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INTERACTIONS IN A MULTI-VARIABLE DRYER CONTROL SYSTEM

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Synopsis The design of more responsive control systems for papermachine dryer sections requires a knowledge of the coupling between web moisture content and changes in basis weight and machine speed. The interactive effect of changes in basis weight and machine speed on the measured moisture content must be known to allow proper compensation.

An estimate of the steady state coupling coefficients was made by forming an approximate mathematical model and calculating the steady state response surfaces for average web moisture content versus machine speed and basis weight. The model was a realistic representation of the partial differential equations relating heat conduction and vapour diffusion within the web. Approximate, constant values of web properties and transport coefficients and the alternating boundary conditions characteristic of conventional cylinder drying were used. Basis weight of 26–90 lb/1 000 ft^2 and speeds of 800–1 800 ft/min were studied.

The calculated coefficients showed that, for typical production conditions of 42 lb board at 1 400 ft/min, a 1 lb change in basis weight would be expected to produce a 2 per cent change in web moisture content; a speed change of 100 ft/min would produce a 5 per cent change in moisture content. The dependence of the coupling coefficients on the level of basis weight and speed was also demonstrated. The coupling coefficients for basis weight and for speed both increased approximately linearly with the operating speed, whereas the increases in both coefficients through basis weight changes were less significant. These results are of use in the design of non-interactive control systems for papermachine dryer sections.

Although the calculated results were restricted to the steady state gains for this system, an indication is given of the possible use of a more complex model in studying the dynamic behaviour of the drying system.

Introduction

THE control of web moisture content in a conventional cylinder dryer is complicated by the simultaneous changes in moisture that can occur because

Under the chairmanship of P. E. Wrist

of changes in basis weight and machine speed.(1, 2) Fig. 1 gives a schematic diagram of a simple linearised model of moisture content changes that can be used in a control system that compensates for the effect of changes in basis weight and speed on moisture level. Equations (*1*)–(*3*) show the definitions of the steady state coupling coefficients for the three-variable response surface.

$$M = M(P,B,S)\ldots\text{steady state}\ldots \qquad (1)$$

$$M-M_o = \left(\frac{\partial M}{\partial P}\right)_{B,S}\Delta P+\left(\frac{\partial M}{\partial B}\right)_{P,S}\Delta B+\left(\frac{\partial M}{\partial S}\right)_{P,B}\Delta S \qquad (2)$$

$$\Delta M = KP\Delta P+KB\Delta B+KS\Delta S \qquad (3)$$

If the conventional dryer system were a device that filtered out the effects of machine speed and basis weight, then the coupling coefficients *KB* and *KS* would be zero. This can occur in practice if the web is overdried to the point that the web moisture is only slightly affected by changes in speed or basis weight. Such a situation, though offering fewer difficulties in control, is inefficient, uneconomical and may be detrimental to the physical properties of the product. In most situations, then, the changes in basis weight and speed will be reflected in concomitant changes in moisture content. Because drying a heavier sheet is more difficult, an increase in basis weight will increase the final moisture content. Likewise, since the moisture content is a function of several complicated rate processes in the dryer section, an increase in machine speed will decrease the time available and increase the final moisture content of the paper. To design a control system, however, one must progress beyond these elementary qualitative ideas to quantitative descriptions of the system and the actual values of these coupling coefficients. To do this requires either a detailed model of the drying process itself or extensive experimentation on a mill basis.

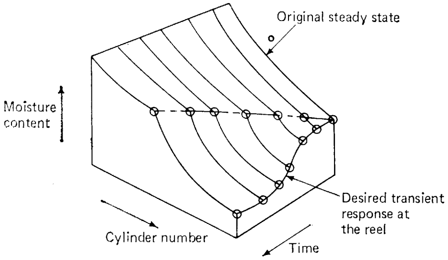

Fig. 1—Coupling of moisture response

Distributed parameter, constant coefficient model of cylinder drying

THE phenomena occurring during drying have been studied on the fundamental level by several investigators.(3–7) The primary possible mechanisms in this system are vapour diffusion, heat conduction and capillary transport. The form of the strongly coupled equations is as follows—

Energy balance

$$\frac{\partial}{\partial t}((T-T_d)C_w) = -\text{div}\ Q-\lambda\ vap-U\ \text{grad}\ T \quad (4)$$

Mass balances

$$\frac{\partial}{\partial e}(\rho_v E(1-S)) = -\text{dib}\ N_v+vap \quad \ldots\text{vapour}\ldots \quad (5)$$

$$\frac{\partial}{\partial t}(\rho_w ES) = -\text{div}\ (\rho_w U)-vap \quad \ldots\text{liquid}\ldots \quad (6)$$

$$\frac{\partial}{\partial t}(\rho_f(1-E)) = 0 \quad \ldots\text{fibre}\ldots \quad (7)$$

Rate equations

$$Q = -k_e\ \text{grad}\ T \quad (8)$$

$$N_v = V\rho_v+\frac{M_v}{(1+y_v)}(y_v\left(\frac{-N_a V\rho_a}{M_a}\right)-D_e\ \text{grad}\ y_v) \quad (9)$$

$$V = -\frac{k_v}{\mu_v}\text{grad}\ P \quad (10)$$

$$U = -\frac{k_c}{\mu}\text{grad}\ P_c \quad (11)$$

On the basis of knowledge of commercial behaviour of the system, local vapour accumulation and the capillary terms were neglected, so that the following system of approximate equations was used.

$$C_w\partial T/\partial t = k_e\ \text{div grad}\ T-\lambda\ vap \quad (12)$$

$$\rho_w E\partial S/\partial t = -vap \quad (13)$$

$$vap = -D^*\ \text{div grad}\ y_v \quad (14)$$

$$y_v = f(T, S) \quad (15)$$

The last equation (*15*) is the experimental isotherm for water vapour desorption.

A digital finite difference solution was developed under the reasonable assumption that transport at rightangles to the plane of the web was much more significant than that parallel to the web. The boundary conditions corresponded to the use of Schmidt's revised method for the steady state approximation(8) at the surfaces of the web with appropriate resistances of the cylinder and the ambient air. Since the surface of a board dries out quite rapidly, the approximation was made that the degree of saturation at the surface was zero, thus decoupling the heat and mass transfer equations for the surface increments only. This greatly simplified the calculations and is a realistic assumption for most of a dryer with well-ventilated pockets. This approximation would not give realistic results in a dryer with poor control of pocket conditions or very high partial pressures of water in the pockets.

The surface temperature and saturations were adjusted in the space-time sequence corresponding to 240 angular degrees of contact with 5 ft diameter cylinders with 3 ft draws between cylinders. A machine of 80 cylinders was used as an example. The integrations were performed using the simplest integration routine and a heuristic stability monitor. The average moisture was recorded at the moment of contact with each cylinder.

Selection of operating conditions

AN ARRAY of six basis weights covering 26–90 lb/1 000 ft^2 and six machine speeds ranging 800–1 800 ft/min were used. A constant steam temperature of 159°C corresponding to 70 lb/in^2 (gauge) was used. The calculation was continued until either the average degree of saturation dropped below 0·005 (roughly 2 per cent moisture content) or the 80th cylinder was reached. The initial time step in all cases was 0·005 s real time and was decreased as required by the stability monitor. The calculations for the 36 combinations of speed and basis weight were performed in 2 h 20 min on the IBM system 360, model 44 digital computer at The Institute of Paper Chemistry's computing centre. This initial calculation resulted in the response surfaces of average sheet moisture content versus cylinder number and machine speed for each basis weight. The data were then further processed to obtain the desired coupling coefficients. A typical response surface is shown in Table 1.

TABLE 1—RESPONSE SURFACE OF MOISTURE FOR 42 lb WEB
Average moisture content, g/g oven-dry fibre

Cylinder	*Machine speed, ft/min*					
	800	*1 000*	*1 200*	*1 400*	*1 600*	*1 800*
1	1·933	1·939	1·942	1·945	1·946	1·947
10	1·488	1·566	1·632	1·681	1·718	1·747
20	1·056	1·214	1·320	1·398	1·454	1·496
30	0·677	0·886	1·023	1·133	1·220	1·292
40	0·323	0·574	0·731	0·871	0·974	1·060
50	0·030	0·291	0·500	0·662	0·787	0·894
60	0·0	0·041	0·259	0·444	0·581	0·707
70	0·0	0·0	0·045	0·235	0·393	0·525
80	0·0	0·0	0·0	0·048	0·206	0·360

Coupling coefficients derived from the response surfaces

THE coupling coefficients defined earlier also depend very importantly on an implicit definition of the position in the machine where the measurement is taken. For example, the numerical values of gain may be different for moisture measurements at cylinder 60 and the values at the reel.

To illustrate this point, the cross-section of average moisture content at cylinders 60 and 80 are given in Tables 2 and 3. Successive column and row differences were used to estimate the coupling factors defined earlier and these these are given in Table 4. The very high moisture contents for the heavier basis weights at higher speeds do not represent usual operating ranges, but are given to indicate the shape of the response surfaces over a larger range. The gains were taken as the average of the slope at each side of the given data point. For example—

$$KB\,(80{,}42{,}1400) = \tfrac{1}{2}\left\{\frac{0{\cdot}206-0{\cdot}040}{42{\cdot}0-38{\cdot}0}+\frac{0{\cdot}924-0{\cdot}206}{69{\cdot}0-42{\cdot}0}\right\} = 0{\cdot}034\ \text{lb}^{-1}\,. \qquad (16)$$

These tabulations show, as expected, that the steady state coupling coefficients are dependent on the speed and basis weight. If one concentrates on the region surrounding 42 lb basis weight at 1 400 ft/min, the following pattern of coupling coefficients emerges—

Pattern of coupling coefficients at the 80th cylinder

$$\begin{array}{lccccccc} \text{—|——}\rightarrow \text{B} & & KB\,(\text{lb}^{-1}) & & & KS\,(100\ \text{ft/min})^{-1} & \\ \downarrow & & 1{\cdot}2 & & & (1{\cdot}2) & \\ \text{S} & (0{\cdot}6) & 2{\cdot}0 & 2{\cdot}1 & (1{\cdot}0) & 5{\cdot}2 & 6{\cdot}5 \\ & & 3{\cdot}4 & & & 7{\cdot}8 & \end{array}$$

Thus, at 42 lb and 1 400 ft/min, the calculations indicate that an increase in basis weight of 1 lb would increase the moisture by approximately 2 per cent and a speed increase of 100 ft/min would increase the moisture by about 5 per cent. This kind of information is useful in designing non-interactive control schemes for papermachine dryer sections.

TABLE 2—AVERAGE MOISTURE AT CYLINDER 60
Moisture content, g/g oven-dry fibre

Speed, ft/min	*Basis weight, lb*					
	26	*33*	*38*	*42*	*69*	*90*
800	0·0	0·0	0·0	0·0	0·588	0·928
1 000	0·0	0·0	0·0	0·041	0·801	1·087
1 200	0·0	0·0	0·073	0·259	0·948	1·212
1 400	0·0	0·038	0·279	0·444	1·059	1·306
1 600	0·0	0·193	0·435	0·581	1·155	1·375
1 800	0·0	0·350	0·565	0·707	1·236	1·433

TABLE 3—AVERAGE MOISTURE AT CYLINDER 80
Moisture content, g/g oven-dry fibre

Speed, ft/min	*Basis weight, lb*					
	26	*33*	*38*	*42*	*69*	*90*
800	0·0	0·0	0·0	0·0	0·230	0·647
1 000	0·0	0·0	0·0	0·0	0·482	0·851
1 200	0·0	0·0	0·0	0·0	0·667	0·989
1 400	0·0	0·0	0·0	0·048	0·815	1·105
1 600	0·0	0·0	0·040	0·206	0·924	1·197
1 800	0·0	0·0	0·184	0·360	1·013	1·274

TABLE 4—SUMMARY TABLE OF STEADY STATE COUPLING FACTORS

KB $(\text{lb})^{-1} \times 100$
$N = 60$

Speed, ft/min	*Basis weight, lb*			
	33	*38*	*42*	*69*
1 000	0·0	(0·5)	(19)	2·0
1 200	(0·7)	3·1	5·5	1·9
1 400	2·4	4·5	3·5	2·0
1 600	2·7	4·3	2·9	1·6

KB $(\text{lb})^{-1} \times 100$
$N = 80$

Speed, ft/min	*Basis weight, lb*			
	33	*38*	*42*	*69*
1 000	0·0	0·0	(0·9)	1·8
1 200	0·0	0·0	1·2	2·0
1 400	0·0	(0·6)	2·0	2·1
1 600	(0·4)	3·9	3·4	2·0

KS $(100\ \text{ft/min})^{-1} + 100$
$N = 60$

Speed, ft/min	*Basis weight, lb*			
	33	*38*	*42*	*69*
1 000	0·0	(1·9)	6·5	9·1
1 200	(0·9)	7·0	10·6	6·5
1 400	4·8	9·6	8·1	5·2
1 600	7·9	7·7	6·6	4·4

KS $(100\ \text{ft/min})^{-1} + 100$
$N = 80$

Speed, ft/min	*Basis weight, lb*			
	33	*38*	*42*	*69*
1 000	0·0	0·0	0·0	11·0
1 200	0·0	0·0	(1·2)	8·4
1 400	0·0	(1·0)	5·2	6·5
1 600	0·0	4·6	7·8	5·0

The results also show the way these proportionality factors change with machine speed and basis weight. Terms *KS* and *KB* both increase rapidly with machine speed and less strongly with basis weight. Over a small region, a reasonable representation of the results would be that the change of either coupling coefficient with speed is linear and the change with basis weight is negligible. There exists the possibility of using this information in more complex control schemes than that shown in Fig. 1.

Critique of the model

ALTHOUGH the results of the model calculations are useful to indicate relative trends, several shortcomings should be pointed out. The calculations in this model assume constant, average values of the transport coefficients. The data of Matters & Han(2) and McMaster(3) show the actual dependence of these factors on moisture content and web porosity. In addition the contribution of the caliper shrinkage of the web to the thermal and mass-diffusion dynamics is excluded. Of great importance is the simple boundary conditions that were used. Increases in pocket humidity or changes in cylinder or pocket temperature will certainly have an effect on the actual drying rate. The model is thus not suitable for dryer design calculations, but does show the relative interactions on a realistic basis without the use of equivalent web temperatures(9) or estimation of steady state contact factors.(10 11) The model should therefore be more dependable over a range of conditions for process control development than previous semi-empirical models.

Dynamics of dryer sections

A SIMILAR simplified mathematical model could be used to study the dynamic response of the dryer. The method of using such a model is described below, but the results are still incomplete. The present model could be used to study the time response of the system if one could assume a quasi-steady state boundary condition during the change. Such an assumption is not realistic enough, however, to obtain useful results. If the assumption were true, then on no account could the equilibrium time for the dryer exceed the transport delay of the system (approximately 1 min). Observed time lags are significantly larger than this. Therefore, the dynamic interaction of the system outside of the web must be imposed on the present model. A major contribution to the dynamic response is the thermal capacity of the cylinders and a compatible dynamic model of the cylinder boundary condition is in the process of being developed.

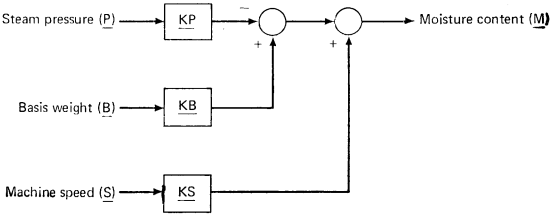

Fig. 2—Development of transient response from model calculations

Assuming that such a more complicated model were already available, however, how would one use it to study the dynamics of the dryer under various upsets? The proposed method involves the segmentation of the dryer and the imposition of a step function in the boundary conditions, for example, in the steam temperature. From a series of calculations at increasing distances from the reel, one could build up the step function response of the reel moisture as a function of time as shown schematically in Fig. 2. Unfortunately, the strongly coupled, non-linear characteristics of the drying process seem to preclude any less tedious method.

The resulting curves could then be compared with other empirical or semi-empirical response functions for less complex dynamic models in practical control systems.

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Discussion

Dr L. A. Kirk There was a gentleman who wrote to a rather eminent professor, querying a particular point that he did not understand and he received the answer back, 'If you had read my earlier papers, you would have had no need to ask this question.' I hope I am not going to place myself in that position, but I think that the symbols are unexplained. Nevertheless, I am going to hazard a guess what they mean. If equation (*15*) refers to the rate of evaporation from a free water surface, an experimental relationship (of which there are many) would be required to evaluate it. Are the actual results sensitive to the particular form of rate of evaporation relationship that is adopted or have I misinterpreted equation (*15*) altogether?

Dr R. A. Holm Equation (*15*) is the equivalent equilibrium isotherm—that is, the amount of water vapour content in a web at the given temperature and saturation. This is not a rate equation, it is simply the normal equilibrium desorption curve. While the web is very wet, we have essentially the vapour pressure of water. Many of the approximate models that are used assume that you have pure water. If you get towards the dry end, it becomes more and more difficult to extract that water, the vapour pressure becomes lower and this has a significant effect on the final result.

Dr J. A. Robinson Could I ask for clarification about what you showed on the last slide? You said that the speed gain was calculated at constant stuff gate position. Does this mean that the gain between the speed and the moisture content is calculated at constant fibre flow to the machine and therefore under conditions of varying basis weight?

Dr Holm I think not. In this case, the condition of, say, 42 lb nominal basis weight was set at the wet end, then the drying was calculated, so the fibre weight is actually constant.

Dr Robinson The data then is very interesting in connection with the problem of controlling moisture content by speed on a dryer-limited machine. If one makes a speed change at constant fibre flow, there will be a change in basis rate as well. Using your data, at 42 lb and 1 400 ft/min, a 100 ft/min increase in speed would result in a drop in basis weight of approximately 3 lb. The net effect of summing the changes in moisture content due to *KS* and *KB* would be −6 per cent +5·2 per cent = −0·8 per cent. That is, speeding the machine up has caused a decrease in moisture content. This is, in fact, in line with what we have observed on a linerboard machine: the gain between speed and moisture content at constant fibre flow is close to zero, sometimes positive sometimes negative. This presents severe problems in implementing moisture/speed control, unless it is dynamically decoupled from basis weight control.

Dr Holm Thank you very much. We would welcome more detailed data on this point from other sources.

Dr B. W. Smith Your equation (*3*) has three constants in it and, as I understand it, you have shown how these constants varied with the basis weight and speed. I would have expected that they would vary also with moisture content of the web into and coming out of the dryers. Have you any evidence of this?

Dr Holm In this particular case, we assume conditions of constant pressing. I believe the moisture content was about 65 per cent and we did not vary this. It would be possible to insert a different level of moisture and recalculate to determine the response at different input moistures.

Mr M. I. MacLaurin I am becoming very confused by the basis weight units used by Kodak. These are neither lb per 3 000 ft^2, nor one of the metric forms, nor even a British or American lb per some peculiar size of ream. I would like to make a plea that, when these proceedings are published, the equivalent in g/m^2 be given when other units for basis weights are quoted.

Dr I. B. Sanborn I presume this is strictly a simulation result, but I wonder if part of the project that you are currently involved in would include correlation of your models with an actual machine.

Dr Holm I mentioned that we have two parallel programs under way. The process control work has been sponsored by the Institute of Paper Chemistry, therefore this is what I am discussing here. The design studies are sponsored by a private group and this includes such comparison, but I am not free to discuss these results now.

Dr D. Wahren For a very crude estimate of the interaction between rapid basis weight and moisture content variations in the machine-direction, it is assumed that the drying capacity is constant, owing to the high thermal inertia of the dryer section. This means that the amount of water evaporated per unit time and unit area is assumed to be constant for short intervals of time. The drying capacity per unit width is thus given by—

$$D = (W_{wo} - W_{wp}) . u$$

Furthermore—

$$W = W_f + W_w$$
$$m = W_w / W_f$$

Combining and differentiating—

$$\partial m_p = (m_o - m_p)\left[\frac{\partial W_f}{W_f} + \frac{\partial u}{u}\right]$$

Since $m_o \gg m_p$, one obtains approximately for constant speeds—

$$\partial m_p \approx m_o \frac{\partial W_f}{W_f},$$

which is not a quantitatively correct expression, of course, but serves to show the importance of the moisture ratio entering the drying section. At constant thick stock flow rate and varying speed, $W_f . =$ const. or

$$\frac{\partial W_f}{W_f} + \frac{\partial u}{u} = 0$$

which yields $\partial m_p = 0$. This checks well with Dr Sanborn's remark.

W = Basis weight
m = Moisture ratio
u = Machine speed

Subscripts
f = fibre
w = water
o = after presses
p = at reel-up

Dr A. Kohl Has your Institute made similar studies to find the influence of pH changes and freeness changes on the moisture content?

Dr Holm The parallel design studies are more exact. Freeness changes have been investigated and found to have an effect in the expected direction. We have had nothing to do with pH changes so far.

A Speaker Did you investigate the dynamics of the drying cylinder? Secondly, has the work of the Institute of Technology and Design Study been incorporated or used as a base for this additional design study work?

Dr Holm I will answer your second question first. The work done by Dr Snow at the Institute of Technology was done independently and parallel to this work. This is an independent study and it is not built up upon that work. We both use finite difference techniques, as did Nissan and many other researchers in the past.

Dr Sanborn The Snow model was not a dynamic model, it was to determine the steady state of the operation of the drying section for various operating conditions. Is your detailed model also a static design model?

Dr Holm As you can see from the results we presented today, the work so far concerns the steady state. It is a dynamic calculation, but for a particular fixed condition on the machine.

Mr I. Tanner Assumptions and approximations have to be made for achieving a solution to these equations. Various assumptions have been made by researchers in this field in the past and they have reached different solutions for the steady state operation of the dryer system. They appear to choose assumptions that give solutions that best match the physical system against which they wish to test their theory? Thus, no general and all-embracing solution exists. Could you comment on the accuracy of your model? You say that you still wait for someone to test your model against a physical system. Could you therefore comment on the accuracy of your method, compared perhaps with the crudest mathematical model one could envisage, which would be to assess the amount of water entering the dryer section and to consider a heat energy balance?

Dr Holm This model was developed to be used in such studies. As reported, it is at the stage that it is about to be used. It has not yet been compared with all the various approximate empirical models.

Mr E. Justus I thought that your simulation was most ingenious and I tried to follow it with interest, but there is one point that I did not quite understand about the curve in the film that represented dryness. I believe that the 'legs' of the diagram keep going up and down. What is the meaning of this?

Dr Holm The jumping 'legs' show the fluctuations in the calculated moisture content right at the interface.

Mr Justus Then according to this calculation, this moisture returns to that interface, to that surface of the sheet, immediately on leaving the dryer?

Dr Holm No, rather immediately on contacting the dryer. The majority of the drying, at least for a heavy board like this, occurs as the moisture is flashed off when the hot face of the board is exposed to the pocket.

Mr J. D. Maloney A point that may be of interest to this symposium is what happens to a computer process control installation on a papermachine after it has been in operation for a number of years—that is, after the initial training programs are over, after the installing team of system engineers, programmers and process and control engineers have long left the scene and when a mill process engineer is left to maintain and develop the system.

The Mead Corporation has such a system, one of the oldest in the industry, installed late in 1962. This application is still in operation after two changes in basic hardware. Although the system has continued to evolve by modifications to accommodate machine changes by adding new control features, progress has been slow. This has been primarily due to the fact that development has been limited essentially to the efforts of one man.

In retrospect, it is quite evident that the use of a digital computer in a papermill is much more than adding a piece of sophisticated control equipment to the operation. In many respects, it requires a whole new philosophy of mill operation in order to obtain full benefit. In addition to understanding and co-operation from all levels of mill operation and management, there has to be a strong and continuing desire to supplement the art of papermaking with technology. This is not easily accomplished, at least in the Unted States; there are a number of mills where a generation of management will have to go by before this new philosophy can be fully implemented.

The addition of a computer system may be likened to a heart transplant. There are many factors that tend to reject it. Similarly, in a papermill, there are factors that cause a computer system to deteriorate or be rejected, such as lack of a champion for the cause, lack of enthusiasm from mill management, fear on the part of the operators and foremen of what is new and reluctance to give up the art, lack of adequate instrument maintenance support and lack of process and control engineering talent to name the most important.

Many operators say that they like computer control and would not want to run the machine without it. In the most part, this is because it makes their job easier. It might be compared to power steering on a motor car; it is nice to have, because it makes driving easier, but it gets you there no faster. In terms of a computer installation, just because the operators like it, does not necessarily mean that it is a profitable venture.

Over the years, I have developed a rule stating that, in operating and line management, enthusiasm is inversely proportional to the levels above the operators. Operators like it, but management easily sees the costs, not the benefits that justify the installation. This is not to say that computer systems do not contribute to profit. It is to say that to sort out the benefits attributable to the systems approach using a computer from many other changes made to improve productivity and quality is next to impossible. Management judgment must be used in making such a partition.

In summary, a distinct and continuing effort must be made in the training of operators, foremen, superintendents and managers, as well as in the upgrading of instrument maintenance if a process control computer installation is going to be a continuing success.

Mr R. A. C. Stables I would like to comment further on some of the considerations in computer systems architecture.

As users, you can choose between two alternative approaches when planning your process computer installation—and most computer suppliers will be prepared to go either route with you—

1. Install a single, large central processor with a very complete and sophisticated high-level software system (and the latter is important to minimise system costs and the need for computer expertise).

2. Install a hierarchy of several smaller computers each dedicated to one portion of the process and receiving general objectives only from higher-level computers (as described in Mr Keyes' presentation).

If you choose the single, central processor route, do not overlook the need for the following—

1. Convenient access to a large programming facility for program generation.

2. A good means of preventing program errors on one section of the system from destroying good on-line programs operating elsewhere.

3. A method to ensure that low priority programs will in fact operate when the computer becomes really busy.

I should mention that these problems have been solved by hardware in the new Bailey 855 machine, but it is not my intention to commercialise. Instead, I would recommend to your attention the following considerations on the hierarchy system of several smaller dedicated machines—

1. With the availability of low cost hardware, such an organisation is now very competitive with the single computer approach on a totally installed and operating basis (software and start-up costs included).

2. The software is broken down into well-defined, manageable packages, for which it is much easier to predict time and memory requirements, therefore total costs (this has probably been the most important single problem in planning and evaluating computer installations).

3. Multiple computers provide greater reliability in that it is far less likely that a single hardware or software fault can have a catastrophic effect on the entire process.

4. This approach permits the user to proceed one step at a time as psychological, technological and economic limitations (in that order of importance) permit. (This is the most important argument for the multi-computer approach —as others have stressed this week, the major limitations to success are psychological.)

Although not a hierarchy of *general* purpose mini-computers, these were some of the reasons for the multi-computer system organisation chosen for the Powell River system, which Mr Mardon described on Wednesday. This was an early approach to what many believe will be a trend of the future in computer system architecture.

Mr W. T. Whight I feel that we have had today too much imbalance between theoretical background or learned dissertations on what should be done and what actually *has* been done and the results obtained or expected. Mr Madeley's contribution was a refreshing contrast to today's heavy going.

I was surprised that no comment was made on the computer control of flow box contribution from Mr Jones and myself. We stated that we regarded flow box head as a dependent variable—this comment was in no way disputed. We quoted *results*—an improvement in total head variation by a factor of 5 over an analog system, a final variability of 0·2 per cent or 0·1 in w.g.

Perhaps, I may say a few words with reference to Mr Johnston's paper on sub-optimum grade change procedures. We have intuitively developed a strategy similar to what we described. We calculate by simple flow ratios the new grade desired values, by taking the current running conditions and new required substance and (if required) wire speed. We modify these values to allow for expected retention changes, then ramp the DDC controller settings to the final values. We have obtained results that we feel cannot be much improved by any more sophisticated method. Wire speed changes at a rate of 100 ft/min per min and basis weight changes are complete in 5–6 min or less.

With modelling, we have obtained basis weight variability to within ±1·25 per cent of desired value without the benefit of erudite modelling techniques. We estimate we have obtained 90 per cent of possible improvement without going to these costly and time-consuming preliminaries. These may be done later (in our case by Mr Hem), although benefits are already being felt.

Dr Smith We have had complete accounts of the savings that were achieved with analog control computers and we have had complete agreement among all digital computer users that it is impossible to discover what the precise savings are. I suggest that this is inherent in the difference between the two approaches—but what precisely is the inherent difference?

Mr J. Mardon I regard the current existence of *read only memory* as a very important development that relates to the hierarchal system described by Mr Staples.

Mr H. B. Carter I would like to raise a question of using head as a dependent variable. At the speeds reported, I have no experience; but, in high-speed newsprint machines, where the position of the jet landing on the forming board is extremely critical, I think the use of head is utterly taboo.

The Chairman This comment reinforces once again the dangerous nature of generalisations in papermachine operation and in papermaking.

Dr O. L. Forgacs In listening to these proceedings, one gets the impression that the sensing and measuring devices at our disposal in the pulp and paper industry are generally satisfactory. Yet, all of us still have great difficulty in obtaining reliable on-line measurements for quantities as basic as consistency. I feel that particularly the research institutions, well represented at this meeting, can make an important contribution by working towards better and more reliable instrumentation.

The Chairman Although supporting your position for improved instrumentation, we have nevertheless expected papermakers to make paper for the last 100 years with the present lack of instrumentation. Perhaps our first objective in process control is to achieve consistently what they can do on their best day with present tools and not to wait for perfect instrumentation before making any moves at all to improve our operations.

Dr Sanborn Could Mr Maloney say, in the handling of process engineers out in the mill, how they fit into the mill organisation after a considerable time following the initial installation?

Mr Maloney There is process engineer associated directly with the computer and working with the operators. He is part of the mill technical staff, not a part of operations.

Mr G. D. Madeley I would like to take up some points made by the last two or three speakers. At a fundamental research symposium, one expects a lot of theory, but this theory is of no use unless it is related to practice.

I am a little disappointed that so few people have given the results of what they are doing. In terms of the cash returns, our computer is giving a return that balances the cash outflow, so we have passed the point when the installation changes from loss to profit. We wish we could capitalise on our improved substance control.

Our market has changed in the last few months so that we have been unable to reduce our substance level. Without our computer control, however, we would have to sell 2 per cent extra fibre on area-based orders. Now that we have moisture content under control, we know that we can increase it at the reel by 1 point. Anyone can calculate the savings in these areas.

The problem of instrumentation is absolutely vital to a computer installation. We have had many months of trouble with some instruments. One that I would particularly like developed is for moisture measurement.