Metrology—economics of paper drying

Many papermakers are surprised when they learn the magnitude of variations in basis weight and moisture and their effect on dryer capacity.

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Many paper machines are production limited because of the effect variations in basis weight and moisture have on dryer capacity. Often moisture streaks at the reel necessitate overdrying much of the sheet to remove the excess moisture in these streaks. Many papermakers are surprised to learn the magnitude of these variations when they first install continuous on-line basis weight and moisture equipment at the presses or at the dry end. The effect these variations have on limiting throughput is significant but often ignored because of the lack of a simple means of calculating the improvements in an accurate manner.

While the effect of small changes in average reel moisture has been described,[1] little has been said of the combined effect of incoming moisture, final moisture, and basis weight on steam consumption and machine speed. This article develops and demonstrates the use of two graphs to give a picture of the dramatic increases in speed achievable by leveling both moisture and basis weight variations.

Basic description of paper drying

To understand the economics of paper machine drying, it is first necessary to have at least a basic understanding of the technology of the drying process. Figure 1 shows a simple curve for drying a material on cylinder dryers at a constant temperature. In the early stages, water moves freely to the surface where evaporation takes place. This is often referred to as the *constant rate period.*[2] As the paper becomes drier, the sheet builds up an increasing resistance to the water flow in vapor form. This is called the *falling rate period.*[2] The final equilibrium moisture depends on the material, the material temperature, and the relative humidity of the surrounding air.

Drying cannot be thought of simply as a process of heat transfer. The water vapor evolved by heat must be physically removed. Thus, drying in the early stages may be impeded either by poor heat transfer or by an inability to remove the water vapor (poor ventilation). In the later stages, the amount of water evaporation is small and diffusion is the only important mechanism.

Methods of operating paper machine dryers

Virtually all paper machines remove the water in a sheet by cylinder dryers, but the philosophy of dryer operation varies significantly with respect to economics. Some machines operate with the dry end steam valve wide open and are in fact using all the steam available. These machines might be termed *steam-flow limited systems.* However, this method of operation is rather delicate to control because of the effect of small parameter variations on final moisture. Most machines operate with stipulated temperatures (or steam pressures) on the various dryer sections to avoid such sensitivity, so it may be assumed that these machines have some available steam flow capacity. They might be referred to as *temperature limited systems* because the drying is limited by the shape of the drying curve.

All dryer sections are usually not operated at the same temperature. The initial drums at the wet end are usually at a lower temperature to avoid various operational problems such as picking or sticking to the drums. The final section is run at a higher temperature to compensate as much as possible for the falling drying rate. Although the

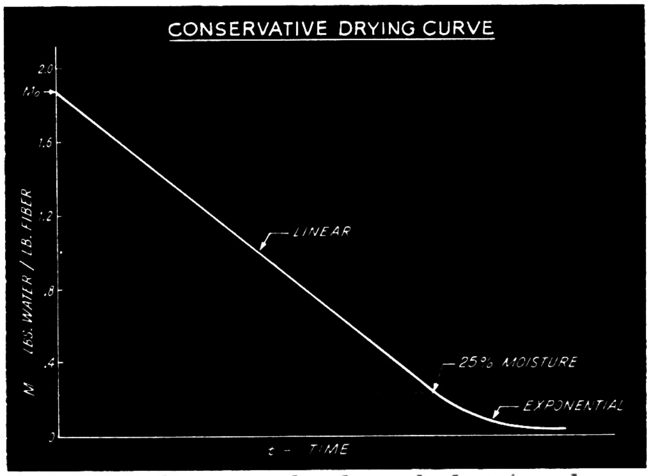

Figure 1. The dryer curve plotted on a dry basis (pounds water per pound fiber) is linear to about 25% moisture.

changes in temperature along the machine do not produce exactly the smooth drying curve of figure 1, this graph serves as a reasonable model for all practical purposes.

Development of the paper machine drying graphs

The steam flow limited graph (figure 2) is simply a mass balance of the drying system in terms of percent moisture, basis weight, speed, and average evaporation rate. The graphed relationship itself, therefore, does not involve any theoretical model, although there are minor inaccuracies which are due to the method of scaling. These are discussed under "Limitations of the Graphs."

The mass balance does not describe a true steam flow limited system although it is probably a good approximation. Average evaporation rate is related to steam flow by drying efficiency (pounds water evaporated per pound of steam). To interpret a percent change in evaporation rate as a percent change in steam flow assumes a constant efficiency, which is unlikely, but for small changes it is probably a reasonable premise.

The temperature limited graph (figure 3) is based on the simple conservative model of figure 1. Because paper machine drying practice varies widely and there is no real norm, no exact general model could be constructed. On the other hand, a specific model for one machine would be of little general interest or use. The model used here has a constant initial evaporation rate down to 25% moisture. Beyond this point the absolute moisture (pounds water per pound fiber) decreases exponentially toward a value of zero. The curve constants were selected to give a conservative speed increase of 5% for an increase in final average moisture from 3% to 4% at constant basis weight. Although this or any model can be criticized for a number of reasons, it is doubtful that any other plausibly shaped curve using the latter assumption would give much different results. For a detailed mathematical development of this graph, the reader should refer to the appendix.

Limitations of the graphs

If either graph were scaled in terms of actual basis weight, speed, etc., it would be a valid graph of the relationship described. However, this would limit the graph to a narrow range of values. To avoid this difficulty, the speed and basis weight scales are laid off so that each ascending value is 1.02 times greater than the preceding value. This means that for a large change from the initial starting conditions, the given scale will become inaccurate. The table gives a comparison of scale readings versus actual changes in percent. The error is small if incremental changes are confined to less than 6% and not too damaging with increments of 10%. Of course, the actual scale values could be used, but it is doubtful that the increased accuracy is worth the increased reading difficulty.

Error in speed, basis weight or evaporation rate scales

Indicated change %	Actual change %
2	2.0
4	4.04
6	6.12
8	8.24
10	10.4
−2	−1.96
−4	−3.88
−6	−5.77
−8	−7.6
−10	−9.4

Use of the graphs

To prepare either graph, first draw a vertical line from initial moisture to a final moisture. From the point of intersection, project a horizontal line to any convenient basis weight line on the right hand side of the graph. Then complete the graph by extending a vertical line from that point to the bottom of the graph. This rectangle represents the base or initial operation.

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If now a second rectangular shape is drawn, it represents a change in operation. In this way, one can determine the percent change in speed for a change in initial or final moisture, or the percent change in evaporation rate if speed is held constant. The basis weight and speed scales apply anywhere on the right hand side of the graph.

Example: Suppose the steam flow limited graph is used to draw a base rectangle for 65% initial moisture and 4% final moisture (figure 2). Now if initial moisture is reduced to 64% by more effective pressing, it can be noted that the new rectangle terminating at the same final moisture and basis weight lines will give a 5% increase in speed at constant average evaporation rate or a 5% decrease in average evaporation rate (steam consumption) at constant speed. If, as another example, when the final moisture is raised to 5%, either an increase in speed of 1.5% is obtained at constant evaporation rate, or a decrease of 1.5% in average evaporation rate is obtained at constant speed. Similarly, a 1% reduction in basis weight at constant moisture will give only a 1% increase in speed or reduction in evaporation rate.

If the temperature limited graph of figure 3 is used, the results are somewhat different. A 1% decrease in initial moisture will produce only about a 4% increase in speed, but a 1% increase in final moisture will also produce about a 4% increase in speed. It is not appropriate to equate a change speed with an increase change in average evaporation rate on this graph. If it is desired to determine changes in average evaporation rate (steam consumption) at constant speed, one should use the steam flow limited graph.

Typical results achieved

Now let us look at an example of optimizing dryer performance on a 500 tons per day board machine producing 16 point carton stock. Strip chart recordings of basis weight, size press moisture, and press moisture are shown in figure 4. The charts on the left illustrate some of the moisture and fiber profile problems which existed prior to a systematic wet end tuning. Wet end tuning consists of minimizing machine direction variation by optimizing all the machine parameters from the machine chest to the couch. Also a thorough job was done in leveling moisture and basis weight profiles by adjusting all the related machine variables from the headbox to the size press.

After months of investigation and experimentation, the resulting profiles on the right (figure 4) were achieved. In the case of basis weight, the profile range was reduced from four pounds per 1,000 square feet to 1.2 pounds per 1,000 square feet permitting a 2.4% reduction in the average; size press moisture profile was reduced from 2.4% to 0.9% permitting an average increase of 1.1% moisture; and the most dramatic improvement was achieved when the average moisture into the dryers was reduced from 63.4% to 60.45% (wet basis) while simultaneously reducing the

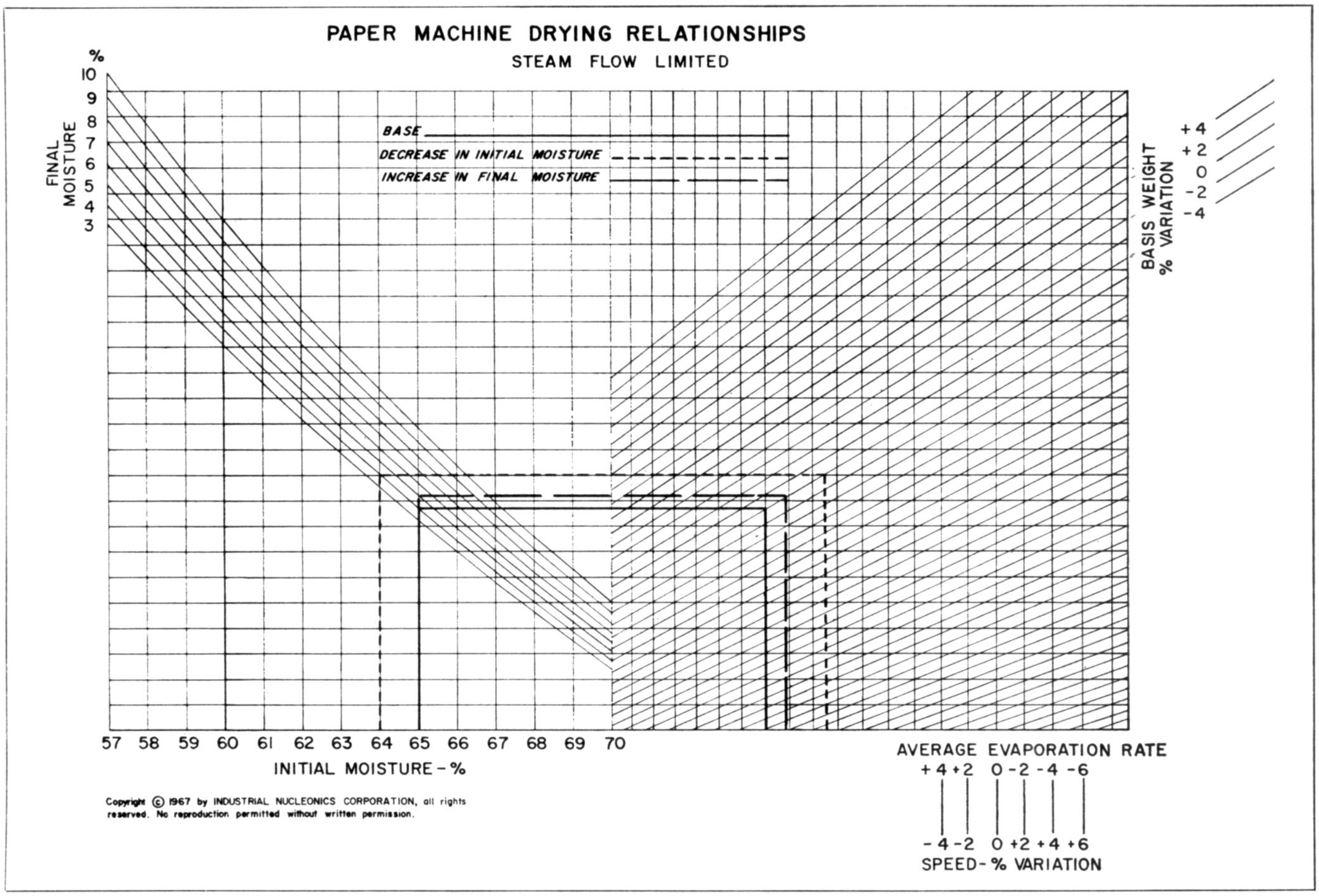


Figure 2. A reduction in initial moisture will permit increased speed much more than an increase in final moisture.

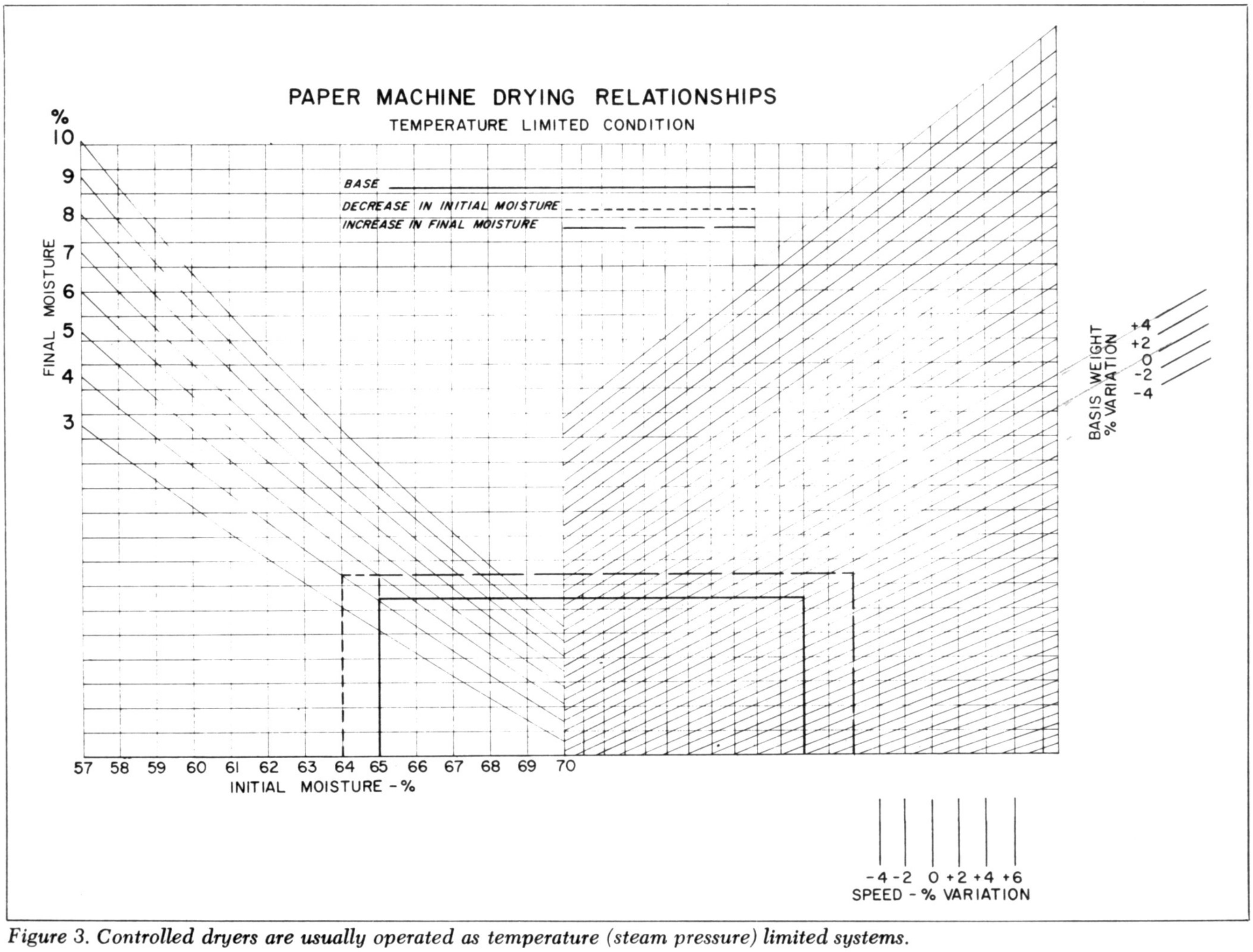


Figure 3. Controlled dryers are usually operated as temperature (steam pressure) limited systems.

wet end profile range from a 2.7% to 0.8% moisture.

All of this improvement represents a great engineering achievement and an obvious improvement in product quality and uniformity. But how can one evaluate the economics of these results other than as the fiber savings from reduction of average basis weight and the replacement of fiber with moisture? The greatest economic improvement comes from the ability to increase machine speed.

To find the effect of profile changes on the paper machine drying graphs requires some engineering judgment. Since the purpose is to find the change in speed or steam consumption, it is necessary to evaluate each profile to determine the limiting condition and establish a point representing that condition. For instance, one would normally assume that the heaviest basis weight would carry the most moisture and, therefore, be a limiting factor on the speed of drying. However, from looking at the left hand charts (figure 4), there is not complete correlation between heavy and wet spots. Consequently, a more conservative point was chosen as half way between the average and the maximum basis weight to represent the limiting condition. A similar point was chosen for the same reason on the press moisture profile. In the case of the size press moisture profile, the point representing a limiting condition was chosen halfway between the average and the minimum level. This is a compromise from the assumption that the driest portions require the longest time in the dryer.

Based on these assumptions, the following changes in effective values should be used to plot the paper machine drying graph (figure 5): initial (press) moisture reduced from 65.15% to 60.75%, final (size press) moisture increased from 3.75% to 5.05%, and basis weight reduced from 63.2 to 61.5 pounds per 1,000 square feet. If all these improvements were achieved simultaneously, it would be possible to increase speed by 24.3%. Usually when a speed increase of this magnitude is attempted other parts of the process become the critical limitation. In this particular case, the supply from the pulp mill became a limiting factor so that only part of improvement could be taken as a speed increase and the remainder utilized as a steam savings.

Economic gains depend upon assumptions involved

The economic gains that can be calculated from these graphs depend on the assumptions involved. The assumptions in the example of the board machine described in figures 4 and 5 are as follows:

1. The product is sold on an area basis.
2. Due to improved uniformity and quality, incremental increases in production can be sold at regular prices.
3. Fractional changes in steam load can be valued at the fuel cost to produce the steam.
4. This machine is operated as a temperature limited system.

The economics can easily be described in an equation using the following symbology:

C_1 = present annualized rate of value of paper at the reel.
C_2 = present annualized rate of value of raw material at the headbox.
C_3 = present annualized rate of cost of steam for drying.
P_1 = fractional speed increase.
P_2 = fractional moisture increase at dry end.
P_3 = fractional increase in basis weight.
P_4 = fractional increase in average evaporation rate.
S = annualized savings.

then

$$S = P_1 (C_1 - C_2) + P_2 C_2 - P_3 C_2 - P_4 C_3$$

In the example described

$C_1 = 500$ tpd (340 days) (\$165/ton) = \$28,000,000/year.
$C_2 = 500$ tpd (340 days) (\$100/ton) = \$17,000,000/year.
$C_3 = 106{,}000$ lb/hr (8,160 hours/year) (75¢/1000 lb) = \$649,000/year.

Figure 5 shows a speed increase of 24.3%. If these same improvements had been plotted on a steam flow limited graph such as figure 2, the speed increase would have been 20%. Therefore, when the temperature limited system is speeded up, it would have to condense 4.3% more steam due to the improved evaporation rate on last dryers.

Therefore:

$P_1 = .243$
$P_2 = .011$
$P_3 = -.024$
$P_4 = .043$

$$S = .243(28 - 17)10^6 + 17(.011 + .024)10^6 - .043(.649)10^6 = (2.67 + .595 - .028)10^6 = \$3{,}237{,}000$$

If maximum advantage were taken of the steam savings instead of the speed increase, then:

$P_1 = 0$
$P_4 = -.20$

and

$$S = (.595)10^6 + .20(.649)10^6 = \$725{,}000.$$

Appendix

The linear exponential drying curve

The drying curve is shown in figure 1. Evaporation rate is assumed to be linear down to 25% moisture. Beyond this point, the curve is assumed to be exponential asymptotic with respect to zero moisture. There is considerable justification for such a model as it is well known that moisture is freely removed during the early part of drying and that drying at the end is primarily a function of the difference between vapor pressure of the sheet and partial pressure of water vapor in the air. A more explicit model could be built for a specific situation, but such would have little general utility.

To derive the equation for the curve shown in figure 1, it is necessary to treat the curve segment for moisture contents greater than 25% separately from the curve segment for moisture contents less than 25%. For moisture greater than 25%, the curve is a straight line (in Cartesian coordinates, $y = mx+b$).

$$M = mt + M_o \qquad (1)$$

where

M = moisture content in pounds water/pound fiber
t = time in minutes
m = slope of the line
M_o = initial value of M (when $t = o$)

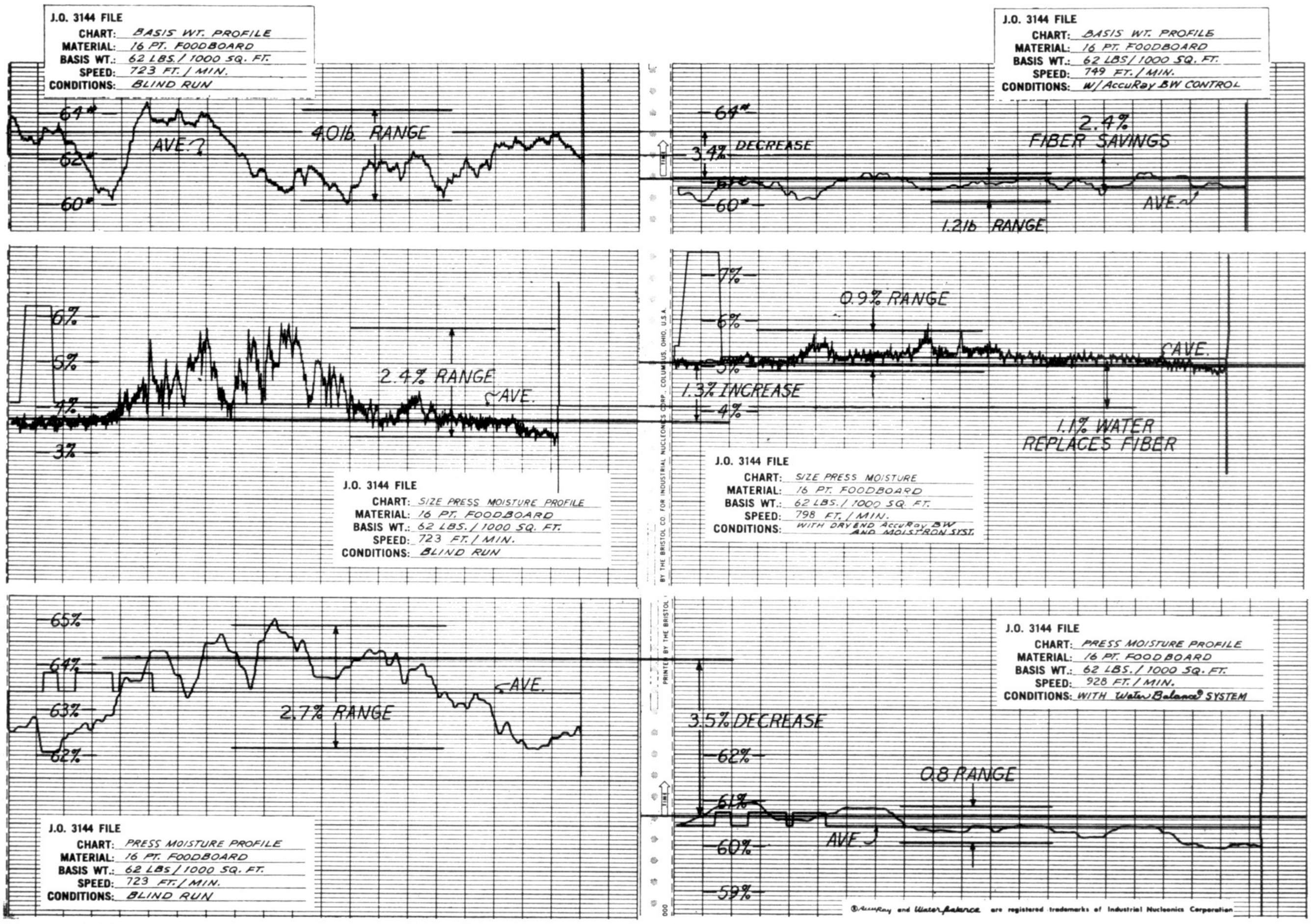
For $M > .25$, from equation (1)

$$\frac{dM}{dt} = m \qquad (2)$$

Equation (2) states that the slope (m) of the line is equal to the rate of change of moisture (M) with respect to time. Hence "m" must be proportional to minus the evaporation rate.

$$m = \frac{-EK}{F}$$

E = evaporation rate in pounds water/square foot/minute
F = fiber weight in pounds/ream
K = ream size in square foot/ream



J.O. 3144 FILE
CHART: BASIS WT. PROFILE
MATERIAL: 16 PT. FOODBOARD
BASIS WT.: 62 LBS./1000 SQ. FT.
SPEED: 723 FT./MIN.
CONDITIONS: BLIND RUN

J.O. 3144 FILE
CHART: BASIS WT. PROFILE
MATERIAL: 16 PT. FOODBOARD
BASIS WT.: 62 LBS/1000 SQ. FT.
SPEED: 749 FT./MIN.
CONDITIONS: W/AccuRay BW CONTROL

J.O. 3144 FILE
CHART: SIZE PRESS MOISTURE PROFILE
MATERIAL: 16 PT. FOODBOARD
BASIS WT.: 62 LBS./1000 SQ. FT.
SPEED: 723 FT./MIN.
CONDITIONS: BLIND RUN

J.O. 3144 FILE
CHART: SIZE PRESS MOISTURE
MATERIAL: 16 PT. FOODBOARD
BASIS WT.: 62 LBS./1000 SQ. FT.
SPEED: 798 FT./MIN.
CONDITIONS: WITH DRY END AccuRay BW AND MOISTRON SYST.

J.O. 3144 FILE
CHART: PRESS MOISTURE PROFILE
MATERIAL: 16 PT. FOODBOARD
BASIS WT.: 62 LBS/1000 SQ. FT.
SPEED: 723 FT./MIN.
CONDITIONS: BLIND RUN

J.O. 3144 FILE
CHART: PRESS MOISTURE PROFILE
MATERIAL: 16 PT. FOODBOARD
BASIS WT.: 62 LBS./1000 SQ. FT.
SPEED: 928 FT./MIN.
CONDITIONS: WITH WaterBalance® SYSTEM

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Figure 4. Dramatic improvements possible with process control and tuning. Chart on the left shows a blind run before process control; chart on the right is after process control.

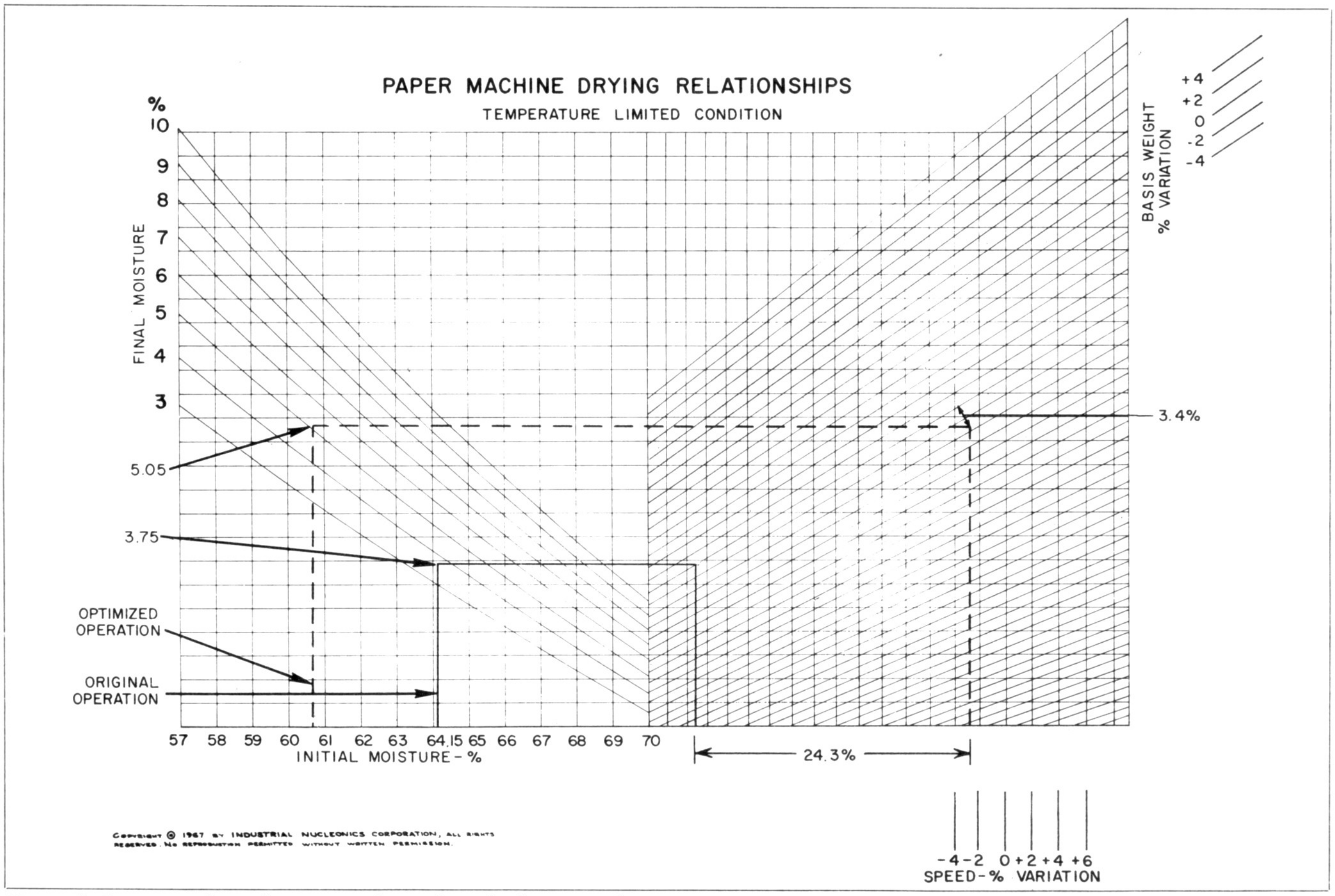

Figure 5. Paper machine drying graphs make calculation of dryer performance easier.

therefore, equation (1) becomes

$$M = \frac{-EKt}{F} + M_o \qquad (M > .25) \qquad (3)$$

For moisture less than 25%, the curve is exponential (in Cartesian coordinates,

$$\frac{dy}{dx} = -\mu y)$$

$$\frac{dM}{dt} = -\mu M \qquad (4)$$

$$\mu = \text{constant}$$

To evaluate "μ," consider the condition that the slope of equation (3) must equal equation (4) @ $M = .25$, therefore:

$$\frac{-EK}{F} = -\mu M \qquad (@\ M = .25) \qquad (5)$$

or

$$\mu = \frac{EK}{(.25)F} \qquad (6)$$

Then substituting equation (6) in equation (4) and integrating

$$\frac{dM}{dt} = \frac{-EKM}{(.25)F} \qquad (\text{for } M < .25) \qquad (7)$$

or

$$\ln(M) = \frac{-EKt}{(.25)F} + a \qquad (7)$$

$$a = \text{constant of integration}$$

To evaluate "a," consider the condition that the same value of "M" and "t" must satisfy both equation (7) and equation (3), @ $M = .25$.

From equation (3), @ $M = .25$

$$t = \frac{F}{EK}(M_o - .25) \qquad (8)$$

From equation (7), @ $M = .25$

$$t = \frac{(.25)F}{EK}[a - \ln(.25)] \qquad (9)$$

Equating equation (8) and equation (9)

$$\frac{F}{EK}(M_o - .25) = \frac{(.25)F}{EK}[a - \ln(.25)] \qquad (10)$$

Solving equation (10) for "a"

$$a = \frac{1}{.25}(M_o - .25) + \ln(.25) \qquad (11)$$

substituting in equation (7)

$$\ln M = \frac{-EKt}{(.25)F} + \frac{1}{25}(M_o - .25) + \ln(.25)$$

Or

$$\ln\left(\frac{M}{.25}\right) = \frac{1}{.25}\left[M_o - .25 - \frac{EKt}{F}\right] \qquad (12)$$

for $(M < .25)$

To review, the equation for the curve in figure 1 is given by the following two expressions:

for $M > .25$,

$$M = \frac{-EKt}{F} + M_o \qquad (3)$$

for $M < .25$,

$$\ln\left(\frac{M}{.25}\right) = \frac{1}{.25}\left[M_o - .25 - \frac{EKt}{F}\right] \qquad (12)$$

M = moisture content in pounds of water/pound fiber
M_o = initial value of "M" (when $t = o$)
t = drying time in minutes
E = evaporation rate in pounds of water/square foot/minute
K = ream size in square foot/ream
F = fiber weight in pounds/ream

To develop the temperature limited graph (figure 3), it should be pointed out that only final moistures of less than 25% will be considered and hence equation (12) will be used. Second, drying time (t) is of concern only in that paper velocity is variable and hence it will be replaced by the speed variable (v) and the length (L) where

$v = L/t$
v = paper speed in feet/minute
L = dryer section sheet length in feet

Then equation (12) becomes

$$\ln\left(\frac{M}{.25}\right) = \frac{1}{.25}\left[M_o - .25 - \frac{EKL}{Fv}\right] \qquad (13)$$

If moisture "P" is defined in terms of pounds water/pound paper, it follows that,

$$M = \frac{P}{1 - P}$$

Then equation (13) becomes

$$\ln\left[\frac{P}{.25(1 - P)}\right] = \frac{1}{.25}\left[\frac{P_o}{(1 - P_o)} - .25\frac{-EKL}{Fv}\right] \qquad (14)$$

Last, if basis weight (B) is defined in terms of pounds paper/ream, it follows that $F = B(1 - P)$

and equation (14) becomes

$$\ln\left[\frac{P}{.25(1 - P)}\right] = \frac{1}{.25}\left[\frac{P_o}{(1 - P_o)} - .25\frac{-EKL}{Bv(1 - P)}\right] \qquad (15)$$

Rearranging terms of equation (15) to allow plotting in figure 3

$$\frac{Bv}{EKL} = \frac{\left(\frac{1}{1 - P}\right)}{\left(\frac{P_o}{1 - P_o}\right) - .25 - .25\left[\ln\frac{P}{.25(1 - P)}\right]} \qquad (16)$$

Where

B is basis weight
E is evaporation rate
v is paper speed
P_o is initial moisture
P is chosen to be final moisture

□

References

[1] Montgomery, A. E., "Variation of Drying Rates of Individual Dryers Through the Dryer Section," *Tappi* 37, Jan., 1954.
[2] Perry, *Chemical Engineers Handbook*, Fourth Edition, 1963.
[3] *Pulp & Paper Manufacturing*, Vol. III, 1955, pp. 357-367.