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# THE CONTROL OF THE CHEMICAL PULP MILL

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***Synopsis*** The paper deals mainly with the control of a kraft mill for either unbleached or bleached pulp, with special emphasis on control of the quality and quantity of the pulp produced. Differences in control strategies and objectives for market pulp mills and pulp mills in integrated systems are elucidated.

The pulping system is described in terms of the various subsystems, important operations in these subsystems and information required for process control both on quality and quantity of the product in each subsystem. The analytical methods used to arrive at this information are compiled, as are the corresponding control actions. Important for the control strategy will then be the frequencies of the disturbances, the time delays (dead time) and the mixing in the local processes. In a modern mill of specified type, at least 50 per cent of the total disturbing variations have frequencies less than 12 h, whereas control loops of the important final product qualities in most cases cannot take care of disturbances with period times less than 12 h. An optimum control strategy should therefore be based primarily on local control in each subsystem to take care of the disturbances occurring in the processes.

The wood quality is important for the final results and mixing of wood to produce a homogeneous raw material is therefore essential for a good control. Important items of the wood preparation are also removal of bark and chipping to a reasonably uniform size.

Cooking is no doubt a key operation. A description is given of the two different systems used (batch and continuous cooking), with special reference to the several variables influencing the cooking results. Similarities as well as differences between the two systems are pointed out. Both are mainly feedforward systems. The cooking result can be judged fairly accurately from pulp lignin content determinations (such as kappa number). The sampling procedure for these determinations is important for the accuracy of the control. Homogeneity problems should be included in the control concept.

Bleaching is usually carried out in several stages, starting with cheaper but degrading chemicals (such as chlorine) and ending with more expensive but fairly selective chemicals (such as chlorine dioxide). This gives an intricate balance between the degradation and the cost of the bleaching, which requires an adequate choice of

*Under the chairmanship of Dr S. A. Rydholm*

objectives for each stage and a good knowledge of the critical levels of the degradation. The most important source of disturbance is the variation of the lignin content in the unbleached pulp, which should, at least partly, be taken care of by mixing. The control of this variable should for the rest be carried out mainly in the first stage.

### *Introduction*

THE control of chemical woodpulping aims at keeping the mill processes in such a condition that the optimum results are obtained. The market pulp mill has to meet the quality demands of several different papermachines, whereas only a limited variety of pulp can be economically justified. The contact with the paper process is only indirect and the decisions on quality control will be based on pulp price relationships and on more or less well-defined specifications from the customers. Off-grade pulp can easily be sold with a price reduction, which in some cases can be fairly small. The best economic output is usually obtained at a high and steady production as the variable costs per unit are only little influenced by the production level within a broad range. The integrated pulp and paper mill has a direct contact between the pulp and the paper processes and the pulp should suit only a limited number of papermachines and paper qualities. This makes it easier to adapt the pulp quality to the actual situation and to find accurate criteria for pulp quality, which in many cases can be exploited to reduce the production costs. Off-grade pulp produces off-grade paper, which has a very low value, because alternative uses of the paper are not too frequent. Therefore, it is usually slushed and with a considerable quality risk mixed into the paper furnish. The quality control of the pulp is in this case of considerable economical importance, too, although the specifications may differ from those of the market pulp mill. The quantity decisions depend on the integrated economy of the mill and are therefore greatly influenced by the productivity of the papermachine on various paper qualities. This usually leads to variations and rather frequent changes in production level, although in each case at the highest feasible level. Note that the pertinent quantity is the net production.

The integrated mill, which produces an excess of market pulp, is an intermediate case. Quality control must consider both alternatives, which may justify a certain sectioning of the pulpmill. The quantity decisions can very often be based on the assumption that the market pulp should fill up the marginal capacity of the pulpmill.

### *General considerations on quality control*

IT IS difficult to define the pulp quality accurately from the demands of the paper side. The pulp should give good runnability on the papermachine and satisfying serviceability of the paper. The former means low drainage

resistance, good pressing and drying behaviour on the papermachine after the necessary beating of the pulp. The latter means good properties of the paper for strength, cleanliness, colour, surface smoothness, porosity, etc., all of which are fairly easily measured in the papermill. These paper properties are built up from several different fibre properties, as well as from various machine variables in the papermill. Dimensions and flexibility of the fibre, mechanical damage to the fibre wall, lignin and hemicellulose contents of the pulp, physical and chemical conditions of the major pulp components (cellulose, hemicelluloses, possibly lignin), presence and state of impurities (specks, pitch or inorganic components) are all important for the quality of the papermaking pulp. Most of them can be measured only indirectly, some of them only after time-consuming analysis.

The cost of the quality control is an integrated part of the total optimising problem. Fully unbiased control cannot therefore be accepted as economic. The optimum control strategy requires current knowledge of how the process affects the pulp properties. It must also be established what characteristics can easily be measured of those that discerningly describe the important, intrinsic properties of the pulp.

### *Process dynamics and control strategy*

THE control strategy has to consider that the chemical pulp mill consists of various departments from the receipt of the wood to the delivery either of a pulp slurry or dried pulp in bales, each department with its own objectives. The residence time in each is considerable and in many cases decisive for the control, as will be discussed later on. The possibility of local control is reasonably good. The balance between local control and entire control will therefore be of utmost importance in optimising the mill.

The various departments in a mill producing bleached pulp are presented in Fig. 1, which shows the important operations in each department and the fundamental information required for process control (the arrows indicate the direction of the control actions). Important ingoing and outgoing flows are also indicated. A mill for unbleached pulp is built up in a similar way, excluding the two last departments (bleach plant and final screening).

The quality information required for process control has been established in various ways (mostly indirectly) and, in almost all cases, according to testing methods, the results of which depend on the testing procedure. The interpretation of data is therefore delicate and it is even more difficult to correlate them with the pertinent control action. There is no doubt that the lack of good testing methods, especially continuous ones, is a serious drawback in the pulp industry, which we hope will be removed within the near future. In Table 1,

the current methods have been related to the fundamental information indicated in Fig. 1 for the quality control and in each case to the most adequate local control action. The analyses of the final pulp quality have counterparts in the local control, some of them being quite obvious, others more farfetched. It is therefore possible to find a control action for each quality aspect of the final pulp, although the detailed pattern would be outside the scope of this survey (compare with Rydholm[1]).

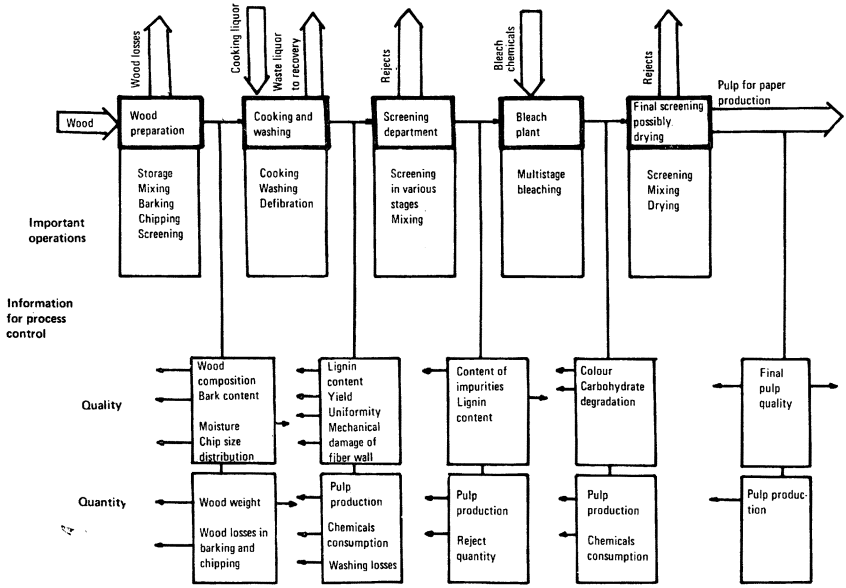



***Fig. 1***

The methods indicated in Table 1 will not satisfy our criteria for optimised control until proper frequencies of the analyses and control actions have been established. To give a background for this, Table 2 shows the residence time of the wood material in each department of a modern mill with a woodroom containing ice melting chamber, dry barking drums, chippers, chip screens and chip silos, a continuous digester equipped with digester washing and a final filter wash, blow tank, screening department and high density storage, an equalising bin and a five-stage bleaching sequence (chlorine-alkali-chlorine dioxide-alkali-chlorine dioxide). The bleaching plant might be equipped with a prebleaching stage for higher grades and installations for extra charges of hypochlorite and chlorine for savings in the costs of bleaching chemicals. The

TABLE 1 RELATIONSHIPS BETWEEN SIGNIFICANT PROPERTIES AT VARIOUS STAGES IN THE PROCESS, MEASUREMENTS OR ANALYSES AND CONTROL ACTIONS IN THE PROCESS

| *Process* | *Analysis* | *Control action* |
|---|---|---|
| *Wood preparation* | | |
| Wood composition | Log classification before barking | Selection of wood, mixing |
| Bark content | Log classification after barking<br>Bark content in chips | Pretreatment before barking, intensiveness of barking |
| Chip size distribution | Classification in slot screen | Chip length, screening |
| *Cooking and washing* | | |
| Moisture | | Liquor/wood in cooking |
| Lignin content | Kappa number | Batch cooking: standardise all digesters to produce equal results, then adjust the standard cooking time<br>Continuous cooking: temperature |
| Yield | Carbohydrate analysis, alkali resistance, etc. | Charge of cooking liquor |
| Uniformity | Laboratory screening (pulp viscosity) | Charge of cooking liquor, circulation conditions, better control of lignin content |
| Mechanical damage of fibre wall | Laboratory evaluation of paper properties | Decreased blow pressure or blow temperature |
| *Screening department* | | |
| Content of impurities | Speck count | Setting of reject flows, improve barking and better control of average lignin content |
| Lignin content | Kappa number | Batch cooking: standard cooking time<br>Continuous cooking: temperature |
| *Bleaching plant* | | |
| Lignin content | Kappa number | Charge of chlorine and alkali |
| Colour | Brightness of standard sheet | Charge of hypochlorite and chlorine dioxide |
| Carbohydrate degradation | Pulp viscosity | Restrictions on the charge of degrading chemicals (chlorine dioxide instead of chlorine, possibly of hypochlorite) |

TABLE 1 (*concluded*)

| | |
|---|---|
| *Final pulp quality* | |
| Runnability on the papermachine<br>Serviceability of final product | Brightness<br>Brightness stability (kappa number)<br>Speck count (including shives, etc.)<br>Fibre weight<br>Fibre length<br>Pulp viscosity<br>Extractives content<br>Pitch deposits<br>pH value<br>Inorganic components (Conductivity)<br>Standard beating and sheet formation, evaluation of paper properties<br>Beating resistance<br>Drainage properties of stock<br>Strength properties of paper<br>Optical properties of paper<br>Behaviour of paper towards air, water and oil, respectively |

normal sampling interval for various analyses of wood material and pulp is also illustrated as are the time from control action to measurement in each case and the control intervals.

According to our experiences, the variation in pulp quality can roughly be characterised by a number of randomised disturbing variables. This can be expressed in the following equation—

$$\sigma_{tot}^2 = \Sigma k_i \sigma_i^2$$

where $\sigma_{tot}^2$ = variance of outgoing variable,
$\sigma_i^2$ = variance brought about by each disturbing variable,
$k_i$ = parameter defined by the process.

Important for the choice of control strategy will then be the frequencies of the disturbances, the time delays (dead time) and the mixing in the local processes. Since the disturbing variations with a frequency lower than 12 h are at least 50 per cent of the total feedback from the final product, quality analyses alone are not satisfactory. According to Table 2, the time delays between control action and measurement are so long for the important qualities that control loops cannot take care of disturbances with period times lower than 12 h. An optimum control strategy should therefore be based primarily on local control within each department taking care of occurring disturbances in the processes.

A duly sized mill has its quantity determining section in the final department (in case of an integrated pulp and papermill, the papermachine). The capacity is therefore controlled from that end and the preceding departments run to match this department. Buffer storage between the departments is necessary to compensate transitory discrepancies in capacity (other discrepancies could not possibly be accepted in a normal mill). When determining these buffer volumes, one must balance the cost of production losses against the cost of buffer volume according to the disturbance frequencies and amplitudes. As an example of this, it could be mentioned that a mill with one continuous digester feeding one papermachine during one year had a digester time efficiency of 96 per cent. Owing to a total buffer corresponding to about 18 h run at nominal papermachine capacity, this resulted in an efficiency of at least 99 per cent of the available papermachine capacity.[2] The cost of this buffer was small compared with the gain in marginal capacity of the mill.

Buffer volumes are very often built to permit preventive maintenance in a department without disturbing the operation of the others. In an integrated pulp and paper mill, the papermachine maintenance down-time is usually decisive for buffer dimensioning. A proper dimensioning should also consider that higher concentration of pulp or chemicals in storage gives a better volume

TABLE 2 MEAN RESIDENCE TIME AND MIXING OF THE WOOD MATERIAL IN EACH DEPARTMENT OF A PULPMILL: TIME BETWEEN CONTROL ACTION AND RECORDING OF VARIOUS MEASUREMENTS OF QUALITY DATA, SAMPLING INTERVAL AND SUITABLE CONTROL INTERVAL IN THIS MILL

| | *Control action measurement* | *Sampling interval* | *Control interval* |
|---|---|---|---|
| *Wood preparation* (*mean residence time* of logs 6–12 h, mixing 0·5–1 h mean residence time* of chips 1–7 days, mixing 3–12 h*) | | | |
| Log classification, wood yard (visual estimation) | | 20 min | 4–24 h |
| Bark content of logs after barking (visual estimation) | | 4 h | |
| Bark content in chips | | 12 h | |
| Chip size classification on slot screen | | 12 h | |
| *Cooking and washing* (*mean residence time* 5–7 h, mixing 0·5–1 h*) | | | |
| Moisture | | Continuous measurement, laboratory spot tests | 5–15 min |
| Kappa number | 1·5–4·5 h | 1 h | 3–15 h |
| Carbohydrate analysis (or alkali resistance) | | Spot testing | |
| (Pulp viscosity) | | (8 h) | |
| Laboratory evaluation of paper properties (Freeness) | (0·1–1 h) | Spot testing (1–2 h) | (1–2 h) |
| *Screening department* (*mean residence time* about 0·5 h, mixing about 0·25 h*) | | | |
| Speck count (or laboratory screening) | | 8 h | 8 h |
| *High density storage* (*mean residence time,* say, 10 h, mixing 1 h*) | | | |
| *Bleaching plant* (*mean residence time 10–15 h, mixing about 1 h*) | | | |
| Kappa number feedforward | 0·5 h | 1 h | 1–4 h |
| Brightness feedforward/feedback | 0·2–1 h<br>1·5–6 h | 1 h | 1–8 h |
| Pulp viscosity | 1·5–6 h | 2 h | 2–10 h |
| *Final pulp quality* | | | |
| Brightness | | 1 h | |
| Brightness stability | | 24 h | |
| (Kappa number) | | (1 h) | |
| Speck count | | 1 h | |
| (Fibre weight) | | (2 days) | |
| (Fibre weight) | | (2 days) | |
| Pulp viscosity | | 2 h | |
| (Extractives content) | | (8 h) | |
| (Pitch deposits) | | (24 h) | |
| pH value | | Continuous measurement on pulp slurry, laboratory spot tests | |
| (Inorganic components) | | (24 h) | |
| (Conductivity) | | (24 h) | |
| Laboratory evaluation of paper properties | | 24 h | |

* Corresponding to the buffer volume of the system

efficiency (for example, high density pulp storage or storage of thick black liquor). Normal high density pulp storage will, however, not produce any obvious mixing, which may be important in certain cases.

### *Local control of the quality*

THERE are three considerations—wood preparation, cooking and bleaching.

*Wood preparation*

The wood to a chemical pulp mill, especially a kraft mill, is usually extremely heterogeneous—in some cases, consisting of various wood species; in all cases, with a certain individuality of each log. Variations in storage conditions are frequent also at the straightforward truck hauling of the wood from the forest. One of the most important operations in wood preparation is therefore an equalising of the wood by mixing logs or chips.

In modern forestry, barking is done primarily at the pulpmill, which will also facilitate the identification of various wood species and a possible sorting out of interesting groups of wood species. The barking is usually carried out either in single-log machines or preferably in barking drums, now usually dry ones. The wood is then cut into chips to make it fully accessible to the cooking chemicals. The chipping is carried out by rotating inclined knives mounted on a dish. They cut the wood more or less at rightangles to the fibre direction, at the same time sucking in the log.[3]

The aim of wood preparation is thus to produce a homogeneous wood mixture in the form of clean chips of the right size, preferably with a fairly constant water content. The chip size distribution can now be properly characterised in a slotted screen, which separates the fines from the chips and classifies the chips according to chip thickness. The bark content can roughly be estimated by a manual sorting out of chips containing bark. The fines tend to clog strainers in the digester, especially in continuous ones, as do acute angular chips. The thicker chips will not be sufficiently cooked, since the cooking reactions are homogeneous enough only to a fairly small depth (in normal cases, about 3 mm). Bark can be pulped in the kraft process, but it then produces cells that have poor drainage and bleaching characteristics. It usually also gives medium-sized particles, which are difficult to remove quantitatively in the screening and can definitely be considered as impurities in unbleached pulp. These particles will be bleached slowly, but will finally disappear as impurities in the pulp at a very high brightness; in many cases, this is excessive and therefore causes bleaching costs to be too high. The disturbing factors in wood preparation are mainly wood quality and varying wood storage conditions, temperature (especially very low ones) and machine deficiencies, the latter caused primarily by wear. The barking can be controlled by

the intensity of the pretreatment of the logs and by the degree of the filling of the drum (damming the discharge) or the pressure of the barking tool on the log. Adjustments in, say, the filling of a barking drum can be made only at long intervals because of the work involved. Seasonal variations in barking resistance, being the most important ones, can be controlled in this way. Note that excessive intensity of barking may cause severe wood losses.

Chipping is controlled primarily by the knife setting, that is, by the choice of chip length. The sharpening cycle of the knives is also very important as are the clearance of the knives to the counterknife (which should be small) and the wearing of the counterknife. The knife cutting speed should not be excessive, since higher speeds tend to produce crushing instead of clean cutting, especially with brittle wood (for example, at very low temperatures). In winter, a different knife setting is therefore chosen to avoid too many fines (that is, longer chips). The chip size distribution can be controlled also by chip screening. The rejection of oversized material is thus not very selective, whereas fines are removed more efficiently, provided they are not caked together by ice or snow. The oversized material can be accepted after a size reduction in a suitable mill, whereas the rejected fines usually must be considered as a complete loss, which may have serious economic consequences. One solution of the problem may be to remove the fines, then to charge them back to the chips very carefully below the critical level of fines content in the chips.

Rapid control of chip quality has thus very limited scope. The continuous digester can eliminate short-term variations of a periodic time less than 1 h and similar conditions apply to batch cooking (of course, then depending on the digester size), but this is not enough. Variations with periodic times less than 10–20 h ought to be eliminated for proper control in the further processing. Mixing of chips is therefore important. This can be done if a number of chip silos with different time delays is used. Three towers give fairly good mixing, provided there are suitable delay differences.

*Cooking*

The cooking is a treatment of the wood by chemicals at fairly high temperature to dissolve lignin and make it possible to liberate the individual wood fibres after suitable mechanical treatment (only blowing or mild treatment in an opener for chemical pulping). Lignin should be dissolved to an extent according to the properties desired and considerable amounts of hemicellulose should be removed, whereas the remainder will be built up by a somewhat modified and fairly ordered cellulose skeleton embedded in the remaining, less ordered hemicellulose and the residual lignin. An optimisation usually means that the dissolution should be controlled in such a way that the desired mechanical properties of the fibres are obtained at the highest possible

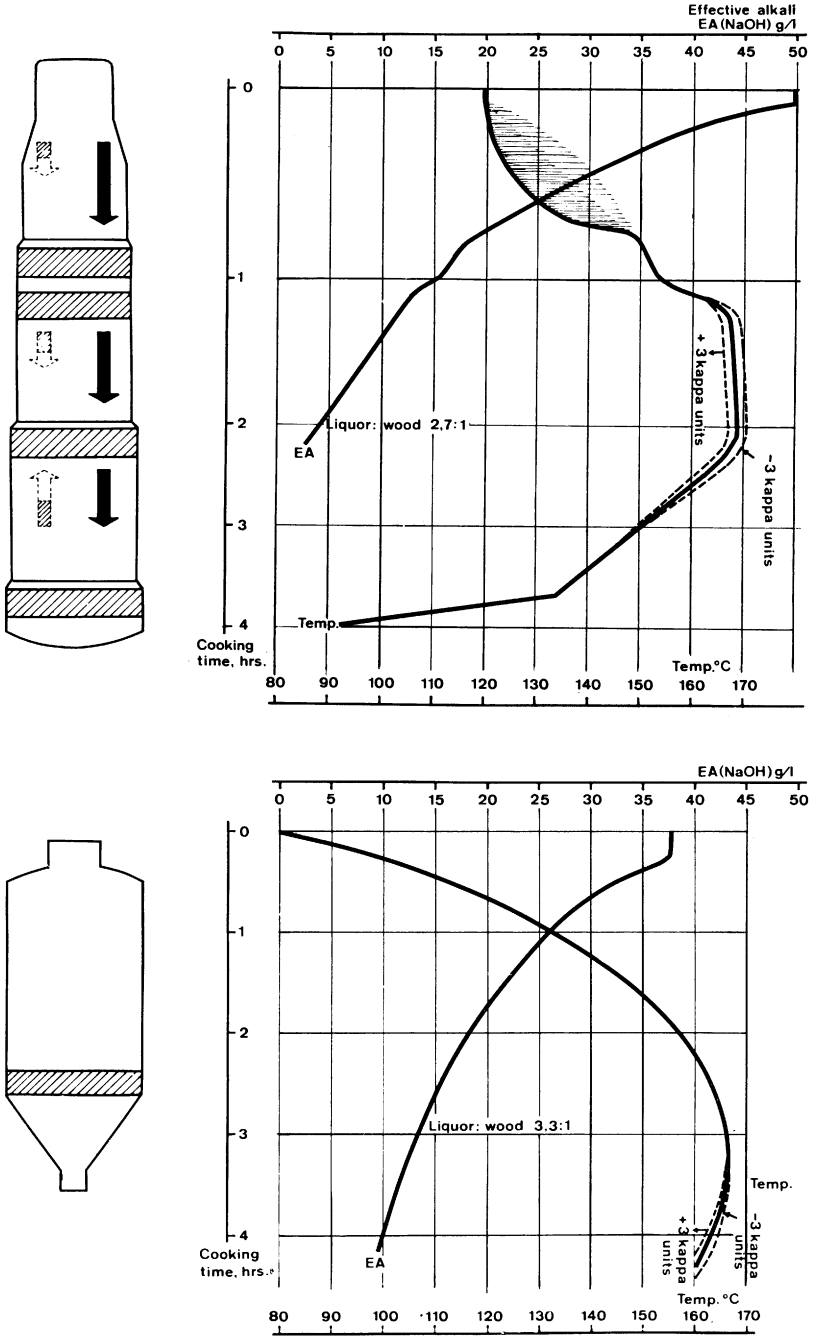

Effective alkali
EA(NaOH) g/l
0 5 10 15 20 25 30 35 40 45 50
0
1
2
3
4
Cooking time, hrs.
Liquor: wood 2,7:1
EA
Temp.
+ 3 kappa units
- 3 kappa units
80 90 100 110 120 130 140 150 160 170
Temp.°C
EA(NaOH) g/l
0 5 10 15 20 25 30 35 40 45 50
Liquor: wood 3.3:1
EA
Temp.
+ 3 kappa units
- 3 kappa units
Temp. °C
80 90 100 110 120 130 140 150 160 170

***Fig. 2***

yield. In kraft cooking, the active cooking chemicals are sodium sulphide, which helps to split up the lignin into fragments and sodium hydroxide, which neutralises *inter alia* the phenolic groups of the lignin fragments and makes these fragments soluble.

The cooking is carried out either batchwise in digesters, which run through a fixed cooking cycle or in a continuous digester, where the wood passes through a series of more or less stationary zones with conditions in general roughly corresponding to the cooking cycle of a batch digester. The important cooking conditions of the two systems are illustrated in Fig. 2, which refers to the cooking of normal chemical pulp from pine to a kappa number of 35, in both cases with a charge of 210 kg active alkali/ton oven-dry wood. The kappa number, which is proportional to the lignin content, can be considered as the determining quality variable, to be discussed later on. It is quite obvious that the two cooking methods resemble each other, although there are significant differences, especially the higher initial alkalinity and initial temperature, as well as the more rapid temperature changes of the continuous cook.

As regards control, batch cooking disturbances are introduced even at the start, except for irregularities in time-temperature schedule, whereas continuous cooking will on one hand moderate the disturbances introduced initially, yet on the other side will later on introduce disturbances not occurring in batch cooking. The latter are caused mainly by changes in the steady state, which is necessary for distinguishing the various zones of the cook. These changes in the steady state are developed by deficiencies in the material balance and will influence all stages of the cook. Important in this respect is the relatively low flow rate of the free liquor in the digester compared with the rate of wood, which is illustrated in Fig. 2 by arrows.

The normal control actions to increase or decrease the kappa number of the pulp are also shown for both batch cooking and continuous cooking in this diagram. In batch cooking, the time at maximum temperature is adjusted to produce the desired level, whereas adjustments in the maximum temperature are used for control in continuous cooking. Note that, for good and simple control, the batch digesters should be equalised in cooking results, after which all control actions can be standardised over the digesters and must not be individual. The sampling can then be simplified. This control strategy will consequently resemble that for continuous cooking. Both cooking systems are essentially feedforward systems, since the control intervals are too long compared with the frequency of the majority of the disturbances. It is therefore essential to control the wood charge, the charge of chemicals (in kraft cooking, primarily the active alkali) and the time-temperature schedule, as being the major cooking variables. To illustrate the importance of various disturbing variables, Table 3 shows the standard deviations of these

variables for normal control of the type of batch cook described in Fig. 2 and the corresponding effects on the kappa number. It is quite obvious that the two most important disturbing variables are the wood charge and the time-temperature schedule. The effect of the wood charge can be decreased considerably by an increased alkali charge, at which, however, the effect of the time-temperature schedule will be somewhat increased.

TABLE 3 EFFECT OF VARIOUS DISTURBING VARIABLES ON BATCH COOKING WITH NORMAL CONTROL CARRIED OUT ACCORDING TO METHOD DESCRIBED IN FIG. 2

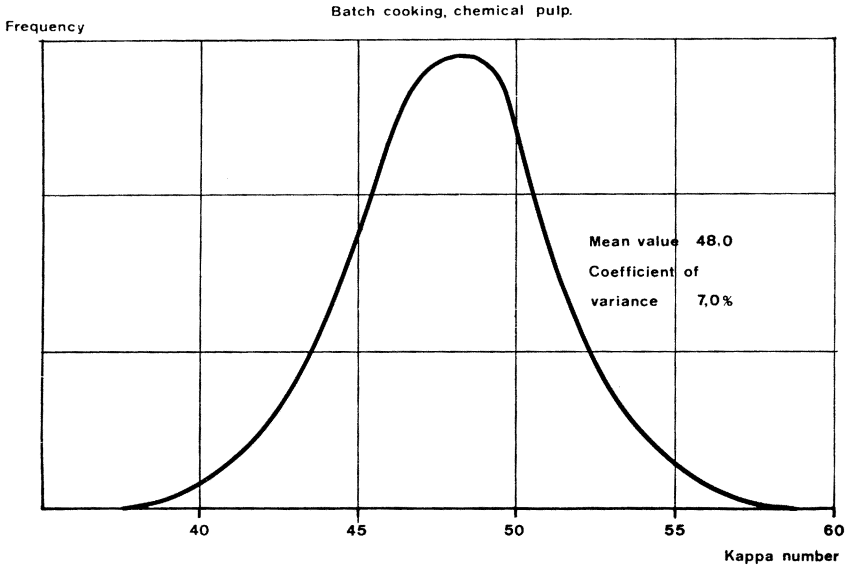
| | *Standard deviation, per cent* | *Kappa number* | |
|---|---|---|---|
| Wood charge | 4 | 3·9 | |
| Titration of white liquor | 2 | 2·0 | |
| Charge of white liquor | 2 | 2·0 | |
| Liquor-to-wood ratio | 0·2 | 1·0 | |
| Cooking schedule— | | | |
| Maximum temperature | 1°C | 3·3 | 3·9 |
| Cooking time | 5 min | 2·0 | |
| Total | | 6·2 | |

The wood charge is in most cases measured by volume (chip volume), since the volume so far has been more accurate than weighing combined with moisture measurement. The volume measurement is carried out on fairly well packed chips in batch cooking, whereas it concerns loosely packed chips in continuous cooking. The accuracy should be very much the same with a proper packing routine, since the coefficient of variance of the intrinsic chip packing seems to be approximately the same, as shown by Table 4. In practice, a higher variability is noticed, mainly because of improper design and operation of chip hoppers and of poor control of the packing procedure (over shorter periods, a smaller variability may be experienced).

TABLE 4 PACKING DENSITY OF CHIPS FROM SCOTS PINE MEASURED IN THE LABORATORY, EXCLUDING OR INCLUDING VIBRATORY PACKING (APPROXIMATELY CORRESPONDING TO PACKING IN MEASURING WHEEL OF CONTINUOUS DIGESTER AND IN BATCH DIGESTER, RESPECTIVELY)

| | *Excluding vibratory packing* | *Including vibratory packing* |
|---|---|---|
| Average, kg oven-dry wood/m$^3$ | 137 | 186 |
| Coefficient of variance, per cent | 3·5 | 3·3 |

The disturbing variables in continuous cooking are more difficult to estimate because of the more complicated course. Similar relationships as for batch cooking should be valid, however, although the relative importance


Batch cooking, chemical pulp.
Frequency
Mean value 48.0
Coefficient of
variance 7,0%
40
45
50
55
60
Kappa number

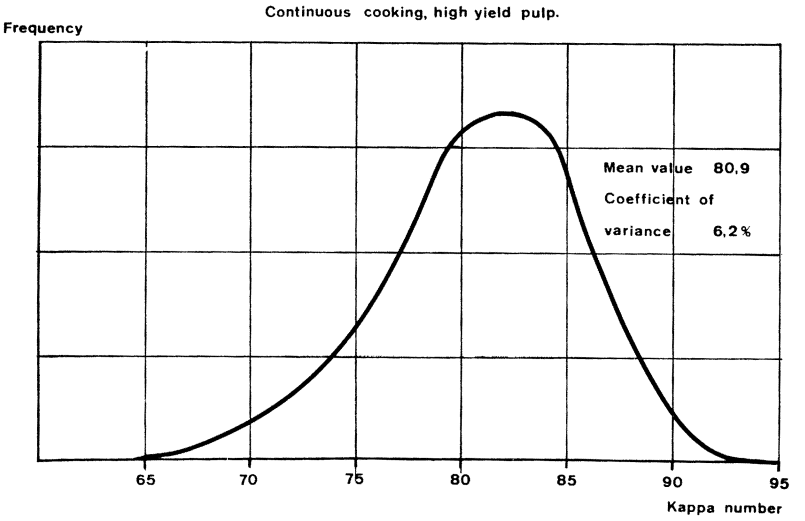

Continuous cooking, high yield pulp.
Frequency
Mean value 80,9
Coefficient of
variance 6,2%
65
70
75
80
85
90
95
Kappa number

*Fig. 3*

may differ somewhat. The time-temperature schedule should thus be easier to control, whereas the importance of the wood charge may increase because of its influence on the material balance of the digester (yet high frequency variations do not necessarily increase the effect of the wood charge).

The total variation of the outgoing variable, the kappa number, seems to be somewhat lower for continuous cooking running at constant capacity with uniform wood and good chips than for batch cooking. Usually, the difference is small. Fig. 3 illustrates the variations when using a batch system and a continuous system in parallel for a mill making kraft liner board. It should, however, be noted that frequent stops or changes in capacity will increase the variation of continuous cooking considerably, but not that of batch cooking. It is advisable therefore to furnish a continuous digester with a considerable buffer storage volume so as to minimise the capacity adjustments. Note that capacity adjustments in batch cooking usually do not influence the cooking conditions, since it will only be a matter of the number of cooks. In kraft cooking, the final pulp quality can be described by lignin content, fibre types, carbohydrate composition (alkali resistance), uniformity and mechanical damage of the fibres. In some cases, the pulp viscosity is also of interest to characterise yield effects or potentials for bleaching. The relevant properties do not fluctuate very much when compared at a constant kappa number (so long as the cooking conditions are controlled in a normal way) and may therefore be measured only at fairly long intervals.[1] The sampling procedure for kappa number determinations is very important for proper control. Thus, sampling after washing and screening requires very long control invervals, whereas sampling in the blow line permits more frequent control actions, although the control intervals are still comparatively long. When sampling in the blow line, care must be taken that the measurements correlate with the observable cooking conditions—that is, effects caused by non-uniformity must be screened out. The unit that should therefore be considered in the control is one cook for batch cooking and, for continuous cooking, a pulp quantity in the blow line corresponding to the smallest uniform thickness of the chip column in the digester (that is, taking irregular discharge by the bottom scraper into account). Somewhat arbitrarily, we have chosen a one metre thick layer for this, which usually corresponds to about 5 min discharge.

Within this unit, the homogeneity can be characterised by screenings content and, in some cases, pulp viscosity for chemical pulp and by a fractionating defibration technique for semi-chemical pulp, the latter being illustrated in Fig. 4. It is very important that the homogeneity is good, because many properties have a non-linear relationship to the lignin content. Mixing pulps with variations in lignin content does not therefore produce the same properties as pulping to a uniform lignin content, especially in the impurities present.

Note that the yield of a kraft pulp is very seldom influenced by non-uniformity when including the screenings.

The conditions in a continuous digester are very difficult to describe in a mathematical model. Many have tried to create models to be able to understand the static and dynamic conditions of the process. Unfortunately, it is very difficult to measure the important variables, because of considerable noise and it is difficult therefore to prove the accuracy of the models. Many have also tried to use continuous alkali analysers for black liquor in various zones of the digester. It is obvious that important knowledge is accumulated during these experiments, but the instrumentation problems are not yet properly solved. The accuracy is by far insufficient.

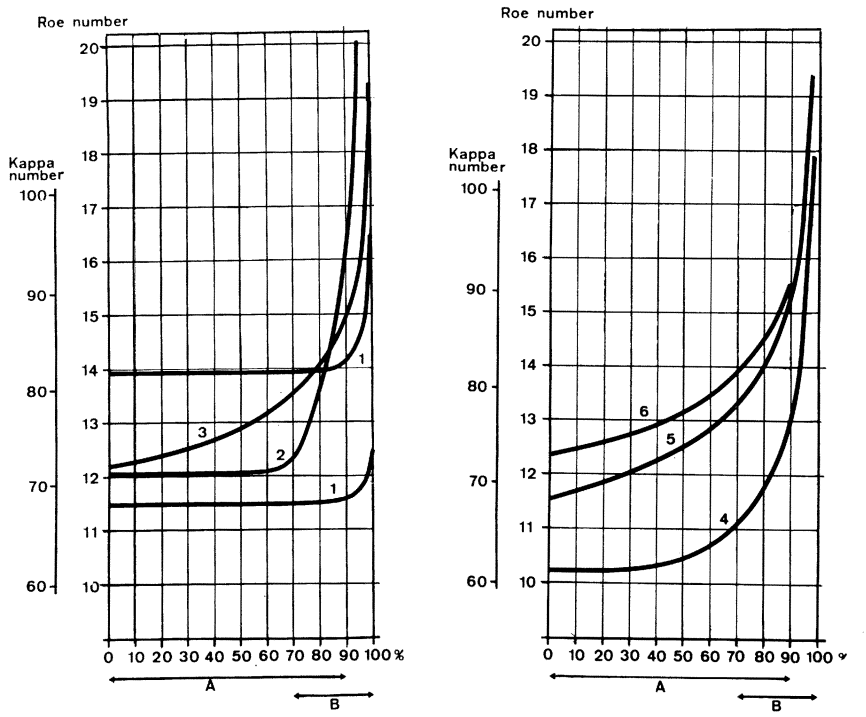



*Fig. 4*

The importance of mathematical models for control is therefore limited so far. Simple models can of course be used for grade changes to eliminate great disturbances in kappa number.

*Bleaching*

The bleaching of a chemical pulp usually aims at a more or less complete dissolution of the remaining lignin and a brightening of the pulp. In most cases today, it is performed continuously in several different stages by alternating use of oxidising bleach chemicals, etc. and alkali. For control strategy, it may be valuable to distinguish between prebleaching and final bleaching. The former is supposed to take care of the main lignin dissolution and to equalise the pulp for the further bleaching. The latter should be carried out by selective chemicals because of the absence of protecting lignin and should exclude any major adjustments of, say, the charges among other things, because these selective chemicals are more expensive. The prebleaching usually extends over the first 2–4 stages (C-E, C-E-H, C-E-H-E, etc., where C = chlorination, E = alkali extraction and H = hypochlorite bleaching), whereas the final bleaching for higher grades consists of D-E-D (D = chlorine dioxide bleaching). It should be noted that chlorine degrades the pulp most and chlorine dioxide degrades it least, which determines the consecutive order of the chemicals. Each stage consists of a mixer for mixing in chemicals, etc., an upflow or downflow tower and a subsequent washing, either separate or connected to the tower (in that case, an upflow tower).

The first stage is usually a treatment with chlorine at normal raw water temperature and is mostly carried out in upflow towers at a fairly low pulp consistency, filling the tower with liquor and fibre, so that the reaction time will be well-defined, except for channelling in the tower.

The subsequent stages are run at elevated temperature, therefore the heat economy demands high pulp consistency. This makes the pulp column compressible, which may be of importance, at least at capacity changes in upflow towers, by producing capacity transients. Except for these transients and possible chanelling, upflow towers should give more exact conditions than will downflow towers, in which the pulp level is more difficult to control.

Each stage comprises a relatively simple process, with fibre and liquor running together, in contrast to what happens in the continuous digester. The significant process variables are the charge of chemicals, the reaction time and the temperature, of which the charge is primary and the others are chosen to match the charge, because they give no significant selectivity within the normal limits. When combining 5–7 bleaching stages (as is usual for kraft pulps), however, the complexity will turn out to be considerable. It is therefore necessary to have a quality criterion after each stage for the process control such as a kappa number, a brightness and/or a pulp viscosity.

It is usually possible to correct erroneous quality after a bleaching stage in subsequent stages up to a certain point, although this leads to higher total bleach costs. These possibilities strongly depend on the type of bleaching

sequence used. Thus, a 7-stage sequence undoubtedly is more favourable in this respect than, say, a 5-stage sequence.

Fig. 5 shows the normal limits of variation of bleaching chemicals costs and of pulp viscosity for pine kraft pulp as a function of the final pulp brightness with various bleaching sequences. The economic and qualitative importance of the process control in the bleaching plant is thus illustrated. It is obvious that bleaching beyond from the optimum is quite expensive as is excessive brightness. In some cases, however, it is necessary to go to an extra high brightness because of the demand to bleach bark specks, etc. On the other hand, the cost of this extra bleaching may economically justify better cleaning of the wood.

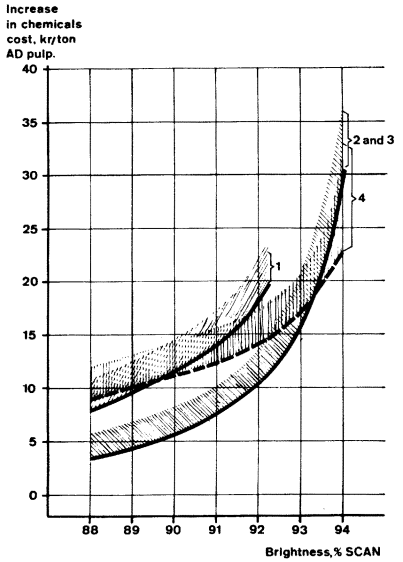



*Fig. 5 (a)*

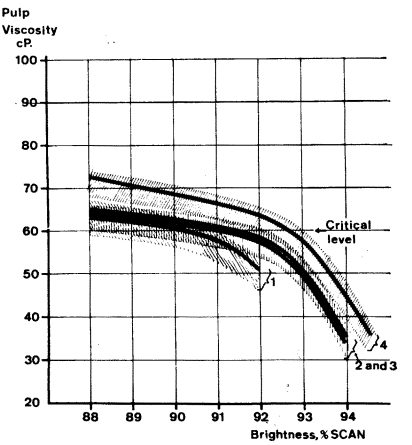



*Fig. 5 (b)*

For a given pulp, the pulp viscosity characterises the paper strength properties of the pulp fairly well.[4] Above 60 cP, the paper properties seem to be fairly independent of the viscosity, whereas they fall rapidly below 60 cP. Optimum bleaching is therefore arrived at by balancing cheap but degrading chemicals (such as chlorine) against more expensive but more or less non-degrading chemicals (such as chlorine dioxide) so that the pulp viscosity will be slightly above 60 cP (only a safety range). The control of the first stage is very important in this respect.

Apart from start-up troubles and machine deficiencies, the most important

disturbing variable in bleaching seems to be the lignin content of the unbleached pulp: equalisation by mixing is here highly desirable. Even if the mixing will not be extensive enough to produce full equalisation, it may contribute to a more precise prediction of the lignin content, which facilitates other control routines. A redox potential measurement some time after the chlorine charge may promptly give an indication of the potential chlorine demand thanks to the very rapid initial chlorine consumption and may be used for control of the chlorine flow. The measurement is, however, influenced by pH value, chloride ion concentration, temperature and reaction time, which all should be well-controlled.[5] Whitewater containing residual chlorine dioxide may disturb the potential considerably. For interpretation of the data, the pulp consistency should also be known in each case. A variation in the lignin content cannot be controlled by only one redox signal, however, since a different lignin content requires an adjustment of the reference value to produce the desired result. Better information is obtained when the normal redox measurement is supplemented by a redox measurement at the end of bleaching. The latter should then influence the reference value of the redox chlorine flow control (properly speaking, the deciding quantity should be the relationship between the two redox measurements).

The control of the subsequent stages is usually based on brightness measurements. Since the human eye is very sensitive to differences in brightness and since manual sampling and normal brightness measurement on standard sheets are fairly rapid, automatic brightness measurements have not been universally adopted, although equipment exists for brightness measurements on the filter web. Redox measurements have been tried in the chlorine dioxide stages with some success, although the redox system is very undefined. A universal application therefore cannot be commended in this case.

An important difficulty in a bleaching plant is the very long total reaction time and the subsequent problems to follow up a specified pulp sample through the bleaching plant. An accurate updating of the pulp through the whole bleaching plant is therefore essential for the operator when deciding about control strategy.

### *Future trends*

THE control of the pulp quality is to a great extent based on manual sampling and laboratory analyses. If the mill has sufficient mixing capacity, laboratory methods are satisfactory to produce pulp of good quality.

The development of automatic analysers will, however, decrease the sampling and control intervals, which means higher corner frequencies for the control loops. This will make it possible to accept smaller storage and mixing capacity. It also increases the need for control computers in the mill.

Good measuring devices and computers are not enough: the most important factor is good controllability. The pulpmill must thus be built as an integrated system. Adequate mathematical models for the important operations in the mill must be developed. System studies must show how to avoid critical departments or operations and, finally, how also to integrate the pulpmill and the papermill.

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# Discussion

*The Chairman* I think Mr Annergren's paper is the first really coherent presentation of the complete control aspects of the chemical pulp mill and will serve as a basis for the systems engineers in their future work.

*Mr B. Kvaavik* You mentioned that one of the inputs to the control system was the brightness. How do you measure this?

*Mr G. E. Annergren* The brightness referred to in the paper is measured after sampling on handsheets in an Elrepho brightness meter in our mills. Visual inspection is used for more frequent analyses.

*Mr E. A. Leaver* I am rather surprised to hear that sampling techniques were used for brightness measurement. An automatic brightness recorder was developed by a paper company some time ago. Over 50 of them have been manufactured under an exclusive license. Although such instruments do not represent perfection in the measurement of this variable, it could provide more representative, immediate and usable information than hand sampling will.

*Mr Annergren* We are aware of this rather interesting technique, but hesitant about it, because the environment is not very favourable for the instrument on our washers. Measurements in the wet stage are also less accurate, especially when the washer is operating inefficiently. Continuous measurements are also of little use in the final stages, if you have chosen a bleaching sequence with good control characteristics. After the first stage though, a continuous measurement would be very interesting. The colour there is very unstable, however, which makes it necessary to base the control on lignin measurements.

*The Chairman* This elusiveness of colour has something to do with the chemical configuration of lignin. After chlorination, it forms a chlorinated *o*-quinoidal system that is quite unstable.

*Mr Kvaavik* How do you measure the moisture content?

*Mr Annergren* There are various methods. A laboratory method using manual sampling, drying and weighing gives good accuracy, provided the sample is big enough. Weighing a digester full of wood before charging with liquor is often used for estimation of the moisture content, since the variations in moisture content dominate the variations in the amount of dry wood. Later, we developed a continuous measuring device.

*Mr G. Bohlin* Indeed, we have tried to use an instrument with a neutron source and a gamma source for this purpose. Our experience showed that the instrument is accurate enough for control of the liquor-to-wood ratio, but inadequate for the alkali-to-wood ratio. The accuracy is 0·5–1 per cent in moisture content. There are other methods such as microwave technique to measure moisture content, but it is impossible to use them when the chip temperature is below 0°C, which is the case for us several months each year. The radioactive method is unaffected by temperature.

*Dr D. W. Clayton* Before we go on, please clarify a point about the standard deviations in Table 3? These are given as 4 per cent and 2 per cent for the wood charge and for the charge of white liquor, respectively, but for the liquor-to-wood ratio the standard deviation is given as 0·2. What would this be when expressed as a percentage?

*Mr Annergren* The standard deviation of the liquor-to-wood ratio is not given as a percentage. It is 0·2 $m^3$/ton oven-dry wood. The table refers only to normal batch cooking, for which the procedure is to charge the wood by volume, measure the moisture content separately in a suitable way, measure the white liquor according to the specification on the alkali charge and calculate the black liquor as a make-up to the total amount of liquor required.

*Dr I. B. Sanborn* For the continuous measurement of chip moisture content, the most reliable means that I know of today is by using a device that works very well on unfrozen chips. It works on a dielectric principle, I believe.

*Dr A. Kohl* We have quite a number of moisture meters installed for wood chips. The normal installation is that the flow of chips is weighed on a conveyor belt and the moisture is measured afterwards either in the main stream or in a by-pass. Because the chips are of various size, a correcting compensation for the density has to be introduced.

*Discussion*

Another possibility is the use of a vibration chute, whereby uniform packing is achieved and the density compensation can therefore be omitted. The read-out of the instrument is in percentage water and for this, together with the measurement the air-dry weight on the conveyor, the oven-dry weight of the chips can be calculated.

This equipment is operated on continuous and batch digesters. Sometimes, the chips pass through a hot steam stage, in which case, the moisture should be measured before and after this operation.

*Mr H. B. Carter* Have you had any experience of using methods of measuring moisture content and weight on chips of different species of wood? We, for example, have had to use balsam fir and black spruce: can you comment on these species?

*Mr Bohlin* We have studied this question and found that the neutron signal is greatly affected by the different wood species; the gamma signal is more independent. It is necessary therefore to have a calibration curve for each species.

*Dr D. Rusten* (written contribution) The moisture content of wood is one of the main factors responsible for the variations in the pulping result and particularly so if the charge of chemicals added is proportional to the weight of wood measured by a chip weighing system. The principle of weighing a certain volume of chips packed in a standardised way—for instance, a batch digester after chip filling—works reasonably well, so long as one utilises one type of wood from a limited area.

If a mixture of wood species of different density is cooked, the problem becomes more difficult. Microwave techniques and measurement of dielectric properties have been used successfully, but they present problems in cold winters when the wood taken in may be frozen. One principle of measurement already mentioned in the discussion utilises a combination of neutron and gamma radiation. The former is sensitive to the hydrogen in the sample, the latter is used to measure the total density. This principle has been tried in a few mills, but has met with such problems as—

1. The two types of radiation are active over different volumes and this varies with the moisture content.
2. The instruments have not been rugged enough for mill use, thus causing frequent breakdown.
3. Hardwood and softwood in varying mixtures may be difficult to measure, but mixtures of softwoods such as larch, spruces and pine have been shown to give satisfactory results, at least when the wood is fast grown and so containing little pitch. As extractives contain another percentage of hydrogen than does the dry wood itself, this may create problems.

It is fair to say that there is yet more to be done to give a fully satisfactory measurement for moisture content of chips in order to be able to control the cooking process properly.

*Dr J. N. Chubb* I would like to ask some questions about the biological cycle as a whole. What do you have to do after felling the trees to prepare the ground for replanting? Do you have to replace any of the materials? What sort of cycle time do you have in the entire process and are there uniform yields on repeated cycling?

*Mr C. R. Silversides* Very briefly, the forests around the world vary considerably. In the great coniferous forests of our pulp and paper industry, the time cycles vary from possibly 75 to 125 years. Formerly, we looked for natural regeneration almost entirely. The criteria of the good forester was that he was able to obtain natural regeneration. Today, however, it is almost universally the practice to plant or to seed and the purpose for this is that, in seeking natural regeneration, there is a time lag of 5–10 years.

Our forest lands have become too valuable to permit of this delay and the practice now is to plant immediately or within two years following cutting. When planting, such trees have a head start of 1–4 years over natural regeneration. In America's southern states, they have a life cycle rotation of perhaps 25 years; in Australia and New Zealand, they can obtain pulpwood size trees at 7–10 years. So there is a tremendous range in our coniferous forests, depending on the geography.

The general practice of our forest industries is to regenerate and support the forest as a source of raw material to the greatest possible extent, but this varies widely among countries. In Canada, 90 per cent of our forests are owned in the name of the Crown and are leased to the industry; in other regions of the world, they are owned 100 per cent by the industry. A very marked development has taken place in the post-war period. Tree harvesting used to be considered analogous to an agricultural harvesting operation; today, certainly in North America, it is considered to be an operation producing an industrial raw material. Our logging operations are therefore becoming highly mechanised and highly controlled and capital intensive in contrast to the previous labour intensive operations.

*The Chairman* This emphasises the sort of time lags that the forester has to deal with.

*Mr J. A. S. Newman* Are the variances in Table 3 those applying at the start or at the end of the study? If it was the former, what did you hope to achieve?

*Discussion*

*Mr Annergren* The figures refer to the conditions described in Fig. 2, which is somewhat hypothetical, since it presents somewhat adjusted average figures from several Swedish pulp mills. They are therefore not altogether valid for our mills, but are fairly close to what can happen there without improved control. The table gives a lead on how to proceed. By installing a device for *H* factor calculations, we have in one case been able to decrease the variation to about half of the indicated variation. The problem in this, however, seems to be the temperature signal, which is not always representative for the cook. An improved chip-filling technique and more homogeneous chip quality will further improve the result.

*Prof. L. W. Zabel* Mr Annergren mentioned the use of the *H* factor*, but this is a rather simplified rate equation. Have you found this sufficiently precise for your use or do you think that something more comprehensive such as Carroll's work would be better?

*Mr Annergren* In the computation, you can take into account only what you measure. The *H* factor covers the variations we can control. If the temperature signal is good, we have found the *H* factor very precise for our purposes.

*Mr D. Attwood* In Mr Annergren's Table 3 (which I am sure will become quite famous), the variance of liquor-to-wood ratio is only unity; but, if you remove this completely as a source of variation, it would hardly affect the total variance of $6{\cdot}3^2$ (that is, 38·54). This implies that liquor-to-wood ratio control is irrelevant, which seems surprising.

*Mr Annergren* It is true that a narrow liquor to wood ratio control is irrelevant to the control of the lignin content of the pulp in batch cooking. There are, however, other reasons for controlling it.

*Mr B. Nilsson* I accept Mr Annergren's comments about redevelopment for computer control. We would much rather complete it with the equipment at the other end of the system, but half a loaf is better than none. When someone has the other equipment, we will certainly be glad to use it.

Mr Silversides said that, with the centralised tree processing equipment, there was no particular problem with slash. I believe the control problem there to be real.

* The *H* factor (a numerical expression) was developed by K. E. Vroom, Pulp & Paper Research Institute of Canada in 1956–57 for treating kraft pulping times and temperatures as a single variable (see *Pulp & Paper Mag. Can.*, 1957, **58** (3), 228–231)

*Mr Silversides* I think you might consider the slash more of an inconvenience than a problem. You may be familiar with the fact that the Logging Research Associates (the developers of this particular full tree system) employed the Ontario Research Foundation to make a detailed study of any possible use or application of twigs, branches and bark, hopefully, so that the companies concerned might develop useful by-products. They were completely unsuccessful in this respect. There is a considerable debate going on at the present time in the forest about the implications of the removal of the organic material involved in the branches, twigs and the bark from the site, because of its potential as a fertiliser. Studies are under way both by the Department of Fisheries and Forestry and by the Pulp and Paper Research Institute of Canada in an attempt to resolve this.

There is a further point. When you remove a full tree, you remove the source of the seed. This is counteracted to a degree by the fact that, when you remove all potential slash and debris from the cut over the area (as we do in the full tree method), you simplify greatly the artificial regeneration of tree planning, because you have removed a good deal of the obstructions normally found on the cut over area.

*Mr P. H. Engelstad* I am anxious to know about the actual improvements achieved by these instruments for measuring moisture content and chip weight. Has Dr Kohl any evidence of what the improvement was in terms of reduced variance or standard deviation in the kappa number of the final pulp before and after the installations were made? Could he also give a rough estimate of the cost of the installations?

*Dr Kohl* The installation of moisture meters on wood chips has two tasks—

1. To change over the purchase procedure of the wood from the volumetric to the oven-dry weight method.
2. To control the digesting process.

Foresters are so far reluctant to go ahead on the first application, but the application of the equipment in the pulping process itself has been carried out by many mills quite successfully. This has been not only to control the flow of the incoming material on an air/oven-dry basis, but also to control the subsequent chemical process. The cost for such an application would be between £3 000 and £8 000.