THE PERFORMANCE OF MILLING TRAINS: SOME THOUGHTS ON IMBIBITION

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The purpose of this paper is to examine, separately, the effects on the ultimate loss of undiluted juice in final bagasse by:

(*a*) the extent to which fibre and juice are separated in the various units of the tandem; and

(*b*) the imbibition process.

Our approach to this problem will be inductive and requires a few assumptions, t.w.:

1. Cane consists of natural fibre and undiluted juice of a uniform brix. The natural fibre in cane and bagasse contains 23.08 per cent brix-free water, corresponding to 30 per cent brix-free water on bone dry fibre.

2. We shall consider a "standard" 15-roller tandem, the units of which discharge bagasse of the following fibre percentages: No. I mill—30 per cent; No. II mill—40 per cent; No. III mill—45 per cent; No. IV mill—48 per cent and No. V mill—50 per cent. This is somewhat better than is achieved by most Natal factories.

3. The tandem crushes "standard" cane, the fibre percentage of which is 15.39 and the brix percentage 16. Hence, the composition of cane can be shown as: 520 parts undiluted juice per 100 parts of fibre, and 104 parts of brix per 100 parts of fibre. The brix of the undiluted juice is 20°.

4. The amount of imbibition water applied is 200 parts per 100 parts of fibre.

N.B.—Our calculations will be based on brix. We cannot base our calculations on sucrose for the simple reason that the sucrose content of the juice in cane is far from uniform. Juice, which is difficult to express, contains less sucrose than juice contained in cells which are easily opened. It is true that the brix of the undiluted juice is not absolutely uniform either, but the deviations from the average value are much smaller than those concerning the sucrose content. Using brix as the basis of our calculations has the secondary advantage that the loss calculated in terms of brix will always be somewhat larger than the actual loss of sucrose, due to the lower sucrose content of the juice which is most difficult to squeeze out. Hence, the actual sucrose extraction will be somewhat higher than the extraction expressed in terms of brix.

If milling were merely the mechanical separation of juice from fibre by the exertion of pressure, it is undiluted juice which would be lost in final bagasse. The imbibition process enables us to dilute the residual juice in the bagasse which is discharged by the consecutive milling units, and for this reason, the juice actually lost in final bagasse is considerably less concentrated than undiluted juice. The loss can, however, still be most suitably expressed in terms of "parts of undiluted juice per 100 parts of fibre", but we have to keep in mind that these are diluted with water.

Since the standard bagasse of our basic assumptions contains 50 per cent (bone dry) fibre, corresponding to 50 by 1.3—65 per cent natural fibre, its juice content is 35 per cent, i.e. 70 parts of juice per 100 parts of fibre.

If no imbibition were applied, this juice would be undiluted juice. Hence, 70 parts of undiluted juice per 100 parts of fibre is the highest *possible loss* in any tandem discharging final bagasse of 50 per cent fibre. This loss is independent of the composition of the cane crushed and the number of units in the tandem. If our standard cane were being milled, the tandem would obviously recover 520—70=450 parts of undiluted juice and the brix extraction achieved would be:

$$\frac{450\times 0.20}{520\times 0.20}\times 100=86.5\%$$

A lower extraction is not possible when the discharged bagasse contains 50 per cent fibre. Higher extraction percentages will, however, be obtained as soon as imbibition is applied and diluted juice is lost in final bagasse. In other words, every unit of extraction in a tandem in excess of 86.5 per cent is caused by the application of the imbibition process, i.e. when bagasse of 50 per cent fibre is discharged. In the event of wetter or drier bagasse being discharged, the minimum extraction percentages are given in Table I.

TABLE I

Fibre Percentage	*Minimum Extraction*	*Fibre Percentage*	*Minimum Extraction*
45	82.3	50	86.5
46	83.2	51	87.3
47	84.1	52	88.0
48	84.9	53	88.7
49	85.9	54	89.4

The minimum extraction percentages of Table I are obtained when no imbibition is applied. When imbibition is applied and the residual juice is repeatedly diluted, total extraction will be higher. The maximum extraction, i.e. the minimum loss is reached when, after every unit, the imbibition liquid mixes homogeneously with all the residual juice present in discharged bagasse.

As far as we know, this never happens in a normal milling train. In fact, mixing of imbibition liquid and residual juice is always incomplete and this is why maximum extraction percentages (minimum losses), are never obtained.

The incomplete mixing is not wholly due to all the juice-containing cells not being opened in the crushing operation. Khainovsky stated, as far back as 1930, that the free juice in bagasse also mixes poorly, due to the presence of small air bubbles entrapped in the already opened cells.

Since it is the extent to which residual juice and imbibition liquid mix which controls the extraction actually attained when final bagasse of 50 per cent fibre is discharged, it is desirable to consider the mixing effect quantitatively and the first question to be answered is: what are the maximum extraction percentages possible? Unlike the minimum extraction percentages, which depend on the fibre content of the final bagasse only, the maximum percentages to be obtained when mixing is complete, depend on the fibre content of the discharged bagasse and on the number of units in the tandem. Table II shows the minimum loss of undiluted juice, i.e. the maximum brix extraction, obtainable in 12-, 15-, and 18-roller tandems, when standard final bagasse of 50 per cent fibre is discharged.

TABLE II

Minimum Loss of Undiluted Juice and Maximum Brix Extraction

Tandem	*Parts of Undiluted Juice lost per 100 parts of Fibre*	*Brix Extraction Percentage*
12 rollers	5.60	98.92
15 rollers	2.15	99.58
18 rollers	0.95	99.82

From Table II, we conclude that if we succeeded in effectuating complete mixing, a more powerful than 12-roller tandem would not be required to obtain an extraction much better than is nowadays obtained with 15-, 18- and even 21-roller tandems. The use of tandems of more than 4 units is only required because our imbibition technique is so ineffectual.

For the sake of completeness, we should say that adding units to a tandem makes it also probably somewhat easier to produce final bagasse of a high fibre content, but the main purpose of these extra units is to enable us to utilise another imbibition step. What we really want, however, is not to increase the number of steps, but to make each step more effective.

Unfortunately, this aspect of milling has never been properly examined. Most imbibition investigations are concerned with the best place at which the imbibition liquid should be applied, and the general conclusions arrived at indicate that the actual location has very little effect on milling performance, even when varied anywhere from directly after one mill to just in front of the next. It seems that whatever mixing occurs, is effectuated mainly with the commencement of pressure applied to the blanket of bagasse, i.e. when the bagasse enters the front opening of the mill.

Improved Imbibition

If we want to improve the effect of imbibition, we usually raise the volume of the imbibition water, and otherwise we seem to assume that the imbibition efficiency improves automatically when measures are taken which reduce the moisture content of the discharged bagasse, or in other words, when we squeeze more efficiently. There is no factual proof in support of this assumption, nor in support of the assumption that a 3-roller unit is the best apparatus to achieve mixing of residual juice and imbibition liquid.

It is apparently highly desirable that, when improvement of milling is considered, proper attention should also be paid to the imbibition aspect of the milling operation. So far, this field seems to have been badly neglected.

To examine the effect of incomplete mixing quantitatively, we shall regard the two squeezings of a mill as one and we will further assume that the imbibition mechanism can be divided into two stages. In the first stage, all the imbibition liquid mixes with the residual juice and in the second stage, the mixture of these liquids is squeezed out by the pressure exerted by the rollers.

When mixing is complete, all the imbibition liquid mixes homogeneously with all the residual juice. Mixing is incomplete when all the imbibition liquid mixes with only a fraction of the residual juice, and the measure of incompleteness can be indicated by the magnitude of this fraction. We denote this fraction as n, n being a fractional number. It is very likely that n normally does not exceed 0.6. Later on we shall see that the incompleteness of mixing can also be expressed in a different way.

We now want to discuss how the loss and extraction data of the type given in Table II can be calculated and will take, as a first example, our standard 15-roller tandem crushing standard cane, discharging bagasse of 50 per cent fibre and using 200 parts of imbibition water per 100 parts of fibre. We assume mixing of imbibition liquid and residual juice to be complete after every mill unit.

The juice and brix distribution scheme of such a tandem is given in Fig. 1.

Juice quantities are shown underneath the horizontal and left of the vertical lines, brix quantities above the horizontal and right of the vertical lines.

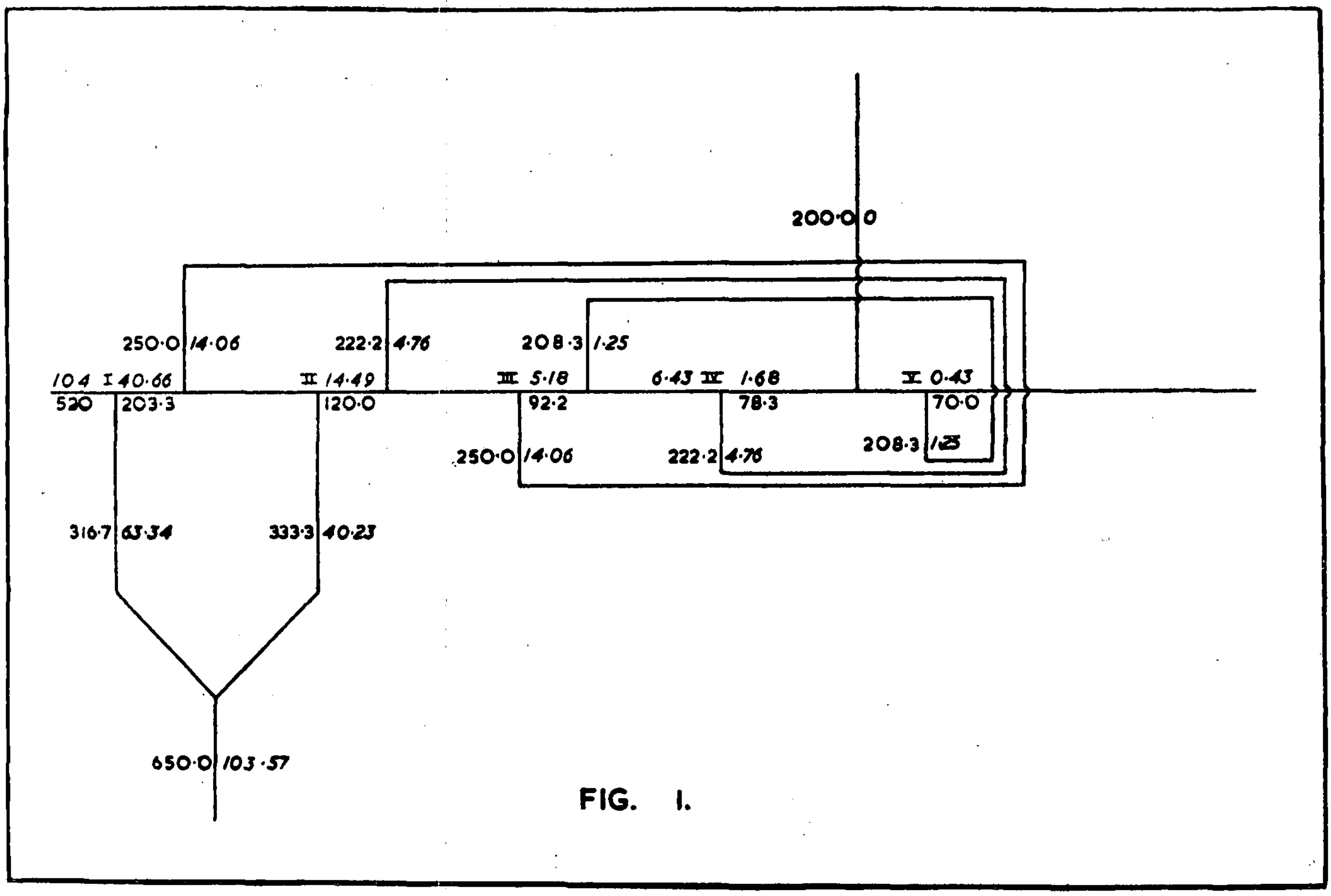

FIG. 1.

Since we know the fibre percentages of the bagasse as discharged by mills Nos. I and V, we also know the juice content. For example, No. IV mill bagasse contains 48 per cent fibre. Hence, per 100 parts of fibre, the bagasse weighs 208.3 parts and contains 78.3 parts of residual juice. 200.0 parts of imbibition water are added, bringing the weight of the liquid in the bagasse to 278.3 parts. This weight is fed into No. V mill, which discharges final bagasse of 50 per cent fibre, containing 70.0 parts of juice. Hence the amount squeezed out is 278.3—70.0=208.3 parts of last mill juice, which is returned in front of No. IV mill, where it mixes with the residual juice in No. III mill bagasse.

Similar calculations yield the quantities of juice discharged by the other mills, and also the juice extraction ratios achieved by individual mills. Since mixing is supposed to be complete in this example, the brix extraction ratios are identical to the juice extraction ratios. This is illustrated in Table III.

TABLE III

Juice and Brix Extraction Ratios for the Tandem shown in Fig. 1

Juice Extraction I $=\frac{316.7}{520}=0.6090$	Brix Extraction I $=\frac{63.34}{104.0}=0.6090$
Juice Extraction II $=\frac{333.3}{453.3}=0.7353$	Brix Extraction II $=\frac{40.23}{54.72}=0.7352$
Juice Extraction III $=\frac{150.0}{342.2}=0.7305$	Brix Extraction III $=\frac{14.06}{19.25}=0.7304$
Juice Extraction IV $=\frac{222.2}{300.5}=0.7395$	Brix Extraction IV $=\frac{4.76}{6.43}=0.7392$
Juice Extraction V $=\frac{208.3}{278.3}=0.7485$	Brix Extraction V $=\frac{1.26}{1.68}=0.7500$

Knowing the brix extraction ratios, we can now proceed to calculate the brix distribution scheme as shown in Fig. I, but first it is necessary to say a few words about the brix distribution scheme, where in this case, mixing is incomplete.

We denote the juice extraction ratios as e_{I}, e_{II}, e_{III}, etc. and the brix extraction ratios as E_{I}, E_{II}, E_{III}, etc. When mixing is complete $e=E$ and when mixing is incomplete $E \times e$. The ratio between e and E is given by the fractional number R, e.g.

$$R_{II}=\frac{E_{II}}{e_{II}};\ R_{III}=\frac{E_{III}}{e_{III}},\ \text{etc.}$$

R is, like n, a figure illustrating the incompleteness of mixing. The relationship between R and n is rather complex, as will be shown later on. To simplify the calculation of the distribution scheme, we shall substitute a, b, c, d and e for E_{I}, E_{II}, E_{III}, E_{IV} and E_{V}, or for e_{I}, e_{II}, e_{III}, etc., when $R=1$, and relate all brix quantities to 100 parts of brix entering the tandem in cane. We further denote the quantity of brix extracted by No. III, No. IV and No. V mills by x, y and z. The brix distribution scheme of the tandem can now be calculated by using the following formulae:

$$x=\frac{100c\{(1-a-b+ab)(1-e+de)\}}{\{(1-e)(1-c-d+bc+cd-bcd)\}+bcd}$$

$$y=x(b+\frac{1}{c}-1)-100(1-a-b+ab)$$

$$z=\frac{x}{cd}(1-c-d+bc+cd)-\frac{100}{d}(1-a-b+ab)$$

Brix lost in final bagasse$=100(1-a-b+ab)-bx$.

It is not always necessary to use all these formulae, but we must know x and either y, z or the loss of brix in final bagasse to complete the scheme. We can also use the fact that:

brix in bagasse I = brix in juice II + brix in final bagasse
brix in bagasse II = brix in juice III + brix in final bagasse
brix in bagasse III = brix in juice IV + brix in final bagasse
brix in bagasse IV = brix in juice V + brix n fiinal bagasse

By skilfully using the most suitable combination of the given formulae, various distribution schemes can be quickly calculated and used to study the effect of certain variables on the loss of brix in final bagasse.

In Fig. 2 (below, another distribution scheme is shown which could well be met with in actual practice:

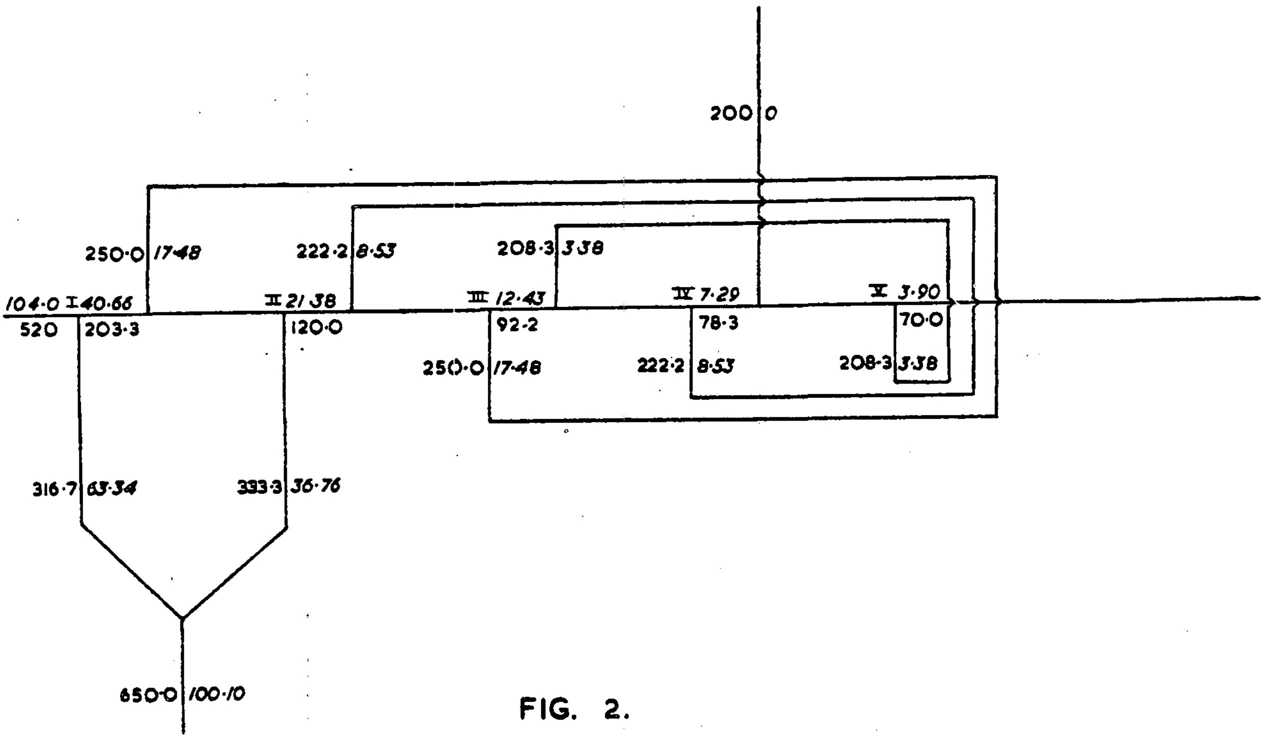

FIG. 2.

For the calculation of this scheme the following R-values were used:

$$R_{II}=0.86;\ R_{IV}=0.73$$

$$R_{III}=0.8\ ;\ R_{V}=0.62$$

The R-values decrease in the direction of the last mill, since it is very likely that it becomes more and more difficult for the imbibition liquid to mix completely with the decreasing, probably best hidden, quantities of undiluted juice. The total brix extraction percentage of this tandem is 96.26, i.e. 3.32 parts lower than the scheme represented in Fig. I, where mixing was supposed to be complete. It is interesting to note that in both tandems, the volume of juice squeezed out by No. II mill is larger than that squeezed out by No. I mill. This fact emphasises the importance of No. II mills in respect of the performance of the whole tandem.

Brix lost in the bagasse of No. II mill has to travel a long way before it is again available for recovery, to mixed juice. Mill engineers are well advised to see that No. II mills render maximum performance.

To demonstrate the incompleteness of mixing of imbibition liquid and residual juice, we have introduced first n, the fraction of residual juice which mixes with all the imbibition liquid, and later R, the ratio between the weight of brix actually expressed, to the weight of brix which would have been expressed if mixing were complete.

The relationship between n and R for any mill is given by the formula:

$$n=\frac{\beta-\eta b}{\eta\,\alpha-a}$$

where, expressed per 100 parts of fibre,

a=parts of residual juice in bagasse of preceding mill.

b=parts of imbibition juice applied.

α=parts of brix in residual juice in bagasse of preceding mill.

β=parts of brix in imbibition juice applied.

$$\eta=R\frac{\alpha+\beta}{a+b}$$

A pertinent question concerning the matter under discussion would be: What contributes more towards a better extraction (*a*) producing a drier bagasse; or (*b*) the promotion of better mixing residual juice and imbibition liquid?

It is not possible to answer this question in the general form in which it is asked, but as an example of how to deal with the subject, the following will be found useful.

We want to compare, for a certain mill, the effects of producing a drier bagasse with an improved mixing, and assume that the previous mill discharges bagasse which, per 100 parts of fibre, contains j parts of residual juice, in which bj parts of brix are present. Added to the bagasse, are i parts of imbibition liquid containing b: parts of brix. A fraction n, of the residual juice mixes with all the imbibition juice, and the mill concerned produces bagasse containing 100 f per cent fibre. It is not difficult to show that the amount of brix squeezed out by this mill is given by the formula:

$$x=(j+i-\frac{100}{f}+130)\frac{(bi+nbj)}{(i+nj)}$$

By applying the above formula to any mill, we can find the effects which we seek. For example, for No. II mill of Fig. 2 the data shown in Table IV apply:

TABLE IV

Showing the Effect of Increasing f and n respectively on the amount of Brix Extracted (×)

f(n+0.554)	x	n(f=0.40)	x
0.40	36.76	0.554	36.76
0.41	37.45	0.58	37.20
0.42	38.09	0.62	37.83
0.43	38.70	0.66	38.46
0.44	39.28	0.70	39.03
0.45	39.84	0.74	39.60
0.46	40.37	0.78	40.13

Table III shows that increasing the fibre content of the bagasse discharged by No. II mill to Fig. 2 from 40 per cent to 46 per cent, has about the same effect on the amount of brix discharged as increasing the fraction of the residual juice which mixes with the imbibition liquid from 0.55 to 0.78. 1 per cent more fibre corresponds to an approximately 0.04 higher n.

In the foregoing pages, we have endeavoured to develop a general picture of certain aspects of the functioning of a milling tandem. The quantitative relationship between the loss of brix suffered in final bagasse, the fibre percentage of the bagasse as discharged by the mill units and the imbibition operation, appeared rather complex, as was shown in a set of formulae.

It is of course highly desirable to prove experimentally, the correctness of the assumption on which our calculations are based. This would not be too difficult, provided a tandem is made available for such a test, and preliminary measures taken which would guarantee a successful run.

Mr. Rault said that the problem of a more intimate contact between imbibition water and residual juice contained in a bagasse was a puzzle which baffled many sugar engineers and as suggested by Dr. Dowes-Dekker, was often at the root of variations in mill extractions that could not be explained by any defects in the running of a mill which should be judged by its uninterrupted run at high capacity and the dryness to which the bagasse could be lowered. Its main purpose was nevertheless the lowering of the sucrose content in the treated bagasse, which was also a function of the displacement power of juice by the water added during milling. In spite of the heavy machinery and power requirements, milling was on the whole a comparatively quicker method of juice extraction than the slow diffusion methods which relied entirely on mixtures of residual juice and added water. The mills number six units against the minimum of twelve compartments of the diffusion battery, continuous or not, and its flexibility was larger in the way of capacity as well as water economy and quality of final fuel. It is peculiar that in spite of the higher efficiencies of Australian Maceration baths and Nobel carriers of Javan fame, these systems have not found favour nowadays. Our high fibred raw material in South Africa demands the use of heavy imbibition, but its admixture effect is far from satisfactory, in spite of the use of knives and shredders. He hoped that the S.M.R.I. would guide the industry in finding the most suitable machinery for solving this problem of higher imbibition efficiency.

Dr. Douwes-Dekker said that the diffusion process was different in that there was no squeezing out of juice; the diffusion process was a much more lengthy process than the milling one. He said that up to now we did not know how to improve the mixing of maceration with residual juice. He thought the answer could be found by experimentation, but he said that it was difficult to obtain the use of a milling train for this experimental process work.

Mr. Grant said that Mr. Gunn had found that by increasing extraction one increased the absorption. He thought this might depend upon grooving. With bigger grooving there was a higher moisture content of the bagasse. He thought that this might be due to the gap between the top of the groove and the corresponding root of the other groove. This was the point of low pressure.

Dr. Douwes-Dekker said that Mr. Gunn had found that extraction increased with decreased re-absorption. In general he said that at increasing amounts of fibre being pushed into the discharge opening extraction increased up to a maximum after which extraction dropped through increased re-absorption.

Mr. Gunn said that all the evidence from Queensland was worked out on a two roller and a three roller experimental mill. There it was found that re-absorption increased with extraction and this was natural because extraction increased with increased pressure. He said that Egeter had found that up to a point of 1.6 re-absorption, extraction would increase but would decrease after that point.

Mr. Bentley suggested that Mr. Gunn try to plot rate of change of re-absorption against the rate of change of extraction.

Mr. Gunn said that this could be done, but up to the present he had not got the necessary data to do so.

Mr. Rault asked would it not be possible to increase the number of units and thus obtain results somewhat similar to those obtained by diffusion.

Dr. Douwes-Dekker asked Mr. Gunn and Mr. Pole about fibre calculated from dry matter in bagasse and residual juice purities. In Queensland they had found that the purity of the juice left in bagasse was very much lower than that of the extracted juice. This had been confirmed by work done at the Sugar Milling Research Institute. He thought that it would be better to determine fibre directly, by the Australian or Hawaiian method.

Mr. Pole said that he had obtained up to double the brix from the residual juice in the bagasse by squeezing it in a hydraulic press as compared with the brix of the last roller juice.

Mr. Rault said that he had found the same conditions. He did not agree with Dr. Douwes-Dekker that the purity of the residual juice could be very much lower than the last expressed juice as the presence of unbroken cells had sometimes the reverse effect as was found when subjecting the final bagasse to more intense pressing.

Dr. Douwes-Dekker repeated that his remarks did not apply to the bagasse after imbibition had been applied.

Mr. Dent said that in Australia they had considerable success with the pressure feeder and he wondered if some of this good result might not result from the better mixing of the imbibition with bagasse.

Mr. Gunn said that the practice with the pressure feeders was that some of the juice extracted was again returned to the bagasse entering the apparatus.

Dr. Douwes-Dekker asked if the figure of 20.9 lb. per cubic fibre foot escribed volume was normal.

Mr. Gunn said that the lowest figure they had ever had was 18.5 and the highest about 22.5.

Dr. Douwes-Dekker said that for the first mills in Java they were able to increase these figures to 30-35 and he considered 20-22 to be rather low.

Mr. Gunn said that in the last part of his paper he had said that this had prompted the thought that the feed roller was too far open. In order to obtain the figures quoted by Dr. Douwes-Dekker, the feed roller would have to be tightened up. A compression ratio of 2.5 would give at least 26 lb. of fibre per cubic foot of escribed volume.