristic nor a specific beating coefficient.

Notwithstanding his incorrect conclusions, Schubert's investigations are of great scientific interest, and the author has taken the liberty of reproducing a few of Schubert's curves (see Fig. 26 A-E) modified to suit the co-ordinate system adopted in the present work.

All the author's $fp$ curves embody an error of observation, inasmuch as the points corresponding to the lowest pressures all lie slightly too high. In reality the curves should descend rather more steeply at quite low pressures than is shown (as may also be deduced...
from Schubert's curves). The reason is that in order for the samples of stuff to be retained firmly between the block and the pulley it was necessary to make them a little larger than the lower surface of the block. A certain amount of adhesion was thus created between

![Diagram of friction and tearing](image)

**Fig. 41.**

the overlapping portion of the sample and the surface of the pulley. This produced an additional braking effect on the pulley such that the lowest observed values were from 25 to 50 per cent. too high.

Looking at the results of the tearing experiments as a whole, a marked similarity will be noticed between the beating operation in the Beater and the tearing
phenomena under investigation. The following are a few of the points of resemblance:—

(1) Rag half-stuff requires more power for tearing than rag whole stuff—exactly as in the beater.

(2) Sulphite cannot withstand as high a tearing pressure (beating pressure) as rags. (The tests with sulphite whole stuff could only be carried out up to a pressure of about 30 kg. per sq. cm.)

(3) Sulphite was found to tear asunder best in a thick layer—just as in the beater it works best at a thick consistency.

(4) The general shape of the curves is similar to that of the corresponding curves which were drawn for the specific power consumption of the beater.

All these factors point to a close analogy between the tearing process which has just been investigated and the tearing process in the beater, so that it should be possible to apply to the conditions in the beater the experience gained from the tearing experiments.

We shall now try to make use of the above conclusions for the purpose of analysing the specific power consumption of the beater.

Equation (23a) reads:—

\[ \mu = fp_k + \frac{e}{100(s_r + s_i)} \]

If the cutting resistance \( e \) is sufficiently small to be able to be neglected, then since

\[ \dot{p}_t = \frac{1}{\eta} \dot{p} \]

we may rewrite equation (23a) as follows:—

\[ \mu = \frac{1}{\eta} \cdot fp. \]

Under these circumstances it therefore follows that the \( \mu - \dot{p}_k \) curve could be derived from the \( fp - \dot{p} \) curve.
by simply altering the scales of the co-ordinates, \( \eta, c. \), by dividing these scales by \( \eta \). For example, with \( \eta = 10 \), a pressure of 84 kg. per sq. cm. on the \( fp-p \) curves would correspond to an edge pressure of 8.4 kg. per cm. on the \( \mu-p_k \) curves; and a tearing force of 6 kg. per sq. cm. in the \( fp-p \) curves would correspond to a specific power consumption of 0.6 m.-kg. per square decimetre of beating surface per second.

If the tearing curves are compared with the curves for the specific power consumption, it would actually appear feasible to make these two sets of curves almost coincide with one another merely by altering the scales of the co-ordinates. It is, therefore, reasonable to conclude that the value of the term containing \( e \) will generally have only a minor effect on the value of the specific power consumption.

Thus, for example, with \( \eta = 10 \), the \( \bar{\mu} \) curve (Fig. 25c) for beating rags corresponds exactly with the tearing curve for cotton (Fig. 38) and is only slightly higher than the corresponding curve in Fig. 39. With a similar value of \( \eta \), the \( \mu \) curves in Figs. 25b and E, for edge pressures up to about 3.5 kg., coincide very closely with the tearing curves for thick layers (Figs. 41 and 40).

As the edge pressure increases above this value, so the \( \bar{\mu} \) curves ascend much more steeply than the tearing curves would lead one to anticipate. This is, however, quite natural, for the beating pressure will then have become so high that the fibrages are almost severed, with the result that not only is a considerable cutting resistance introduced, but at the maximum edge pressure there will also be direct contact and, therefore, friction between the actual metallic surfaces (\( f = 0.17 \)). Referring to the two curves marked A in Fig. 25E, the lower one represents readings taken after twenty minutes, while the readings for the upper curve were taken with
finished beaten stuff after $4\frac{1}{2}$ hours beating time. They indicate that towards the end of the beating operation the fibrages are much more easily severed or torn than on commencing to beat. The readings for curves C and B in the same figure were taken after $3\frac{1}{4}$ and $6\frac{1}{4}$ hours of beating respectively.

The $\mu$ curves in Figs. 25A and E refer to experiments carried out with Kraft pulp in beater MIII3. The curves in Fig. 25D together with curve A in Fig. 25A were obtained with 8 mm. bedplate bars and curve B in Fig. 25A with 14 mm. bedplate bars. For $\eta<10$, the curves obtained with the thin bedplate bars correspond exactly with the tearing curves for sulphite in thick layers (Fig. 41). On the other hand, curve B in Fig. 25A is of a shape which is characteristic when the layer of stuff is too thin in comparison with the intensity of the tearing action which it is called upon to withstand.

The foregoing examples show that useful information concerning the working conditions can be derived by systematically plotting curves for the specific power consumption of a beater at various pressures and various consistencies and comparing these curves with the tearing curves. As far as the author is aware, systematic tests of this nature have not yet been carried out for the ordinary range of consistencies met with in practice (4 to 8 per cent.). Schubert's results are the only ones available, and they only apply to consistencies up to 4 per cent. and to edge pressures up to 1 kg. The effect of the resistance to cutting can be clearly seen from these experiments: all the curves for 1 per cent. consistency are above those for 4 per cent. consistency, whereas according to the tearing curves one would expect to find lower values. The explanation is that at 1 per cent. consistency the cutting resistance is greater than at 4 per cent.
Unfortunately, it is fundamentally impossible to analyse the specific power consumption with exactitude owing to the fact that equation (23a) contains two terms $\eta$ and $e$ which cannot be directly measured. It is, therefore, an equation with two unknowns and necessitates resort in some measure to estimation.
CHAPTER IV

THE POWER CONSUMPTION FOR ROTATING THE ROLL IN THE STUFF

It has been seen from equation \(18a\) how to determine the amount of power \(N_R\) absorbed in rotating the roll in the stuff when it is raised clear of the bedplate. Moreover, it was pointed out that this power is partly consumed by the whipping of the flybars against the circulating stuff, and partly absorbed in friction losses in the stuff. We shall now proceed to investigate this portion of the total power consumption of the beater.

The power consumed in the whipping of the bars on the stuff has been investigated so frequently\(^1\) that it is almost impossible to add anything new. The stuff approaches the roll quite slowly in an approximately horizontal direction and is then suddenly compelled to take part in the motion of the flybars. In addition to this, if the backfall is incorrectly designed, it is possible for a further quantity of stuff to enter the cells on the backfall side of the bedplate, in which case there will be still more stuff subjected to the whipping action. Finally, even in the best beaters, a certain amount of stuff will always be carried right round by the roll (spitting). Presumably this stuff in its passage over the top of the roll will be flung against the interior surface of the hood several times prior to dropping down in front of the roll and being caught up by the flybars.

\(^1\) Kirchner, "Das Papier. IV., Ganzstoffe," p. 13; and Pfarr, "Hollaender und degen Kraftverbrauch," reprint, p. 15.
again (see Fig. 42). Thus this portion of the stuff will be subjected to the whipping action repeatedly.

It may be assumed that the blows or impacts of the flybars on the stuff are in the nature of impacts between inelastic bodies (the stuff may be compared to lumps of clay). The energy absorbed on impact or the work done on impact will then be proportional to the square

![Fig. 42.](image)

of the speed of the flybars, if the slight velocity with which the stuff approaches the roll be neglected. Now since both bodies are inelastic, on impact an amount of energy will be converted into heat, which is equal to the kinetic energy still possessed by the flybars after impact. Therefore, if 1 kilo of stuff enters the cells, the amount of energy consumed in whipping this quantity of stuff will be

\[ 2 \cdot \frac{v^2}{2g} \text{ metre-kilograms,} \]

where \( g \) is the acceleration due to gravity.
The letter G will now be used to denote the number of kilos of stuff which flow through any given cross section of the trough in one second. This quantity can be determined with some degree of accuracy for a portion of the trough remote from the roll, if the dimensions of the cross section are known and a stick inserted perpendicularly in the stuff. The speed of the stick will be the same as the speed of the stuff, assuming the travel to be uniform over the whole of the cross section. (It will nearly always be found that the stick retains its vertical position, thus showing that there can be no appreciable difference between the speed of the stuff at the top of the cross section and that at the bottom.) This holds good for the average range of consistencies and provided the interior surface of the trough is not too rough or corroded. One would accordingly be inclined to think that the power consumed by the flybars in striking the stuff (whipping) should be given by $G\frac{v^2}{g}$. In point of fact, however, the power consumption will be greater, because one portion of the stuff in traversing the roll will be struck two or more times, while a certain quantity of stuff will not circulate round the trough, but will pass right over the roll and will also be struck several times. The expression for the power absorbed in whipping will, therefore, be:

$$C.G.\frac{v^2}{g} \text{ m.-kg. per sec.}$$

where $C$ is a coefficient (greater than 1) the value of which depends on the shape of the backfall and the effectiveness of the doctor.

It was formerly thought that the amount of stuff ($G$) transported per second by the roll increases with the speed of the flybars. This is not the case. In all
beaters met with under industrial conditions, the transporting capacity of the roll is far in excess of the rate of flow of the stuff round the trough. The latter is only affected to a small extent by the speed of the roll and is chiefly influenced by the height of the backfall, the smoothness of the interior surface and shape of the trough, the slope of the trough floor, and by the consistency of the stuff. As soon as the stuff reaches the crown of the backfall it moves, under the pressure of the freshly arriving stuff, as a composite mass, following the slope of the floor until the roll is reached again. Without a backfall it is, therefore, impossible to produce circulation of the stuff (in the ordinary hollander). The motion of the stuff is not in the nature of a flow in the ordinary sense of the word. It may perhaps be compared best with the valleyward movement of a glacier under the pressure of the upper masses of ice.

We now come to consider that portion of the power consumption which is due to friction losses in the stuff. It will be necessary to investigate this question rather more closely than the previous one, because erroneous ideas are still generally prevalent in connection with the internal friction of beater stuff. All the workers who have so far been engaged in investigating the matter have started with the assumption that stuff may be regarded as a liquid, and have made use of the laws governing the flow of liquids. On this basis the friction is found to be proportional to the square of the speed and the power absorbed in friction to the cube of the speed. These results correspond to the laws

1. Kirchner arrived at the same conclusion in his investigations, "Das Papier. IV., Ganzstoffe," p. 224.
governing the frictional resistance of ships and the 
flow of water through pipes.

It must not be forgotten, however, that these laws 
only hold as long as true liquids are being dealt with. 
Before applying them to the beater it is first necessary 
to examine whether the stuff actually behaves in a 
similar manner to a liquid. The chief properties of 
liquids will, therefore, first be enumerated and it will 
then remain to be determined whether stuff of the usual 
range of consistencies (say 5 to 10 per cent.) possesses the 
same characteristics.

A liquid may be defined as a body the particles of 
which become displaced relatively to one another under 
the influence of even the smallest forces; notwithstanding 
the fact that there is a certain amount of friction 
between the individual particles. Moreover, according 
to Maxwell, if one layer of a liquid is moved relatively 
to another and parallel layer, then the friction between 
the two layers is independent of the pressure (contrary 
to solid bodies), but is proportional to the area of the 
surface and to the difference between the velocities of 
the two layers. Successive layers of a liquid may, 
therefore, possess different velocities, and the velocity 
of any individual particle will depend on its distance 
from the boundary surfaces of the moving layer to 
which it belongs.

The fact that beater stuff can retain a sloping free 
surface is already sufficient to demonstrate that it does 
not fall within the definition of a liquid. Even if stuff 
is allowed to stand in a beater for twelve or twenty-four 
hours its surface may not become perfectly horizontal. 
A certain minimum of effort 1 is, therefore, required

1 Eichhorn reports in one of his tests that a spanner weighing 11 lbs. 
remained on top of the stuff in the beater without sinking in more than 
half-an-inch.
in order to produce relative movement between the particles of stuff. The resistance to this movement does not, however, decrease to zero when the relative velocities approach zero. It is, therefore, impossible for the laws governing the internal friction (viscosity) of liquids to apply to the stuff in the beater; for these laws lay down that the friction is proportional to the difference in velocities. Beater stuff, therefore, cannot be regarded as a liquid, and it is incorrect to apply to the beater such formulae as Froude's for the resistance of ships or those for the flow of liquids through pipes.

By carefully observing the behaviour of moderately thick stuff in the beater the impression is obtained that a considerable amount of internal friction is at work. The stuff "rolls" round the trough in a characteristically turgid manner. The friction against the sides of the trough is obviously less than the internal friction of the stuff itself, and only where the surfaces of the trough are specially rough or corroded is the friction against them sufficient to disturb slightly the adjacent portions of stuff.

If the laws covering the behaviour of liquids were applicable to stuff, it would mean that there would exist in the beater conditions of flow similar to those in a liquid moving faster than its critical velocity. That is to say, the speed of the stuff would increase towards the centre of the stream, and there would be an eddy motion (in these circumstances the resistance is approximately proportional to the square of the velocity). Such conditions of motion, however, do not obtain in the beater.

A simple experiment will explain the matter still more clearly. If a coloured straight line is painted square across the surface of the stuff at the upper end
of the open side of an ordinary beater trough, it will be found that when this portion of the stuff has reached the lower end of the same side of the trough, the coloured straight line is still straight and still at right angles to the sides of the trough. This experiment and the one already referred to with the upright stick inserted in the stuff, together show that the velocity of the stuff is very nearly constant over the whole of its cross section. No internal movements take place in the stuff other than those naturally produced by the curvatures and contractions of the trough. The motion of the stuff does not even resemble the flow of a liquid at less than its critical velocity (where the resistance is proportional to the speed), for even under these conditions of flow the particles in the centre of the liquid stream would travel more rapidly than those at the sides.

At the points of curvature, or where the stuff is in juxtaposition to the roll, it certainly is possible for cleavage surfaces to be formed, and a sliding action then occurs. It is also well known that so-called dead spots are liable to be formed where a portion of the stuff remains stationary and does not circulate while the remainder of the stuff flows by. The friction between the stationary and the moving surfaces, however, does not appear to produce any internal motion in the stuff, and it must, therefore, be assumed that the force necessary to overcome the frictional resistance between two layers of stuff is independent of the relative speeds of the layers. If the frictional resistance diminished with the speed, then as the speed was reduced one would expect to find some internal motion in the stuff.

There would thus appear to be some ground for the following assumptions:

1. That the internal friction of the stuff in the beater is independent of any difference in the speeds
of different portions of it (similar to the case of solid bodies).

2. That the friction between two surfaces of cleavage is independent of the pressure between them, so that an increase in pressure does not bring the particles forming the two surfaces into more intimate contact with one another (corresponding to the friction in liquids).

3. That the friction is proportional to the area of the surface at which friction occurs (corresponding to the friction in liquids).

We thus are called upon to deal with a special kind of friction, the unit of which may be described as the force (in kilogrammes) required to move one layer of stuff over an adjacent layer, the area of the surface of cleavage being 1 sq. m. (coefficient of friction of a pulpy mass).

It is possible to investigate the truth of the above assumptions by means of experimental apparatus comprising a beater roll fitted into a tall, enclosed casing, stuffing boxes being provided at the points where the shaft emerges from the casing. The roll is driven by a variable speed motor. If the casing is filled with pulp up to above the level of the top of the roll, the power required to drive the roll can be measured at various speeds and various pressures. Care must, of course, be taken that the cells are actually filled with stuff. Such experiments are very troublesome to carry out, and were for this reason omitted from the present work.

Observations were, however, obtained with the aid
of the simpler apparatus illustrated in Figs. 43 and 44, consisting of two wooden "boats." Each boat was weighted with sufficient shot to make it weigh 1.02 times as much as the volume of water which it displaced.
The specific gravity of the beater stuff also being 1.02, it followed that the boats when immersed in stuff tended to remain in equilibrium. The wood was well varnished so as to avoid any possible change of weight due to absorption of water. A rectangular hole (0.20 × 0.25 m.) was formed in one of the boats and fitted with sheet metal cross strips as shown in Fig. 43. This boat was thrust down into a beater in such a way that the hole was filled with stuff; and with the aid of a spring balance it was then dragged through the stuff. The spring balance registered the total resistance to movement. This resistance was partly due to the fact that the boat had to cleave for itself a passage through the stuff, and partly to the internal friction of the stuff acting over an area of $2 \times 0.20 \times 0.25 = 0.1$ sq. m.

The boat without the hole (Fig. 44) was used to
### Table XXI

<table>
<thead>
<tr>
<th></th>
<th>About ½ Hour after Filling</th>
<th>Finished Beaten Stuff.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( a )</td>
<td>( b )</td>
</tr>
<tr>
<td>Sulphite pulp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0 per cent. consistency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rag stuff:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5 per cent. consistency</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to American sources it has been found possible to utilise successfully the internal friction of the stuff for the purposes of determining its beating condition. Cf. Paper, 1917, No. 23, A. B. Green, "Management of the paper room."
measure the resistance due merely to the cleavage of a passage. The difference between the readings of the two boats gave the resistance due to internal friction over an area of 0.1 sq. m. It appeared that the value of this friction was quite independent of the speed at which the boat moved. The results of these experiments are shown in Table XXI., the "a" values having been obtained with the boat shown in Fig. 43, and the "b" values with that shown in Fig. 44.

It is probable that the sharp variations in the value of the coefficient of friction, which occur notably during the first stages of beating just after the beater has been filled, are partly attributable to the stuff not being thoroughly broken up and varying in consistency in different parts of the beater. It is probably also due to this that the power consumption of a beater generally fluctuates so considerably during the first half hour or so after filling.

Following what has been said above, the frictional resistance over a surface area of A sq. metres will be $\phi A$, and is independent of the pressure or the speed. If this surface is moved at a speed of $v$ metres per second, then the amount of work required to overcome the frictional resistance will be $\phi A v$. The accuracy of the latter statement has unfortunately not been established with absolute precision; and having regard to the nature of the available experimental data exact proof is impracticable. It will be found, however, that in adopting this theory of the friction of the stuff as a basis of calculation, nothing arises which is incompatible with it; which fact tends in a measure to substantiate the truth of the theory.

In the case of the beater, which involves measuring the friction between the stuff rotating in the cells and the practically stationary stuff in the trough or backfall
pocket, the area A must be represented by that portion of the surface of the roll which is submerged in the stuff (LU), as shown in Fig. 42. For the sake of simplicity the working surfaces of the bars may be included in this area. If the stuff located in each cell were not eddying, then the difference in speeds to be considered would for all practical purposes be equal to the speed of the flybars, viz., $v$ metres per second. On this assumption the energy consumed per second in overcoming friction would be $\phi LU v$ metre-kilograms. In reality the conditions are not quite so simple, for, as will be seen from Fig. 7, the difference in speeds is only $v_\alpha$. As against this, however, there are other frictional losses due to internal friction in theeddies and to the friction of the stuff in the cells against the surfaces of the flybars. In addition, there may be a rotary movement of stuff in the backfall pocket which will also cause friction losses.\footnote{It is not necessary to take account of the friction of the end faces of the roll against the stuff; because the bangers will ensure that any stuff entering the clearance between the walls of the trough and the ends of the roll will be at once removed.} It must be assumed that all these friction losses each increase in proportion to the speed of the flybars, and the total friction loss can, therefore, be expressed by $\epsilon\phi LU v$ metre-kilograms per second, where $\epsilon$ is a coefficient which is independent of the speed of the flybars.

At this point reference may be made to Haussner's experiments on the internal friction in stuff.\footnote{Haussner, "Der Hollaender," pp. 10-38.} Haussner regarded the stuff as a liquid, and employed the formulae governing the flow of liquids through pipes; but he nevertheless reached a conclusion which, to some extent, tallies with the view expressed above, namely that the internal friction is independent of the
difference in speeds between contacting layers of stuff.

His experiments were conducted with stuff flowing through a pipe of 40 mm. bore; but could only be carried out at quite thin consistencies. Already at consistencies of 3 to 4 per cent. the effect of the pipe walls was such as to cause the stuff to form lodgments through which the water drained out. Had larger pipes been used, the stuff would no doubt have flowed through at considerably higher consistencies under the pressure which was available.

The object of the experiments was to determine the value of the coefficient of resistance $\zeta$, which is contained in the ordinary expression for the loss of head in a pipe. This expression is as follows:

$$h_i = \frac{\xi l}{F} \frac{u^2}{2g},$$

where $l$ is the length of the pipe.

$u$ is the length of the wetted perimeter.

$F$ is the cross-sectional area.

$\nu$ is the speed of the stuff.

$h_i$ is the loss of head due to the resistance of the pipe.

Notwithstanding the fact that no observations were obtained at high or even moderately high consistencies, Haussner claims to have settled that the coefficient of resistance of a pipe to the flow of stuff through it is given by the following expression:

$$\zeta = \frac{B}{C - \rho \sqrt[3]{\nu}} \cdot D,$$

where $\rho$ is the consistency expressed in percentage, and $B$, $C$, and $D$ are constants depending on the nature of the stuff.

In attempting to corroborate this conclusion it was found that when the stuff only travelled slowly through
the pipe the loss of head was very much greater than the value for $\zeta$ given by the above expression. Haussner compensates for this by introducing the term $A\rho^2/w^2$, so that the equation becomes

$$\zeta = \frac{A\rho^2}{w^2} + \frac{B}{C - \rho \sqrt{w}} - D.$$  

According to Haussner the first term $\left(\frac{A\rho^2}{w^2}\right)$ alone in this equation is the determining one when the rate of travel of the stuff is slow and the consistency fairly thick. Neglecting the last two terms and inserting the value $\zeta = \frac{A\rho^2}{w^2}$ in the formula for the resistance of a pipe to the flow of liquids, we have

$$h_r = \frac{A\rho^2}{w^2} \cdot \frac{lu}{2g}.$$  

It will be seen from this that Haussner's investigations also lead to the conclusion that the pressure required to deliver stuff through a pipe is independent of the velocity, where the consistency is fairly thick. This conclusion agrees closely with that formulated by the author on the basis of the experiments with the wooden boats.

The power consumed in merely rotating the roll in the stuff is made up of the power consumption for whipping plus that for overcoming the frictional resistance between the roll and the stuff: it may, therefore, be written as:

$$N_R = \frac{1}{75} \left( \frac{CG - \rho^2 + \epsilon \phi LUV}{\rho} \right).$$  

During the course of the tests carried out with beaters with individual drive from a variable speed motor, frequent readings of the power consumption $N_R$
were taken at various roll speeds. The values of \( N_R \) determined in this way will now be examined with a view to confirming the truth of equation (24). This can best be done graphically and by employing a fresh variable \( T = \frac{75N_R}{v} \) in place of the variable \( N_R \). It should be noted that \( T \) will now represent the total resistance offered by the stuff to the rotation of the roll, if this resistance be imagined in the form of a force acting tangentially to the surface of the roll. Substituting \( T \) for \( N_R \) in equation (24) we then get

\[
T = \frac{CG}{g}v + \epsilon \phi LU - (24a)
\]

in which \( T \) is expressed as a function of \( v \). This is the equation to a straight line originating at a point \( T_o = \epsilon \phi LU \) distant from the \( T \)-axis, and having a slope \( \tan \beta = \frac{CG}{g} \), \( \beta \) being the angle between the straight line and the \( v \)-axis. The equation may, therefore, be simplified and written as follows:

\[
T = v \tan \beta + T_o - (24b)
\]

For the purpose of investigating the experimental results, the values found for \( T \) at various roll speeds \( v \) are plotted and a straight line drawn through them in each case. The values of \( T_o \) and \( \tan \beta \) can then be measured direct from these graphs. If now the amount of stuff \( (G) \) transported per second and the internal coefficient of friction \( \phi \) have been determined previously to taking the power consumption readings, then it is quite simple to find the values of \( C \) and \( \epsilon \) respectively from the equations:

\[
C = \frac{g}{G} \frac{\tan \beta}{(25)}
\]

and

\[
\epsilon = \frac{T_o}{\phi LU} (26)
\]
**Fig. 45A.**

- **Beater S 3 28\%**
- **Furnish 265 kg.**
- **Consistency 8.3\%**

**Fig. 45B.**

- **Beater S 3 30\%**
- **Furnish 280 kg.**
- **Consistency 8.2\%**
**Fig. 45c.**

Beater S3. 3/4 in.
Furnish 290 kg.
Consistency 8.3%.

**Fig. 45d.**

Beater S3. 2/8 in.
Furnish 225 kg.
Consistency 8.3%.
Beater S3. 3% 17
with rebuilt backfall and doctor fitted in hood.
Furnish 225 kg.
Consistency 8%
Beater 53.15% f.17% with rebuilt backfall and doctor fitted in hood.
Furnish 250 kg
Consistency 7.8%

Fig 45c.

Beater 55.3% f.17%
Furnish 195 kg
Consistency 54%

Fig 45d.
## Table XXII. (see Figs. 45A-d).—Beater No. S3 with Sulphite

<table>
<thead>
<tr>
<th>Date</th>
<th>Furnish, Q.</th>
<th>Consistency, r</th>
<th>$N_r$</th>
<th>$v$</th>
<th>T</th>
<th>U</th>
<th>LU</th>
<th>$\tan \beta$</th>
<th>$T_0$</th>
<th>$CG = 9.81 \tan \beta$</th>
<th>$\epsilon_\phi = \frac{T_0}{LU}$</th>
<th>Fig.</th>
<th>Remarks</th>
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<td>1.73</td>
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<td>45</td>
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<td></td>
<td></td>
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<td>kg.</td>
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<td>2.8</td>
<td>43</td>
<td>28</td>
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</tbody>
</table>

**THE ACTION OF THE BEATER**

- No wedge-shaped doctor was fitted to the hood. The width of the backfall pocket was 50-60 mm.
- The width of the hood was 60 mm.
### Table XXIII. (see Figs. 45E-G).—Beater No. S3 with Sulphite

<table>
<thead>
<tr>
<th>Date</th>
<th>Furnish, Q.</th>
<th>Consistency</th>
<th>$N_R$</th>
<th>$\sigma$</th>
<th>T</th>
<th>U</th>
<th>LU</th>
<th>$\tan \beta$</th>
<th>T</th>
<th>CG = $9.81 \tan \beta$</th>
<th>$\phi = \frac{LU}{T}$</th>
<th>Fig.</th>
<th>Remarks</th>
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*A doctor was fitted in the hood as shown in Fig. 42. The width of the backfall pocket was reduced from 50-60 mm to 10 mm.*
The values found experimentally are shown in Tables XXII. to XXIV., those for \( v \) and \( T \) also being plotted in Figs. 45A-H, and a straight line drawn as closely as possible through them. (It will be explained later why, in drawing this line, no notice was taken of the point corresponding to \( v = 5 \) m. per second.) The values deduced from the graphs for \( \tan \beta \) and \( T_e \) are also shown in the tables. (In evaluating \( \tan \beta \) it must be remembered that the scale adopted for the \( v \)-axis is ten times larger than that of the \( T \)-axis.) The last columns of the tables contain the values of \( CG \) and \( e\phi \) as calculated from those of \( \tan \beta \) and \( T_e \). No direct observations were taken of \( G \) and \( \phi \). This is unfortunate, as they would have been illuminating and have afforded some measure of check on the calculated results. At the time of carrying out the experiments, however, the importance of mathematical treatment was not realised as fully as it came to be later, and the desirability of taking the observations in question did not suggest itself.

The Power Consumption Occasioned by the Whipping Action on the Stuff.—It will be seen
from Table XXII. that with the consistency remaining practically unchanged the value of CG increases very rapidly as the furnish \((Q)\) increases. During the various experiments the rate of travel \(G\) did not vary appreciably, so that the increase in the value of CG must be due to the factor \(C\) increasing in value, probably owing to fresh stuff entering the cells after the latter had passed over the bedplate. For the observations recorded in Table XXII. no hood was fitted to the beater, and when filled with the maximum furnish, the level of the stuff reached to 300 mm. above the crown of the backfall. It is, therefore, easy to understand that the high power consumption may be attributable to the re-entry of stuff into the cells.

In drawing straight lines through the points in the graphs, the point corresponding to the lowest flybar speed is disregarded, and frequently falls considerably above the straight line. This is due to the fact that at a flybar speed of about 5 m. per second the stuff possesses so little centrifugal energy that it is not flung off the roll quickly enough. The roll, therefore, carries it right round, and heavy spitting takes place, thus producing an abnormally high point in the graphs.

For the observations recorded in Table XXIII. a doctor was fitted into the hood of the beater, as shown in Fig. 42, the edge of the doctor being only about 8 mm. distant from the roll. The backfall was made a little higher and the width of the backfall pocket reduced from 50-60 mm. to 10 mm. These alterations produced no appreciable reduction in the power consumed for whipping; but slightly increased the rate of travel, thus reducing the value of the coefficient \(C\).

The experiments with beater No. S5 (see Table XXIV.) were carried out with a consistency of only
5.4 per cent., and showed that the greater part of the
c power consumption $N_r$ is absorbed in whipping the
stuff. This can also be seen from the graph in Fig.
45H, for the line here forms a very large angle with the
$v$-axis. With this beater no difficulty was experienced,
owing to the stuff not being flung off the roll properly
at low roll speeds.

The Power Consumed in Overcoming Friction
in the Stuff.—Table XXII. shows the values for $\phi$
found from Figs. 45A-D, at consistencies of about
8 per cent. These values vary between 27 and 33 kg.
per square metre. For the moment it is sufficient to
note that there is no apparent discrepancy between
them and the figures for $\phi$ shown in Table XXI. which
correspond to the wooden boat experiments. When
it is remembered that the former values were obtained
at roll speeds of 5 to 8 m. per second, while the latter
relate to speeds of only a few centimetres a second, it
must be agreed that the two sets of results coincide
very closely with one another. It was to be expected
from the beginning that the coefficient $\epsilon$ must be less
than 1. The foregoing lends additional probability to
the assumption that the internal friction in the stuff is
independent of the speed factor.

After the backfall had been altered and a hood
fitted as described above, the values found for $\phi$
(see Table XXIII. and Figs. 45E-G) became much
lower. This was to be expected, owing to there being
no eddy motion in the backfall pocket. The clearance
between roll and backfall being only 10 mm., the whole
of the stuff in the backfall pocket was able to keep pace
with the flybars; and instead of there being friction
of stuff against stuff (internal friction), the friction
now took place between the stuff and the smooth sheet
copper surface of the backfall.
Table XXIV. shows that at 5.4 per cent. consistency the friction loss is only small. This also was to be expected, for the internal friction diminishes rapidly as the consistency decreases.

The various points which have just been discussed indicate that it is no easy matter to ensure efficient delivery of the stuff by the roll. An apparently unimportant alteration to the shape of the backfall or an unsuitable roll speed may be sufficient to cause unnecessary waste of power.\(^1\) The speed of the roll must be such that at a minimum of power consumption it will just deliver the quantity of stuff corresponding to the circulation round the trough. If the roll runs too slowly, the centrifugal energy of the stuff will be too small to allow it to be flung over the crown of the backfall. The roll will then commence to spit; and the cells will have to handle the stuff which is carried right round the roll in addition to that which circulates round the trough. This means that they will be required to hold more stuff, and so the power consumed for whipping will be increased.

If the roll speed is too high, the power consumption for whipping will go up (the tangential force \(T\) increases) unless the increased centrifugal force causes the roll to spit less. At the highest roll speeds a sudden diminution in the tangential force \(T\) has frequently been remarked; and possibly this is due to a reduction in the spitting action.

(If it were true that the laws governing the frictional resistance of ships also apply to beater stuff, it would

---

\(^1\) The whole of the considerations involved in this connection have been dealt with thoroughly by Kirchner: "Das Papier. IV., Ganzstoffe," pp. 214-234, a study of which the author recommends to those interested in this aspect of the subject.
then be necessary to write equation (24) in the form

\[ 75N_R = Av^2 + Bv^3, \]

whence

\[ T = Av + Bv^2, \]

where A and B are coefficients which are independent of \( v \). This equation represents a series of parabolas which all pass through the origin of the system of co-ordinates. Their axes are parallel to the ordinate axis; and as A and B are always positive the co-ordinates of the vertices of the parabolas will all be negative. If, for example, such a parabola is drawn through one of the experimentally found points in Fig. 45\( \epsilon \), the impossibility of making the parabola coincide with the remaining points will at once be realised. (The parabola is shown dotted and marked "\( a.\)"") The limiting parabolas to the above equation are also shown, and it is quite clear that no parabola within these limits can pass through the remaining experimental points.

It is thus established that the internal friction in beater stuff does not obey the same laws as apply to the frictional resistance of liquids.)
CHAPTER V

PARALLEL BEATER BARS. MAXIMUM AND MINIMUM CUTTING ANGLE

ALTHOUGH flybars and bedplate bars exactly parallel to one another have seldom if ever been employed for any length of time, accounts of experience in working them are on record. For example, the author was informed by an experienced beaterman that with a beater roll about 1,200 mm. length on face, no cutting effect can be obtained, unless the bedplate bars are set back at least 50 mm. From another source it was stated that the power consumption of the beater is so great when the bars are parallel that the belt is thrown off. Clayton Beadle and Stevens, in their oft-quoted treatise, say that if roll and bedplate bars are parallel to one another, a maximum drawing-out effect but practically no cutting action will be obtained. At the same time the beater will require more power, as a greater amount of power is needed to draw out the fibres than to cut them. It is not intended to enter here into a criticism of this explanation of the increase in power consumption; but it will be shown that the theory of the adhesion of fibrages to the bar edges explains how it is that a beater with parallel bars takes a great deal of power and only exercises a slight cutting effect.

It will be assumed that in the case of the lawn-mower already referred to, the stationary knives are parallel to the revolving ones, and that the knives
are wrapped round with hemp fibres along their entire length. It will then be impossible without using force to cause one of the revolving knives to pass a stationary knife: resistance to motion will be offered along the entire length of each knife. It will be otherwise, however, if the knives are set at an angle to one another. At any particular moment the stationary knife will then only offer resistance at a single point, and it will be possible to move the mower and overcome this resistance with ease.

Let us now compare this example with the conditions obtaining in the beater.

A beater with roll and bedplate bars set obliquely to one another will absorb practically a constant amount of power over short intervals of time, since the cutting resistance is exerted at a large number of individual points.\(^1\) The smaller the angle between the roll and bedplate bars, the smaller will be the number of points of intersection (see equation (2)), and the greater will be the fluctuation in the number of points of intersection during the course of rotation of the roll bars. Since, when there are few points of intersection, each individual point exerts a greater cutting resistance, the operation of the beater must, therefore, become unsteady. This becomes most noticeable when the bars are exactly parallel, as in that case each bar will offer a resistance to the rotation of the roll along its entire length at the moment of engagement. This resistance may be so great that the momentum of the roll, together with the pull of the belt, will be insufficient to overcome

\(^1\) (i) the number of bar intersections, remains practically constant the whole time. Kirchner has shown that the area of contact (F) at various positions of the flybars does not fluctuate much if the bars are set fairly obliquely; and as (i) varies with (F) it follows that (i) also will not change much.
it: and instead of cutting the fibre the roll will be lifted up over the layer of fibre on the bar edges, and then drop again. This jumping action of the roll will necessarily involve a considerable additional power consumption. It is thus seen that the effects of setting roll and bedplate bars parallel can be fully explained by the fibrage theory.

Having regard to the above it is clear that the cutting angle \( a = a_L \pm a_r \) must not be too small. The minimum permissible limit may be taken to be:

\[
\tan a = \frac{50}{1200} = 0.042; \quad \text{that is to say, } a > 2.2^\circ.1
\]

It has been shown previously that the shortening effect of the beating tale is proportional to the cutting length, and we have

\[
L_c = \frac{n}{60} \cdot m_x \cdot m_y \cdot \frac{L}{\cos a_L}.
\]

From a first glance at this equation one might be led to suppose that the shortening effect increases with the angle \( a_L \), seeing that \( \cos a \) occurs in the denominator. This is, however, not the case, for the term, \( m_x \cdot \frac{L}{\cos a_L} \), as a whole, represents the aggregate length of the working edges of the bedplate bars. It is this length, and not merely the size of the angle \( a_L \), which determines the cutting effect. If the area of contact (L.B') of the bedplate is fixed, it is only possible to increase the cutting effect either by using thinner bars or by spacing the bars more closely together.

Either of these measures will result in the aggregate length of the bedplate bars, and therefore also the

\[1\text{ The minimum cutting angle should be greater when handling half-stuff or if the roll is light, as the latter then has a greater tendency to jump.}\]
cutting length, being increased. The more effective of the two will probably be to employ thinner bars; for this will also give a higher beating pressure (for the same weight of roll).

It is generally considered that the greater the cutting angle adopted, the greater will be the shortening effect obtained on the stuff.\(^1\) This view is based principally on the extensive cutting effects observed with elbow, zigzag and similar bedplates. The most likely explanation of this fact, however, is that such bedplates usually possess a far greater aggregate length of bar edge than ordinary bedplates with straight bars.\(^2\) If the bars are bent zigzag fashion they will form a larger angle with the flybars, and a thin bar bent in this manner will be just as strong mechanically as a thicker bar set at a smaller angle with the flybars. By employing thinner bars a longer aggregate cutting edge can be embodied in the same area of bedplate, and this is the only reason why such bedplates appear to give a comparatively large cutting effect. Jagenberg, who possessed an instinctive knowledge of the mode of operation of the beater, was also of opinion that the cutting angle is apt to be made excessively large; and that for the purpose of obtaining the most efficient shortening action, the cutting angle should be kept as small as possible.\(^3\)

If the cutting angle is very large it may happen that the flybars will carry away the fibres on the bedplate bars so that the fibres remain uncut; or if

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2. Hofmann states that the bars in elbowed bedplates are frequently only 2-4 mm. thick, and also draws attention to the comparatively large cutting surface of zigzag bedplates.

the bedplate bars are elbowed the flybars may force the stuff into the elbow angles of the bedplate bars and only a part of the fibres will be cut.

This is demonstrated by the fact that the maximum wear on the flybars takes place at the points which engage with the angular portions of the bedplate bars. Clayton Beadle, therefore, seems somewhat illogical in expressing the view that the maximum cutting effect is obtained with a cutting angle of 45°. It must, on the contrary, be assumed that the cutting effect per metre length of bar has already commenced to decrease at this angle, or as Jagenberg puts it, this extreme angle represents "too much of a good thing." Since there is a minimum limit for the cutting angle which can be usefully employed, it is to be assumed that there is also a maximum limit to it. This upper limit can be determined from a knowledge of the coefficient of friction \( f \) between the bars and the stuff, as follows:

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Fig. 46 shows a particle of stuff located between a pair of bars engaging with one another. The flybar presses on the particle with a force A, while the bedplate

Clayton Beadle and Stevens, "Theory and Practice of Beating"; Kirchner, "Das Papier. IV., Ganzstoffe," p. 102.
bar exercises a pressure $B$ on the particle. The conditions for equilibrium will then be:

$$\Lambda \cos a_r + f\Lambda \sin a_r = B \cos a_r + f \sin a_r,$$

and

$$\Lambda \sin a_r + B \sin a_r = f\Lambda \cos a_r + fB \cos a_r,$$

whence

$$\tan (a_r + a) = \frac{2f}{1-f}.$$

If we put $(a_r + a) = a$, which represents the total cutting angle, then the expression can be written in the following way:

$$\tan \frac{a}{2} = f.$$

Under certain conditions the coefficient of friction $(f)$ can be as much as 0·30 to 0·40. For $f = 0·40$, $a$ (the cutting angle) is about $43^\circ$.

It thus appears that with a cutting angle of $43^\circ$ there is already a danger of the fibres being carried away by the roll bar edges instead of being cut. This value must, therefore, be looked upon as the upper limit for the cutting angle, and the latter should, therefore, never be less than $3^\circ$ or greater than $43^\circ$. 
PART III

THE CONDITIONS GOVERNING THE FORMATION OF FIBRAGES
THE CONDITIONS GOVERNING THE FORMATION OF FIBRAGES

In the early part of this book three main equations $(10d)$, $(11d)$, $(12d)$ were evolved to express the output of the beater. The applicability of these equations was then investigated with the aid of comparative beating tests.

In a number of cases it was found that the equations gave results which corresponded closely with those obtained experimentally. In other cases, where the calculated values were not in agreement with the experimental values, the discrepancy was explained by the fact that one of the beaters did not give a sufficiently high rate of travel: the stuff circulated so slowly that insufficient quantities were available for the proper formation of fibrages.

The first essential to obtaining satisfactory output from a beater is, therefore, that the conditions should be favourable for the formation of fibrages, and it is thus not without interest to examine these conditions more closely.

Unfortunately, it is impossible to observe the fibrages visually,\textsuperscript{1} for the moment the flybar leaves

\footnote{\textit{Translator's Note}.—The author informs me that on one occasion he was able actually to observe fibrages. The housing of a Jordan refiner in the mill suddenly fractured. One of the fragments fouled the plug, causing it to jam and stop dead. On removing the top half of the housing, fibrages were seen to be adhering to the plug bars precisely in the manner described in the present work in connection with the theory of the action of beating tackle.—R. M.}
the stuff its fibrag is naturally flung off at once. One is, therefore, necessarily confined either to investigating analogous phenomena visually, or else dealing with the matter by theoretical methods.

Previous reference has repeatedly been made to the formation of a fibrag on the blade of a knife, and the most promise seemed to be offered by commencing the investigations with some experiments of this nature.
A smooth steel rod 250 mm. long, fitted with a handle and of square cross section, was employed (see Fig. 47). The rod was drawn through the stuff (see Fig. 48) with one of its sharp edges kept continuously to the front, thus causing a fibrage to collect on this edge. The size and appearance of the fibrage was found to depend on the speed at which the rod was drawn through the stuff. In order to ensure that every part of the rod should be moving at the same speed, it was accordingly necessary to keep it parallel to its initial position during the whole of its advance through the stuff. Moreover, it was important that its speed should approximate roughly to that of a beater flybar, i.e., say 9 to 10 m. per second. To effect this by hand required a certain amount of practice, which was acquired by repeatedly throwing a stone upwards to a height of 14 to 18 ft., for which purpose it is necessary for the hand to travel at a speed of some 9 to 10 m. per second. Having thus attained the required standard of skill the experiments were commenced.

The first showed that at thin consistencies the fibres readily tend to lie transversely across the edge of the rod in a continuous uniform fibrage. The thicker the consistency the more the fibres tend to deposit irregularly and in bundles, particularly if the rod is not moved sufficiently quickly. The "carding" action of the edge of the rod, that is to say its tendency to separate the fibres from one another and so enable them to deposit uniformly across the edge, increases very rapidly with the speed at which the rod is moved. In these experiments the rod was moved through the stuff as described, and the fibrage wiped off each time from the whole 250 mm. length of edge. After repeating this process eight times the total quantity of stuff which had been wiped off was dried and weighed. In this way the weight
of fibrage $\delta$ was determined in grams per metre length of rod. The results are shown graphically in Figs. 49 and 50.

Fig. 49 shows the relation between the size of the fibrage and the consistency of the stuff. At high...
consistencies the size of the fibrage grows extremely rapidly. If the consistency is thin the fibres are much more readily drawn apart, and therefore slide over one another more easily, so that the edge of the rod will not retain as much fibre. Fig. 50 shows the relation between the size of fibrage and the mean length of fibre in the stuff. As was to be expected, it was found that the mean length of fibre has an important bearing on the size of fibrage, such that with an average length of fibre of about 2 mm the rod will retain more than twice the quantity of fibres which it retains from stuff of an average length of fibre of 1 mm. As was also to be expected, the experiments showed that the edge of the rod exercises a selective action, in that it chiefly retains the longest fibres. A fibrage taken from stuff of an average length of fibre of 0.87 mm proved, on microscopic examination, to possess an average length of fibre of 1.01 mm., thus clearly demonstrating the selective action which takes place in favour of the longer fibres.

It is desirable to examine to what extent the results of the rod experiment correspond with practical experience of the behaviour of flybar fibrages.

It is known that the flybar fibrage diminishes in size as the consistency decreases, just as was found in the case of the rod. This is shown by Green's tests (A. B. Green, "Management of the Beater Room," Paper, 1917, No. 23). At a thin consistency (3.6 per cent.) Green observed that, under the same roll pressure, the clearance between roll and bedplate was less than at a higher consistency (about 5 per cent.); that is to say, the fibrages were smaller.

The knowledge that the size of the fibrage varies with the consistency of furnish, helps us also to understand why stuff beaten at thick consistencies becomes
If the size of the fibrage increases so rapidly with the consistency, the treatment of the stuff between the roll and bedplate will be far less harsh as the consistency increases, for the fibrage then acts as a cushion between the bars, and the latter only produce a relatively slight cutting effect.

Practical experience with beaters also shows that the size of the fibrage diminishes as the shortening of the fibre progresses. Thus it is well known that the cutting action of the roll ceases after the stuff has been treated for a certain period, and is only resumed when the roll is let down further. (A good illustration of this may be found in the curves published by Clayton Beadle, "Chapters on Papermaking," v., p. 151.) The explanation is that after beating for some time, the fibrage becomes so attenuated that no more cutting can take place until the clearance between roll and bedplate has been reduced accordingly.

Moreover, the micro-measurements carried out by W. Gruenewald (Zellstoff und Papier, 1921, No. 1, p. 23) indicate clearly that the edges of the flybars exercise a selective action similar to that of the edge of the square rod. Experiments by the same authority show that the shortening action of the beating tackle principally takes effect on the longer fibres, the short fibres slipping through untouched. This is precisely what one would expect of the selective action of the flybar.

It will be appreciated from the foregoing that practical experience agrees in all essentials with what one would expect according to the theory of the fibrage and the rod experiments. This certainly affords a good support for the theory.

We shall now proceed to examine from a theoretical standpoint the conditions which obtain when the stuff
enters the cells in the roll. A knowledge of these conditions renders it possible to design a beater which offers the most favourable conditions for the formation of fibrages.

As the stuff approaches the roll it flows in an approximately horizontal direction. Fig. 51 illustrates a beater roll and shows on a greatly exaggerated scale the dimensions which govern the entry of the stuff into the cells. The horizontal velocity of approach is denoted by \( u \) (mm. per second); and will probably be less nearer the top surface of the stuff than lower down, for there are two factors which have to be considered. On the one hand, the stuff possesses a motion caused by the anterior masses pressing continuously from the backfall towards the approach to the roll: the velocity due to this is probably the same at the top as it is at the bottom of the stuff. On the other hand, the hydrostatic pressure of
the upper layers of stuff on the lower layers tends to impart to the latter an increased velocity of approach. It has already been pointed out that stuff is certainly not a liquid in the physical sense, since a force of definite magnitude is required to slide one layer over another. At a sufficient depth beneath the surface, however, the weight of the upper layers may produce such a high pressure as to outweigh the effect of internal friction; in which case the stuff will flow into the cells in a manner similar to that, for example, of a viscous fluid. It is not proposed to differentiate here between these two component factors of the motion of the stuff, our immediate object being to determine merely the general characteristics of this motion. It will, therefore, be assumed that \( u \) represents the mean horizontal velocity with which the stuff enters the roll cells.

This velocity can easily be found if the amount of stuff (G) transported per second by the roll has been measured by the method indicated in Part II., Chapter IV. Instead of denoting this by \( G \) kilograms per second, we will now express it as \( V \) litres per second. For the moment it will be assumed that the flybars possess no thickness and that the width of the approach channel for the stuff is the same as the width of the roll (L). The depth of stuff in front of the roll may be denoted by \( H \) (metres). We then have

\[
V = uLH.
\]

In actual fact, of course, the flybars possess a definite thickness (\( s_n \)) and the effect of this thickness is to make the effective height of the channel of approach somewhat less than \( H \), the depth of the stuff. The mean pitch of the flybars is given by \( \frac{\pi D}{m_n} \) irrespective of whether they are spaced equally or not; and is denoted by
\(d_v\). The true value of \(u\) is, therefore, given by the equation:

\[ V = u \cdot L \cdot \frac{d_v - s_v}{d_v}, \]

whence

\[ u = \frac{V \cdot d_v}{L \cdot H(d_v - s_v)}. \]

Let us now consider a cell the bars of which are spaced any given distance \(a\) (in metres) apart. From the moment at which a flybar leaves any given position until the moment at which the next flybar occupies this same position, an interval of time \(a\) \(v\) (in seconds) elapses, \(v\) being the speed of the flybars. During this time the stuff moving at a velocity of \(u\) millimetres per second will travel through a distance of \(s\) millimetres, where

\[ s = \frac{a}{v}. \]

Inserting the value found for \(u\), we have

\[ s = \frac{a}{v} \cdot \frac{Vd_v}{L \cdot H(d_v - s_v)}. \]

As the flybar progresses through the stuff its action to some extent resembles that of the cutting edge of a planer; and it, so to speak, planes off a "shaving" of stuff. The thickness of the shaving is approximately \(s \cos \psi\). The equation for \(s\) shows that this thickness is directly proportional to the interval \(a\) between the bars. The length of the shaving is equal to the distance between the surface of the stuff and the first bedplate bar, and is, therefore, the same for all the flybars. It will thus be seen that the amount of stuff which enters a roll cell must be directly proportional to the interval
between the flybars which form that cell. If it be imagined that the stuff in each cell is distributed in a layer of uniform thickness (see Fig. 15), then in the same beater roll there will be an equal depth or thickness of stuff in every cell irrespective of whether the cell is wide or narrow, i.e., irrespective of the spacing of the flybars. The capacity of a cell for transporting stuff is, therefore, in theory directly proportional to the interval between the two flybars which bound it. Equation (16) for the depth of cell filling which was evolved in Part I., Chapter V., without regard to the pitch of the flybars, is, therefore, theoretically correct irrespective of whether the flybars are spaced equally or in clumps.

Experience in practice, however, does not entirely corroborate this theory. Wide cells will transport relatively more stuff than narrow cells, particularly in cases where the bars are arranged on the roll in clumps. Kirchner has demonstrated this with the aid of two examples described in the *Wochenblatt fuer Papierfabrikation*, 1919, p. 191. In the first example a roll with bars spaced 64.5—21.5—21.5 mm. was replaced by a roll with bars spaced 74.5—12—12 mm. apart; and at the same time the thickness of the flybars was increased from 7 mm. to 10 mm. The total number of flybars remained unchanged. It might have been expected that the transporting capacity of the roll would thus have been diminished, because the sum of the intervals between the flybars in each clump had been reduced from 107.5 mm. to 98.5 mm., and because the individual intervals are theoretically of no consequence. Nevertheless, it was found after the change had been made that the travel of the stuff in the beater was greatly improved. It must be concluded from this that the transporting capacity of the wide cells
was increased to a comparatively greater extent than that of the narrow cells was diminished.

In the second of Kirchner's examples, the spacing of the flybars was changed from 50—17—17 mm. to 25—25—25 mm., and the transporting capacity of the roll was then found to be considerably diminished. It is thus seen again that the wide cell fills to a greater extent than the theory would lead one to anticipate. It may be imagined that the stuff being inert requires a certain length of time to set itself in motion after a flybar has passed; and consequently will not penetrate as deeply into a narrow cell as it otherwise might.

It has already been seen that the primary essential for obtaining efficient beating is that sufficiently large fibrages shall be deposited on the edges of the flybars. A necessary condition to the deposit of such a fibrage is, however, that, during its passage through the stuff, the edge of the flybar must encounter at least as many fibres as it is expected to retain. It has furthermore been seen that the edge of a flybar following a wide cell encounters more stuff than one following a narrow cell. It therefore follows that if the circulation is such as to cause a fibrage of the correct size to be deposited on a flybar following a wide cell, then a flybar following a narrow cell will take up too small a fibrage.

Conversely, if the circulation is so rapid as to provide adequate fibrages for the bars following narrow cells, then a great deal of stuff will be transported unnecessarily in the wide cells. This superfluous transport requires power which represents so much loss, and the beating, therefore, loses in efficiency. Arranging the flybars in clumps must, therefore, be regarded as uneconomical. The only advantage of rapid circulation is that due to the proper formation of fibrages, which thereby accrues.
It will be assumed that the fibrage deposited on the edge of the square rod is of the maximum size possible under the given conditions (consistency, mean length of fibre). The size of this fibrage is denoted by \( \delta \) reckoned in grams of air-dry fibre per metre length of edge. The consistency of the stuff in the beater is given by \( \rho \) as before in kilos of fibre per litre of stuff. The interval between two consecutive flybars has been taken as \( (a) \), and the depth to which the cells are filled as \( (x) \): A cell 1 metre long will then contain \( a \cdot x \) litres of stuff, or 1,000 \( \rho \cdot a \cdot x \) grams of fibre.

The most advantageous conditions possible would be produced if all the available fibres were retained by the edges of the flybars so that only fibre-free water actually entered the cells. If 1,000 \( \rho \cdot a \cdot x \), which represents the cell content, is less than \( \delta \) (the largest possible fibrage), then it will clearly be impossible for the beater in question to operate with the largest possible fibrage; and the beater will, therefore, not be working efficiently. In all probability it is practically impossible for all the fibres to be retained on the bar edges; and only a certain percentage of the fibres entering the cells will collect on these edges. It therefore follows that for efficient operation of the beater, 1,000 \( \rho \cdot a \cdot x \) must be greater than \( \delta \). How much greater can only be determined from comparative observations on the working of good and bad beaters.

A number of beater tests will now be taken and the amount of fibre available for the formation of fibrages (1,000 \( \rho \cdot a \cdot x \)) will be calculated and then compared with the corresponding value of \( \delta \) (for example for 1.75 mm. length of fibre—see Fig. 49). If it is found that a satisfactory beating output is obtained when the value of 1,000 \( \rho ax \) is so-and-so many times greater than the value of \( \delta \), this will then afford some support for the
assumption that the fibrages measured in the rod experiments correspond exactly with those deposited on the edges of the beater roll flybars.

(a) For the first example reference will be made to the tests described in Part I., Chapter VI. (Tests No. 2). In the test with the stuff propeller, \( \rho = 0.05 \), the depth \( x \) to which the cells were filled = 11 mm. and \( a = 0.0354 \) m. The quantity of fibre available for forming fibrages was, therefore, 19 grams per metre, or roughly 7.8. In the test without a propeller, \( \rho = 0.05 \), \( x = 2 \) mm., and the amount of fibre available for fibrage formation became reduced to 3.5 grams per metre, or roughly 1.28. The beating output with the propeller was far greater than that in the test without the propeller.

(b) Test No. 13 described in the same chapter was carried out at a consistency of \( \rho = 0.069 \). The cells were filled to a depth \( x = 11.8 \) mm., and the interval \( a \) between the flybars was 0.042 m. The amount of fibre available for the formation of fibrages was 35 grams per metre, or roughly 7.8. In the second test (No. 12) the output of the beater was only about half as great, \( \rho = 0.071 \), \( x = 3.7 \) mm., and \( a = 0.039 \), which gives only 10 grams per metre of available fibre, or roughly 1.88.

(c) The experiments described under section 4 of the same chapter were carried out on bast fibres and at a comparatively thin consistency. The one beater (No. 14) worked with a consistency of \( \rho = 0.041 \), \( x = 2.4 \) mm., \( a = 0.048 \) m.; the quantity of fibre available for fibrage formation was 5 grams per metre or approximately 2.58. In beater No. 15 the consistency was \( \rho = 0.031 \), \( x = 2.0 \) mm., \( a = 0.030 \) m.; while the quantity of fibre available for fibrage formation was 1.9 grams per metre, or roughly 1.68. The specific output of this beater was much lower than that of beater No. 14.
(d) In Part I., Chapter V., section b, an example is described which shows that the output is materially diminished by increasing the consistency. The figures given are: \( \rho = 0.07 \), and \( x = 12.5 \) mm. The spacing of the flybars is 64—21.5—21.5 mm. From this it will be found that the quantity of stuff available for fibrage formation is 56 grams per metre for the bars following the wide cells, and 19 grams per metre for those following the narrow cells. These values correspond to 118 and 48 respectively. The consistency was then increased to \( \rho = 0.076 \), giving a depth of cell filling of only 2.7 mm., and lengthening the beating time by 50 per cent. In this case the amounts of stuff available for fibrage formation were 13 grams and 4.5 grams per metre length of bar following the wide and narrow cells respectively, these amounts corresponding respectively to 2.28 and 0.758.

On then increasing the consistency to 0.08 (8 per cent.) the rate of travel of the stuff became so slow that the depth of cell filling was reduced to \( x = 1.25 \) mm. At this stage it was practically impossible to complete the beating process as the stuff became discoloured grey before it was finished beaten. The amounts of stuff available for fibrage formation were 6.4 and 2.1 grams per metre respectively, corresponding to approximately 0.88 and 0.258 respectively.

(e) According to Kirchner, Arnold Rehn in his well-known experiments worked with a circulation of 95 litres per second. This circulation corresponded to a depth of cell filling of 4.10 mm. The experiments were carried out at 5 to 6 per cent. consistency, \( a = 0.035 \) m. The amount of stuff available for fibrage formation was, therefore, 17.5 to 21 grams per metre, or about 58.

Looking at the results of all the experiments enumerated above, it will be seen that the working of the beater becomes comparatively unsatisfactory, and its output
THE FORMATION OF FIBRAGES

decreases considerably as soon as the amount of stuff available for fibrage formation becomes less than 2½ to 3 times as great as the fibrage formed on the square rod from stuff of an average length of fibre of 1.75 mm. It is noteworthy that whereas at 4 per cent. consistency 5 grams of available fibre per metre were found to be ample (Experiment c), this amount of fibre was quite inadequate in the cases where higher consistencies were employed. Owing to the rapid increase in the size of the fibrage as the consistency increases a far greater "available" quantity of stuff is required: that is to say, for thick consistencies a much higher rate of travel of the stuff is required than for thin consistencies.

As a rule the speed of circulation in the beater is sufficiently high to cause the cells to be filled to the depth required for the formation of fibrages. Sometimes it has to be assisted by one or other form of propeller. In many beaters, however, especially old-fashioned types with very little slope to the floor of the trough, the speed of circulation is too slow to secure adequate fibrage formation. If on occasion such beaters nevertheless give a satisfactory output, this must be attributed to the spitting of the roll. It is naturally a matter of indifference, as far as the mere filling of the cells and the formation of fibrages is concerned, whether the stuff necessary for these purposes is supplied from the normal flow round the trough or whether it is carried right round over the top of the roll.

The author has found in the case of an old beater of this kind working on a consistency of 4 per cent., \( a = 41 \) mm., that the depth of cell filling due to normal circulation round the trough was only 0.5 mm.; while the depth due to spitting was 1.5 mm. It was only when this amount of spitting took place that the still meagre quantity of 4 grams of stuff per metre became available for fibrage formation.
THE ACTION OF THE BEATER

It will thus be realised that under certain conditions spitting may be essential to obtaining output from a beater. Some means of measuring spitting may,

Fig. 52.

therefore, appear desirable. A suitable device has been constructed and is illustrated in Fig. 52. The method of employing it is indicated in Fig. 53.

The amount of stuff discharged per second per 100 mm. width of roll is measured with the aid of a stop watch. The measurement is repeated at various positions across the width of the roll; and in this way a mean value is obtained for the amount of stuff which the roll carries round for every 100 mm. of its width.
SUMMARY

The most important points embodied in the foregoing treatise may be briefly summarised as follows:—

Mode of Operation.—The action of the beater may be regarded as a two-fold one, comprising a cutting action between the edges of the flybars and the bedplate bars which produces a shortening of the fibres; and a wet beating action caused by pressure and abrasion between the working surfaces of the flybars and bedplate bars. The extent to which the fibre is shortened can be determined by microscopic measurement in the manner described by Clayton Beadle. The wetness of the stuff can easily be determined with the aid of the Schopper-Riegler beating tester.

Thus the effect on the stuff of beating can be expressed numerically; and by combining the numerical expressions for the shortening and wetting effects it is possible to characterise any given beating operation.

In addition to the foregoing, the action of the bar edges (partly assisted by the whipping of the flybars on the stuff) tends to draw out, brush, or card the stuff, thus promoting the disintegration of the fibre bundles.

The wetness of stuff may be defined as its capacity for retaining water and, therefore, only parting with it slowly on the wire of the papermaking machine. It is to be presumed that the softening effect produced on the fibres by compression between the bar surfaces has a considerable influence on the readiness with which the stuff parts with its water on the machine wire, that
is to say, on the wetness of the stuff. As its water drains away, wet stuff will form a more compact and thinner layer than free stuff. The numerous tiny drainage channels will thus become more constricted and so will retard the drainage of the water. The softness or plasticity of the fibres, therefore, tends indirectly in two ways to improve the strength of the sheet. Firstly, wet beaten fibres felt better than free stiff fibres. Secondly, the reluctance of wet stuff to part with its water allows more time for the shake on the wire to take effect and felt the sheet.

Wetness is also governed by the extent to which water is absorbed into the hollow interior and walls of the cells (hydration). The crushing and fibrillation of the stuff contribute to producing wetness in so far as fibrillae and small fragments of fibre tend to fill up the interstices or drainage channels in the sheet and so retard the drainage of water.

The new theory of the action of the beating tackle lays down that the stuff is actually beaten while lying across the edges of the flybars and bedplate bars, in the same way as it will lie across the edge of a knife blade if the latter is drawn through the stuff (fibrages). This theory has been confirmed by observations carried out on eighteen beaters in one mill. In these beaters a fairly coarse china clay was employed and considerable wear took place on the front surfaces of the beater bars. This wear, however, only commenced about 2 mm. above the working edge of each bar, the edges themselves having apparently been protected by the fibrages. Stuff eddies or rolls of stuff are formed in the cells between the flybars and probably cause fibrages to be deposited on the edges of the bedplate bars.

The new mode of treatment of the beating operation facilitates explanation of a considerable number of
observations, such, for instance, as the decrease in output of the beater if the circulation is too slow or if the bars are set too closely together. Under these circumstances only a small quantity of stuff is able to enter the cells and the formation of adequate fibrages on the bar edges is thus hindered. This accounts for the great importance which is often attached—particularly in Germany—to rapid circulation.

It has also been established that when working with thick consistencies, good circulation is essential in order to secure a large output from the beater. Arising out of this, Professor Pfarr has developed the untenable theory that output is proportional to rate of circulation.

It is a matter of general experience that the output of a beater diminishes unduly if the flybars are spaced too closely together.

Unless one assumes that the stuff is carried forward by the bar edges it is difficult to understand properly how it can manage to penetrate between the working surfaces of the bars. Friction experiments carried out with stuff sandwiched between a sliding metal block and stationary smooth and fluted surfaces tend to bear out the assumption that the stuff is carried forward by the edges of the bars.

Output.—Let D, L, and P represent respectively the diameter, width, and pressure of the roll, \( m_s \) and \( m_v \) represent the number of bedplate bars and flybars respectively, and \( s_s \) and \( s_v \) their respective thicknesses. \( n \) is the number of revolutions per minute of the roll. The units are the kilogram and metre. If \( L_s \) is the cutting length per second of the beater, then

\[
L_s = m_s m_v L_s \frac{n}{60}.
\]

It has been shown that the shortening effect of the beating tackle is proportional to the cutting length \( L_s \).
and that the wet beating effect is proportional to \( L \cdot (s_x + s_r) \) provided that the consistencies and pressures per centimetre of bar edge are the same in any two cases under comparison.

If \( q \) is the production of the beater in kilograms of stuff per hour (\( i.e., \) the furnish divided by the beating time), \( \lambda_1 \) is the original mean length of fibre and \( \lambda_m \) the mean length of fibre at the conclusion of beating, then the following will be the equation for the cutting effect:

\[
q \cdot \frac{m - 1}{\lambda_1} = c \cdot L .
\]

Further, if \( (\omega_2 - \omega_1) \) represents the increase in the wetness of the stuff caused by treating it between the bar surfaces, then the following will be the equation for the wet beating effect:

\[
q(\omega_2 - \omega_1) = c' \cdot L \cdot (s_x + s_r).
\]

The terms \( c \) and \( c' \) are coefficients which depend on the consistency, beating pressure, and the initial and final state of the stuff; but not on the dimensions of the beating tackle.

Eliminating \( q \) from the last two equations, we obtain the equation for the character of the beating process, viz.:

\[
\frac{\lambda_1(\omega_2 - \omega_1)}{m - 1} = c' \cdot (s_x + s_r).
\]

In order to secure adequate fibration formation on the bar edges, particularly when working with high consistencies, it is important that the cells should be sufficiently filled to enable the stuff contained in them to eddy energetically. The speed of circulation in the beater must, therefore, not fall below a certain limit. With thin consistencies it appears that the quantity of stuff required in the cells is less than at high consistencies.
SUMMARY

The roll pressure exercises some influence on the rapidity with which a given shortening effect or a given degree of wetness can be attained. As the working surfaces of the bars are not completely covered with stuff, but only carry stuff along and in the vicinity of their edges, it is not a question of the so-called specific pressure, as calculated according to Jagenberg's "crushing" formula. The determining factor is the edge pressure per centimetre length of bar edge, which should be found from the following equation:

\[ p_e = \frac{P \pi D}{100m \cdot m_0 (s_e + s_r) L} \]

Experiments have been carried out with a number of fibrous raw materials for the purpose of determining the influence of pressure and consistency on the rapidity with which a given shortening effect or a given wetting effect can be obtained. The results of these experiments are illustrated by means of curves (Figs. 13, 14a, and 18) in which the ordinates represent the numbers of kilograms of stuff beaten per hour to the given final condition, per metre cutting length per second, or per square metre beating surface per second.

The expression "beating time" is often taken to mean the period of time required to shorten the fibres in a furnish to the required extent, the beating action being judged according to the degree of wetness of the beaten stuff. The cutting length \( L_n \), therefore, governs the quantitative output (production), while the qualitative output (character of the stuff) depends on the size of \( (s_e + s_r) \), i.e., on the thickness of the bars.

Since a certain minimum spacing must necessarily be maintained between the flybars, it follows that the output of the beater (the cutting length per second) will increase with the diameter and width of the roll.
The output will also increase with the number of bedplate bars, and with the circumferential speed of the roll. The two latter dimensions, however, cannot be selected entirely at will. No advantage is to be gained by increasing the number of bedplate bars beyond a certain limit, and the speed of the roll must also be kept within bounds in order to prevent the centrifugal action from becoming detrimental. Further investigations in this connection must be reserved for a future occasion.

**Power Consumption.**—If the beater is individual motor driven it is possible to determine the power required for actual beating (power consumption of the beating tackle) as well as the power consumed for rotating the roll in the stuff. Tests of this description, as well as no-load tests, have been carried out and gave the following results:—

The no-load power consumption is principally absorbed in bearing friction. An example is given showing how the bearing friction can be calculated for different roll pressures.

The power consumption of the beating tackle (that is to say, the power consumed in beating the stuff between the bars) is made up of

1. That absorbed in cutting the fibres, and
2. That absorbed by the tearing action between the surfaces of the bars.

A mathematical expression has been found to illustrate the effect of these two factors on the aggregate power consumption of the beater. Hitherto, in calculations relating to the power consumption of the beating tackle the so-called beating coefficient has been employed. In the present work, instead of calculating with the beating coefficient, the specific power consump-
 tion per square decimetre of beating surface per second has been adopted, as this renders the results more readily comprehensible. The specific power consumption is denoted by \( \bar{\mu} \) and \( \bar{\mu} = \mu \times \phi_k \).

Further tests were carried out to determine the effect of the speed of the flybars and of the edge pressure on the power consumption for beating. The results of this work are depicted graphically in Figs. 25A-E; and an attempt is made to explain the peculiar shape of the curves shown.

Special tests have been devoted to measuring the power absorbed in tearing the stuff between the surfaces of the bars; and incidentally an explanation has been found for the apparent discrepancy between Kirchner's measurements of beating coefficients and Haussner's measurements of the coefficient of friction of stuff.

It appears from these investigations that the working of the stuff between the surfaces of the bars, as Kirchner correctly states, is not a rubbing but a tearing operation. This tearing only occurs if the stuff is in a more or less disintegrated or loosely felted condition; it does not occur if the stuff is treated in the beater in sheet or board form, even if unsized; a condition similar to that of well-broken or half-beaten stuff is essential, such as that of unsized, softened, crêped serviette paper, or hand-made, lightly couched sheets of waterleaf. The power required for the tearing action has been measured in numerous instances and under the most widely varying conditions, so as to provide an explanation of all the factors which can affect this part of the power consumption of the beater. Finally, a comparison is drawn between the curve for the specific power consumption, and that for the power absorbed in tearing at various pressures.

Further discussion and experiments are devoted to
the internal friction in beater stuff; and the conclusion is drawn that in all probability special laws of friction apply, which differ from those governing the behaviour of solids and liquids. The following law for the friction of beater stuff suggests itself as the outcome of experiments carried out with the aid of specially designed apparatus:

The resistance to sliding motion along any cleavage plane in the stuff is directly proportional to the area of that plane, and is independent of the pressure on the plane or of the velocity of the motion.

The power required to rotate the roll in the stuff is partly absorbed by the whipping of the flybars on the stuff as it enters the cells, and partly in overcoming the friction between the stuff which revolves with the roll and that which remains more or less stationary in the trough. The former item of power is proportional to the square of the speed of the flybars, while the latter is in direct proportion to the speed of the flybars. It is thus possible to determine each of these two components of the power consumption separately, and this has been done in a number of examples.

The new theory—namely, that the stuff is beaten while in the form of fibrages adhering to the bar edges—is applied to the case in which the flybars are set parallel to the bedplate bars; and affords an explanation of certain peculiarities which are known to arise under these conditions, such as high power consumption and diminished cutting effect.

The size of the cutting angle between flybars and bedplate bars is discussed. It is shown that in order to maintain smooth running and an efficient cutting action, the cutting angle should not be less than 3°. On the other hand, it must not exceed 43°, as otherwise the flybars will tend to push away the stuff instead of
cutting it. It is frequently assumed that the cutting effect increases as the cutting angle becomes larger. No proof could be found for this. Providing only that the cutting angle is not less than 3° there is no reason to believe that the cutting effect increases with the cutting angle.

**Conditions for the Formation of Fibrages.**—The fibrage formed on the blade of a knife when the latter is drawn through the stuff serves as an example of the fibrage formed on the edges of the flybars. The existence of a definite relationship between the size of the fibrage and the consistency of the stuff and its mean length of fibre has been established experimentally. These experiments confirm that the fibrage deposited on the blade of a knife is comparable with the fibrage formed on the beater flybar. If the circulation in the beater is too slow, the roll will not receive sufficient stuff to enable adequate fibrages to be formed on the edges of the flybars, and the desired beating effect will not be attained. The accuracy of this conclusion is substantiated by careful examination of the results of numerous beater trials, many of which were carried out by the author, the remainder having been published from time to time in the technical press.