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PROCESS CONTROL AT THE WET END USING AN ANALOG COMPUTER

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Synopsis No. 1 machine at Chartham Paper Mills produces a high grade of tracing at substances ranging 40–160 g/m². Increased process understanding of the wet end system led to the idea of using a simple analog technique to obtain a more uniform and more efficiently produced product from this machine.

The computer system was installed in January 1968 and has been fully operational since then. It consists of two basic operations, feedforward and feedback control. The feedforward control uses process equations calculated from equilibrium conditions that link together stuff gate flow, breast box flow and efflux ratio with reel-up substance and dry end speed. The feedback control maintains the required substance by feedback to the stuff gate.

Performance analysis of the computer has shown that broke at substance changes has been significantly reduced and wet end conditions are considerably more stable. Present development work consists of incorporating computer dynamic substance control on this machine.

Introduction

THE production on one machine of one grade of paper 24 h a day is of tremendous assistance in analysing the basic system behaviour of that machine. This is true for No. 1 machine at Chartham Paper Mills, which produces high grades of tracing paper at substances ranging 40–160 g/m². Since 1955, continuous progress has been made in standardising stock and machine conditions, leading to a more uniform product. Stuff consistency is controlled to within ±5 per cent of desired value and degree of refining has been standardised and controlled using work set points. During the last few years, increased process understanding of the wet end system led to the idea of using a simple analog technique in order to obtain a more uniform and more efficiently made product off No. 1 machine.

Under the chairmanship of Dr N. K. Bridge

The aims included—

1. Increased uniformity of operation at the wet end.
2. Faster substance changes.
3. More reliable process information from the wet end system.

The present computer system was installed in January 1968 at a cost of £7 000 and has been fully operational since that date.

Operation

THE computer system consists of two basic operations, feedforward and feedback control. The feedforward control uses process equations calculated from equilibrium conditions, which link together stuff gate flow, breast box flow and efflux ratio with reel-up substance and dry end speed. The feedback control maintains the required substance by feedback to the stuff gate.

Feedforward control

At a substance change, the machineman sets the required reel-up substance and dry end speed on the computer panel. The computer automatically changes the stuff gate flow, breast box flow and slice opening according to simple process equations. The breast box flow change on to the machine is at a rate to prevent web breaks at the couch. A speed change during a substance making would again cause the required stuff and breast box flow changes to be put on to the machine. The feedforward system depends on the stuff consistency value set into the computer and feedback control from the dry end continually updates the process equations and takes account of drift variations.

Feedback control

Reel-up substance deviation is displayed on the computer panel. Stuff consistency variation can result in a continual drift of substance from the set point, which was corrected by using machine speed variation before computer control; but, using computer control, correction pulses are automatically fed back to the computer, which makes the required correction using flow changes. The feedback pulses update an equation constant by two amounts depending on the size of the deviation. For deviations greater than (*a*) ± 3 per cent and (*b*) $\pm 1{\cdot}5$ per cent, the computer will make the necessary alteration to bring the deviation to zero. Following one feedback pulse to the computer, no further pulses can occur until the stuff change has had effect at the reel-up.

Necessary stock residence times in the system were determined using lithium chloride tracer experiments.

Adjustment of breast box flow and slice speed

As a result of varying machine conditions, the machineman requires the facility to adjust breast box flow and efflux ratio. By turning a dial on the computer panel, the relevant equation constants can be varied within set limits. Changes of breast box flow or efflux ratio will obviously cause temporary substance deviations at the reel-up and, to prevent pulse feedback, time delays are set back to zero at any alteration to breast box flow or slice speed dials.

There are occasions—for example, press felt changes—when the wet end is running normally, but the dry end is shut down. Since the computer outputs require a dry end speed signal, zero outputs from the computer would result, hence the facility has been included whereby, when only the dry end speed is shut down, the computer input will change to a simulated dry end speed.

When practicable, the computer and its associated equipment has been mounted in or on one cubicle. The cubicle has a panel face of 7 ft square and is 4 ft deep. The operator's controls are mounted on the panel face. These include three recorder controllers for stuff gate flow, breast box flow and slice position, also a substance deviation indicator and dry end speed recorder, a complete draw recorder and various auxiliary controls. Coloured lamps indicate the system condition at any given time. Inside the cubicle, which is fan cooled, there is the computer, its associated servo and logic systems and various transducers. The computer is an analog unit, which automatically solves the process equations and provides set point signals for the three controllers. The computer causes no loss in flexibility of operation. Each controller may be operated in conjunction with the computer by local set point or manual control, irrespective of the control mode of the other two.

Theory of computer system

INVESTIGATIONAL work on No. 1 machine led to the construction of a simple equilibrium process model of the wet end system. From this model, relationships for stuff gate flow, breast box flow and slice speed have been calculated and provide the basis for the computer feedforward system. Feedback control maintains the required substance by feedback from the reel-up substance measurements to the stuff gate.

The equilibrium flow system around the wire section is shown in Fig. 1 and a mass balance taken around the system (Fig. 2 and 3) illustrates the high degree of closure for substances greater than 80 g/m^2. Through factor (fibre flow through the wire divided by breast box fibre flow) was measured using

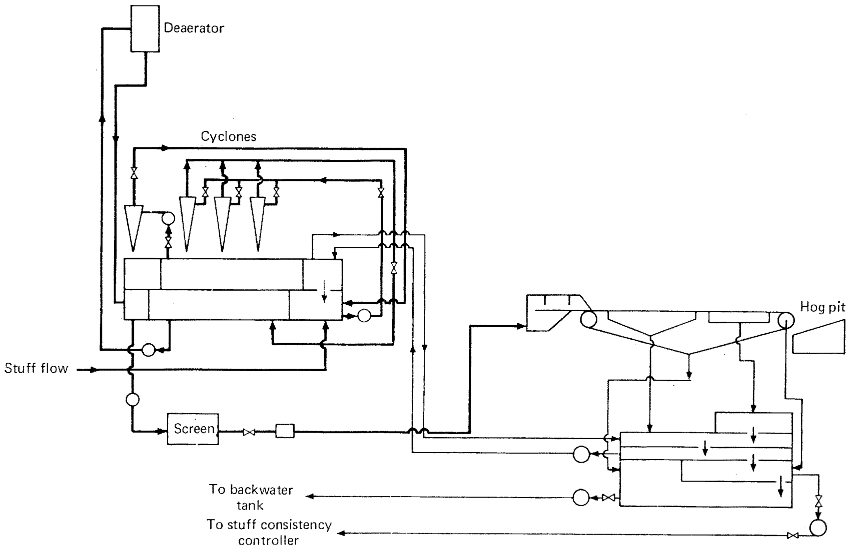


Fig. 1—Flow system around the wire section

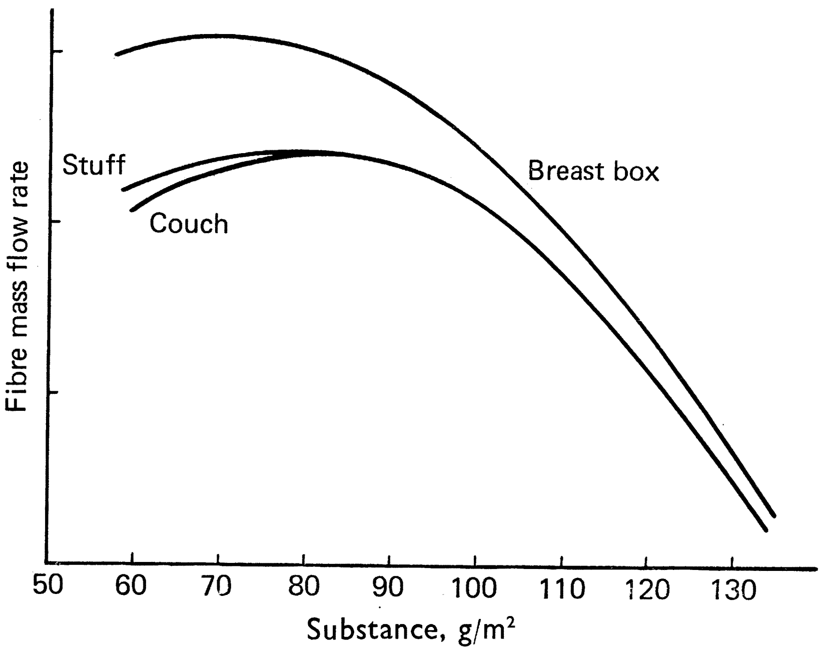


Fig. 2—Fibre mass balance

lithium chloride tracer additions to the stock.[1] The fibre through factor at equilibrium was found mainly to vary with breast box consistency. The lower the consistency, the higher the through factor (Fig. 4). Through factor also varies with stock wetness and wire age, but within our normal range of working these effects were found to be at a minimum compared with breast box consistency. The equations involve the use of a number of constants that are based on average daily running conditions on the machine and are therefore a fundamental description of the machineman's present operation. The constants can be altered at any time to give flexibility to the wet end operation when necessary.

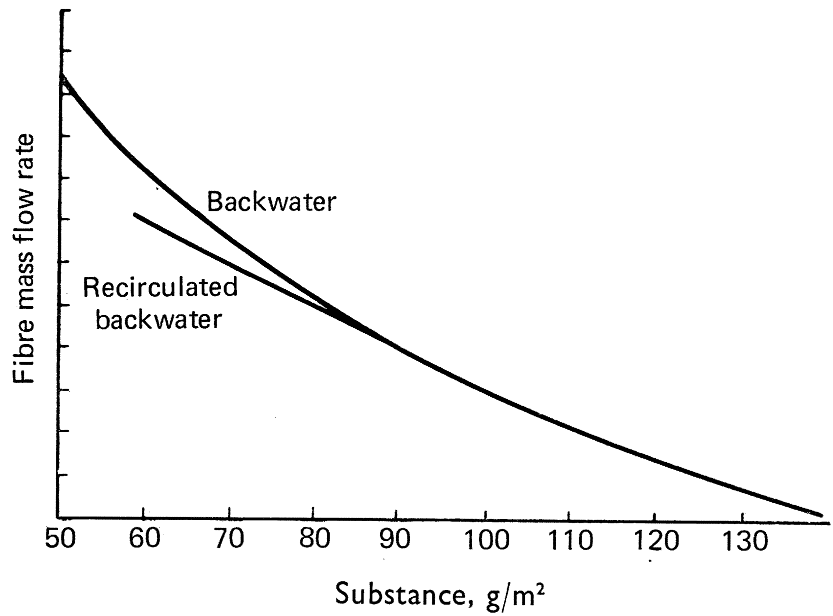


Fig. 3—Fibre mass balance

Stuff gate flow

Assuming fibre loss outside wet end system to be negligible (Fig. 2 and 3),

$$F_M = K_1 . S.V./C_M \quad . \quad . \quad . \quad . \quad (1)$$

where F_M = Stuff gate flow, gal/min,
S = Reel-up substance, g/m²,
V = Dry end speed, ft/min,
C_M = Stuff consistency, per cent.
K_1 is a constant concerning couch fibre production.

This means that the calculation is independent of sheet deckle, since hog pit return is delivered behind the stuff valve.

Breast box flow

$$F_B = \frac{K_1}{K_2S+K_3} \cdot \frac{S.V}{1-f(S)} \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

The term (K_2S+K_3) is breast box consistency as a linear function of S; K_2 and K_3 are constants; $f(S)$ is the fibre through factor expressed as a non-linear function of S and F_B = breast box flow, gal/min.

The through factor substance curve is approximated by the computer using four linear relationships, the through factor being calculated from this for the desired substance input. The curve approximation can be altered in future when necessary.

Slice speed

The average stock velocity from the slice is automatically computed from computed breast box flow and slice opening measurements and displayed on the machine. Slice opening is the average height between the slice apron and

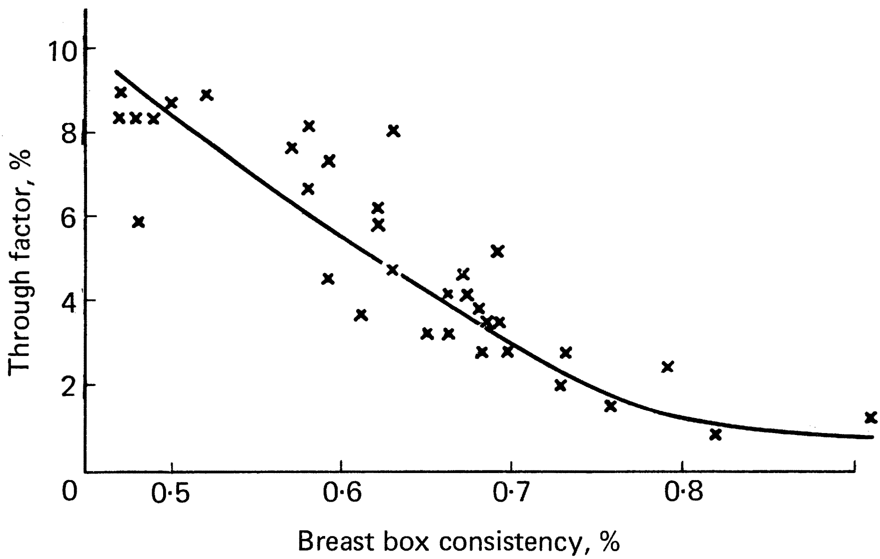


Fig. 4—Fibre through factor against breast box consistency

lip being calibrated with slice wheel readings. The measured slice speed is an average value across the deckle owing to individual lip screw variations. Regular calibration checks and straightening of the lip are necessary.

$$S_o = K_7 . F_B / e . W \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

where S_o = Slice opening, mm,
W = Wire speed, ft/min,
e = Efflux ratio,
K_7 is a constant.

The computer controls the slice opening according to these equations, using breast box flow and wire speed. There is no separate constant for e in the computer, but this can be set to any desired value by varying K_7.

These three equations were regularly checked against actual machine conditions during a period of 12 months before the computer installation in order to prove their accuracy.

The operator's panel

THE information and controls available to the operator have been kept to a minimum consistent with presenting sufficient information and retaining operational flexibility.

Please refer to Fig. 5, which shows a drawing of the operator's panel for the

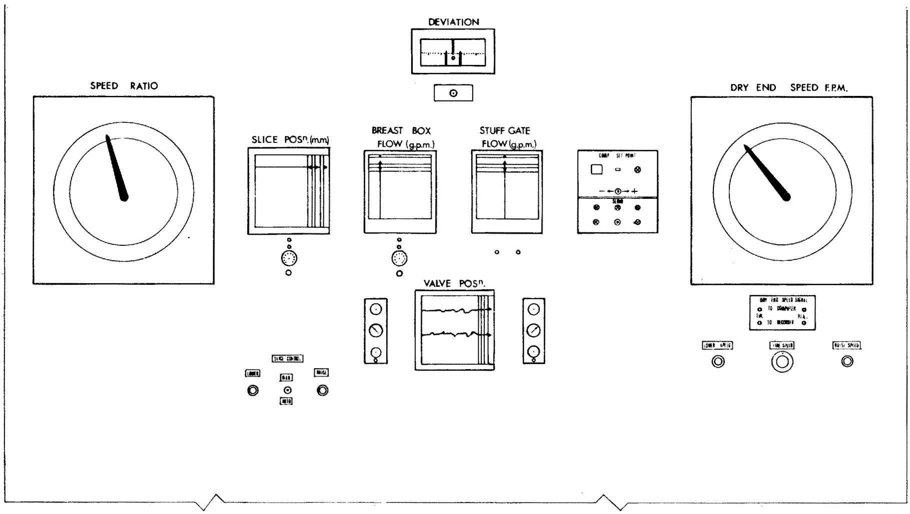


Fig. 5—Computer panel

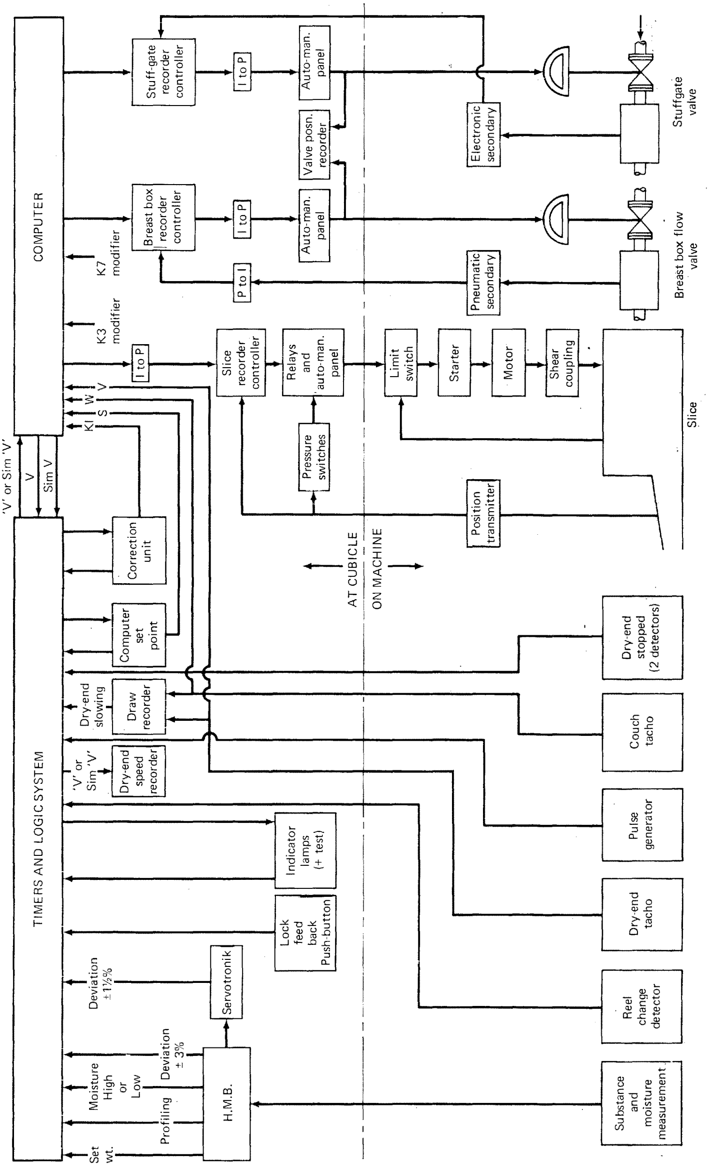


***Fig. 6*—Block diagram of computer system**

computer system. Except for the substance gauge, there is everything necessary to control the machine speed, stuff gate and breast box flows, slice height and to set the desired substance into the computer.

All controls can be overridden to manual control and the condition of the system is shown by means of indicator lamps.

Description of computer system diagram

Control options

Please refer to Fig. 6, which shows a block diagram of the computer system. Shown at the lower right side are the controlled variables of stuff gate flow, breast box flow and slice position. Each variable may be controlled manually at the regulator or by remote manual control if necessary.

The two flow controllers may be operated with manually adjusted set points or with the set points set by the computer. The slice is either on remote manual or computer control.

The normal condition is with controller set points adjusted by the computer.

Signals to and from the computer

The input and output signals for the computer are shown by the arrows at the computer block top right.

Taking the signals in order in an anti-clockwise direction, they are as follows—

1. V or Sim V is a signal in the range 0–10 V representing either actual or simulated dry end paper speed. It is used in the equation for stuff gate and breast box flow. Actual V is used during normal conditions and simulated V when the dry end is shut, but the wet end is running. The system is therefore ready when the dry end is started.

2. The signal V represents actual machine speed and is normally connected by relays back into the computer. It is an attenuated representation of the dry end tachometer voltage.

3. Sim V is the signal that, when linked with substance and via relays, feeds a simulated dry end speed into the computer when the dry end of the machine is stopped or is running at less than the wet end speed.

   It is calculated from wet end speed and substance set point and is based on average draw.

   A test button is provided in the dry end speed recorder so that the relationship between V and Sim V may be checked.

4. K_1 is an equation constant which is adjusted by the feedback system to maintain the substance within the set limits of $\pm 1{\cdot}5$ per cent.

5. S is the desired substance, set manually from the operator's panel.

6. W is the signal from the wet end tachometer, which is attenuated to 0–10 V.

7. V is the signal from the dry end tachometer and is connected to the logic system as described in (*2*) above.

8. The next signal is the slice position set point, which by means of a transducer is converted from 4–20 MA to 3–15 lb/in^2 for the slice controller, which is pneumatic.

9. The K_3 modifier is the operator's adjustment for the breast box flow equation, which allows the flow to be adjusted by the operator within preset limits.

10. The K_7 modifier allows adjustment for slice height in a similar way that K_3 adjusts the breast box flow.

11. The next two outputs are 4–20 milliamp signals controlling breast box and stuff gate flow set points.

Timer and logic system

The origins of the signals to and from the timer and the logic system may be seen by inspection of the diagram, therefore the use rather than the origins of the signals will be described. For clarity, some signals are omitted.

The system consists of two parts, one for timing functions and the other for routine and interlocking signals.

The timer panel has two synchronous motor timers, a pulse counter and two solid state timers. These are controlled by relays.

Input and output signals are via three position switches, for *simulate*, *off* or *on*; they are fused and indicated by lamps.

The timer system will produce either a short or long pulse if the paper substance deviates for more than 5 s outside the 1·5 per cent or 3 per cent limits.

The system will prevent a further pulse, which drives the correction unit, until the stuff has had sufficient time to reach the reel-up from the stuff gate.

Machine speed is allowed for by means of the pulse counter, pulses being at a rate dependent on machine speed.

If K_3 or K_7 is operated, the timer system is automatically reset so that transient changes in substance will not cause corrective action and subsequent overcorrection to take place.

The section related to the interlocking and routing of signals, also has input and output signals switched and indicated so that they may be prevented or generated for test purposes.

The signals are related as now described. When a pulse is generated by the timer panel, it will be routed to drive the correction unit servo in the right direction. This is indicated by an appropriate lamp on the operator's panel.

The pulse will not be generated, even though there is a deviation and the timers have finished the complete delay time, if—

1. The moisture is out of limits—that is, ± 1 per cent of the set value.
2. The profiler is being used. The gauge that measures both substance and moisture may be caused to traverse the machine and thereby draw a cross-machine moisture or substance profile.
3. The reel is being changed. Paper flap at this time causes incorrect reading.
4. There is a paper break.
5. The substance and moisture gauge is being calibrated.
6. The gauge has just been adjusted before a substance change. This prevents conflict between the feedforward and feedback parts of the system.
7. The *hold* manual push-button has been operated. This is used when a transient substance change is likely to occur such as when cleaning the slice.
8. The gauge goes into its automatic cleaning sequence.

A lamp on the operator's panel will indicate *locked* when the above conditions apply, *automatic* if not.

Substance change

When a substance change is made using the computer system, the operator's actions and the resulting consequences are as follows—

1. The substance and moisture gauge is set to the desired substance, which locks the correction servo and unlocks the computer set point ready for it to be adjusted.

   The computer set point cannot be adjusted unless either the *hold* manual button has been operated or the gauge has been reset to a new value.
2. The computer set point is adjusted to a new value causing the following virtually simultaneous actions to occur—

   (*a*) The set points of the three controllers are set to the value required for a new substance at the existing speed.

(*b*) The lamps indicate if K_3 or K_7 modifiers are not set to average conditions, acknowledgement will cause the lamps to go off.

(*c*) The timing system is reset with a longer delay than is normal between correction pulses. This enables the system to reach equilibrium before feedback corrective action can occur.

After the timers have completed their cycle, the set point is again locked and the correction unit will be ready for corrective action within the constraints set by the logic system.

3. The machine speed is set to the value and at a rate required by the operator. Stock flows and slice position will be related to the new speed.

Present experience and future developments

PERFORMANCE analysis of the computer has been broken down into two main groups—substance changes and process uniformity. Extensive results were collected for six months before and after the computer installation. Analyses were carried out by Pira.

Substance changes

Substance changes were broken down into four groups—changes involving less than 10 g, 10–20 g, 20–30 g and above 30 g. Changes up and down the substance range were treated equally. The means of assessing the efficiency of substance changes is in two forms using routine data—change time and broke produced during the change. Change time is a figure that the machine crew note down after the change. The broke figure is an accurate measure and involves subtracting the measured paper yardage entering the finishing department from the machine house yardage figure. All substance changes include other operations, for example, cleaning the breast box, slice or washing a felt, but some include colour changes. Results analysed include all substance changes, except those involving colour changes, felt changes and laboratory experimentation.

The substance change time has been reduced in two out of four substance groups—less than 10 g and above 30 g. For the below 10 g changes, the average change time has dropped from 7·8 min to 6·8 min. For the above 30 g changes, the time has been reduced by 33 per cent. Broke produced during a substance change shows a distinctive improvement since the computer installation; for substance changes below 10 g, the average broke has been significantly reduced by 35 per cent. For above 30 g substance changes, the broke has been reduced by 53 per cent. For changes of 10–20 g, a reduction of 7 per cent and for 20–30 g a 14 per cent reduction. An example of a substance change using the computer system is shown in Fig. 7. Following a set point alteration, the necessary change in stuff flow, breast box flow and slice position can be seen. About $\frac{3}{4}$ h after the substance change, speed was increased by 2 ft/ min, the consequent slight (but required) stuff and breast box flow increases are also shown in the figure.

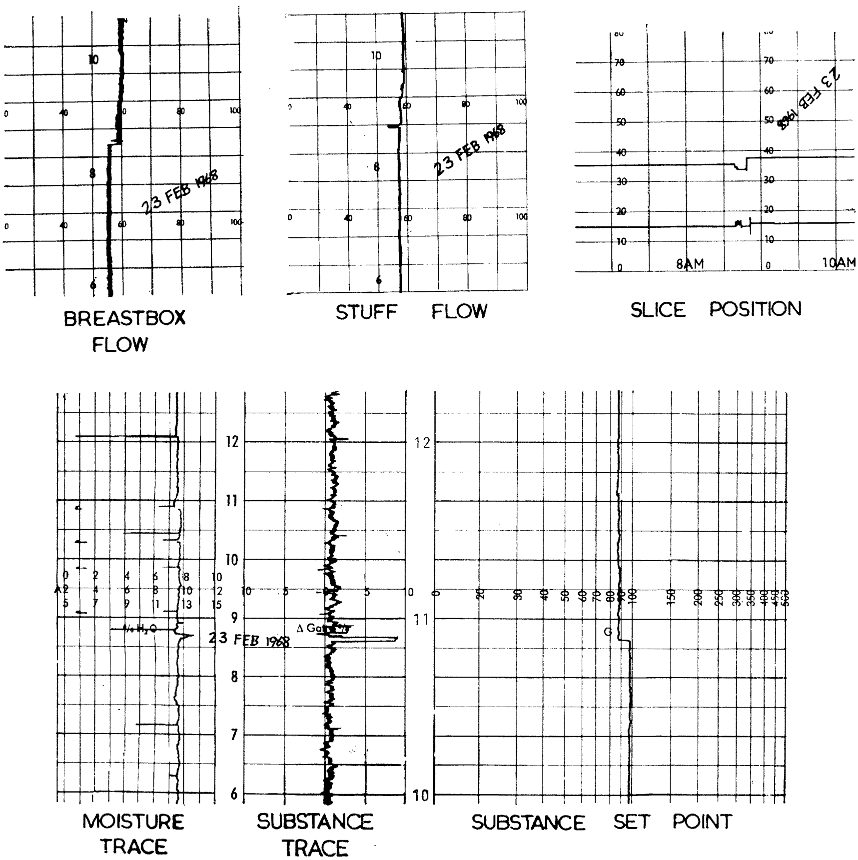
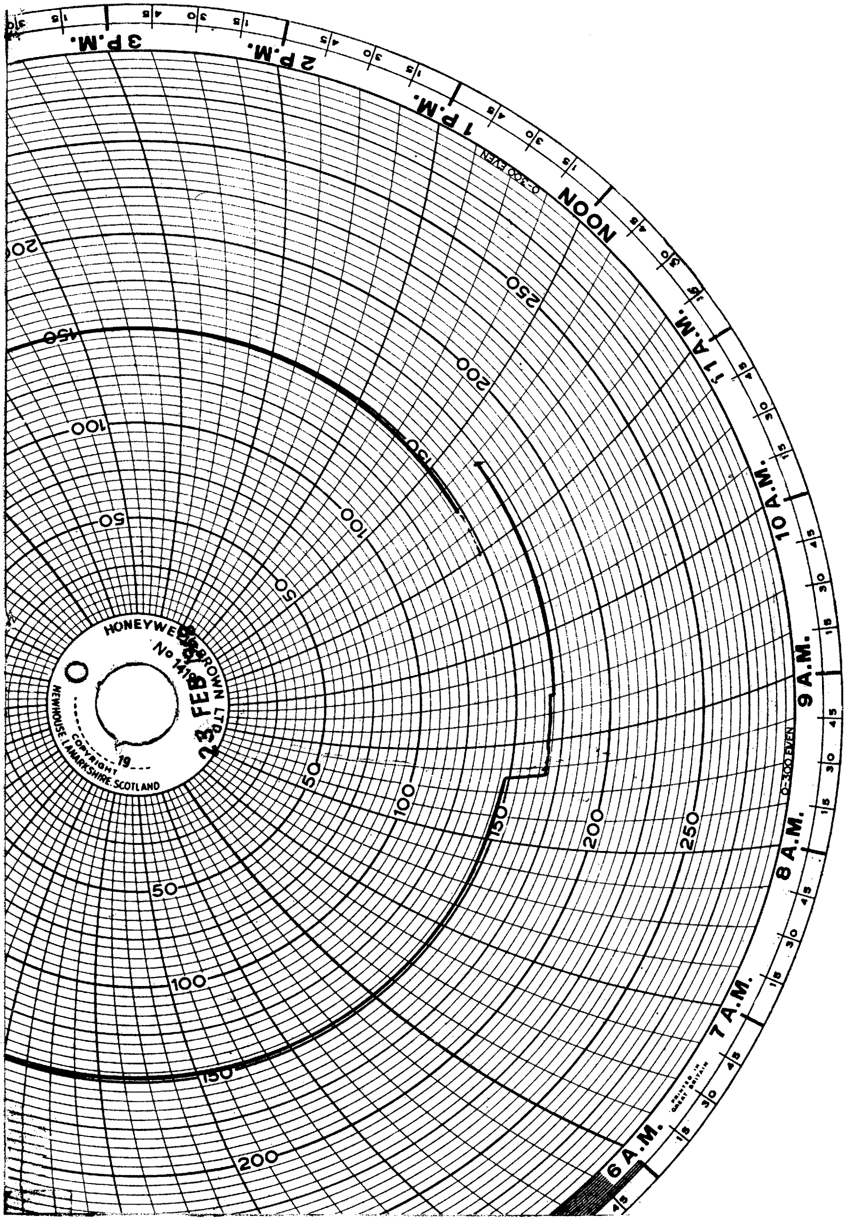


Fig. 7a—Substance change using computer control

Process uniformity

Breast box consistency follows a linear relationship with substance. The analysis has compared the spread of results about this line before and after the computer installation. Since the computer installation, the breast box consistency variability shows a 20 per cent reduction (5 per cent significance).



DRY END SPEED

Fig. 7b

Efflux ratio results have been analysed for spread about the mean before and after computer installation. Results show a 35 per cent reduction in variability (1 per cent significance).

The analysis showed that the reel-up variation within a making has not been significantly improved since computer control. For example, the standard deviation of results for the substance 85–90 g/m^2 has not changed at 1·4, as measured from quality control end-of-reel tests. Feedback substance limits are set at $\pm$1·5 per cent deviation and the deviation does not often exceed these limits. The existing substance variation must be reduced below $\pm$ 1·5 per cent at the reel-up by improving short-term consistency control and the efficiency of mixing in the mixing box.

Since the installation of the computer in January 1968, the basic concept and equipment reliability has been well proven. During 1968, the computer was inoperative for a total of about four days because of technical trouble.

Present development work consists of incorporating computer dynamic substance and colour control on to this machine.

Reference

1. Harris, J. S. and Gale, R. A., *Paper Tech.*, 1967, **8** (1), 27, 31–32; (2), 109, 113–114

Discussion

Dr I. B. Sanborn I strongly recommend that you consider the on-line measurement of colour. There is a dependable instrument available, manufactured in U.S.A. at a cost of 16 000–18 000 dollars. We have had two of them in operation for over a year and, with their aid, colour changes such as you describe are achieved in 5 min by essentially the same technique that you mention. This is within the time for a grade change!

Mr H. B. Carter Does either of the two machines referred to by Dr Farmer and Mr Harris have closed loop control on the head or for the machine speed? I think neither of these was mentioned.

Mr J. S. Harris No, we have not. For head box control, the head takes care of itself and we only operate the slice.

Dr A. R. Farmer There is a breast box level controller in cascade with the main flow controller on the Grove Mill machine.

Mr Carter Why did Mr Harris consider going to basis weight control without first putting these two fundamental machine conditions under their own independent control? Machine speed control is not mentioned at all.

Mr Harris For substance control, we preferred that the feedback should be done using stuff flow. The efflux ratio on our grade of paper is important, but not critical.

Dr Sanborn Why not control speed, for example, on a grade change? We tried out grade changes without having speed control and found it rather cumbersome.

Mr Harris In our intended dynamic grade control scheme, we may include a quick speed control during the grade change only.

Dr Sanborn You mean controlling the basis weight via speed changes?

Mr Harris This we intend to do during the dynamic grade change, then to transfer to stuff flow control afterwards.

Dr Sanborn I do not suggest the control of basis weight via machine speed changes. I am talking about the simple problem of grade change. You can have a very efficient system, but, if the operator sees the light that tells him to change the speed when he is across the room and it takes him a minute and a half to walk over and change his speed, that may account for half the time it takes for a change.

Mr Harris Yes, that is true. In the dynamic grade scheme, the substance and speed will be linked.

Dr Farmer I wish to amplify what I said in my paper on this topic. The servo on the lineshaft drive responds directly to the speed reference signal output by the computer. Machine speed is automatically adjusted during grade changes. The rate of change of machine speed is well within the limits of the drive and grade changes have slowed down sufficiently to allow for the manual adjustment of the couch draw.

Mr G. J. Mummery Would you please bear in mind that we are a very small department and very limited in what we can do in a limited time. We are always trying to do a little better, even if we know there is something even better that we can do later on.

Mr J. Schmied When you make changes in the head stock flow or in the breast box consistency and the speed of the machine, the retention of fines may be changed, which can perhaps complicate the response of the basis weight. Is this not serious for the process equations?

Mr Harris Small changes in the breast box flows do make small changes in through factor. The equations include through factors calculated at equilibrium, but we find through factor variations are negligible for small changes in breast box consistency.

Dr Farmer Through factors are low also at Grove Mill. The wet end material balance equations, when correctly applied, give good prediction of end conditions for grade or parameter changes. Control during the transient will suffer if the estimate for through factor is significantly wrong.

Mr B. W. Balls The question has been raised by Dr Sanborn of controlling a flow box without using total head measurement. This could well arise on Thursday. I shall not be here, so I would like permission, Mr Chairman, to comment now.

I. M. McKnight* described such systems. I have observed that his paper has been almost entirely ignored in the literature on flow box control, yet several systems are working very well, as described. Basically, wire speed sets the inlet stock flow. What goes in, must come out and the liquid level comes to balance without the need to control total head. With a closed box, the level can adjust the cushion pressure. On certain speciality machines, the systems described have succeeded when head measurement would have been useless. Only simple analog computing elements are involved other than a standard instrumentation.

Mr M. I. MacLaurin Dr Farmer quoted £22 000 for the Grove Mill system. The cost for Chartham Mill is given as £7 000. These figures bear comparison with Dr Sanborn's colour measurement cost. It might be fair to say that, with a limited budget, one could choose between buying a colour instrument or a modest computer. I think it is improper to make destructive criticism of a small system on the grounds that a system costing ten times the money is better.

The figures for the small computer systems do sound very low, however. I would like some information about what costs were included in the figures quoted.

Mr Mummery It depends on how you cost it, I suppose. We did most of the building ourselves, avoided any expensive wiring and the like. The total cost with flow meters, etc. included is in the region of £22 000 without installation charges. Is that fair?

Mr Farmer My figures refer to the cost of fully engineered equipment, computer and control desk.

Mr Harris One important point: it is quite dramatic to see the beneficial effect of a simple equilibrium model scheme, even one that ignored dynamic considerations.

* *Paper Tech.*, 1966, **7** (1), 45–52