Effects of machine speed on formation, drainage, and retention

Joseph Marton

Wet-end control must be improved if the industry is to increase the productivity of its high-speed paper machines.

Machine speed is the most prominent of the many factors that affect the productivity of a paper machine. Maximum machine speed doubled every 20 years during the modern era of papermaking, but this progress was sharply accelerated after the Second World War. **Figure 1** shows the rate of speed development since 1900 (*1*). By 1980, maximum speed exceeded 1000 m/min (3300 ft/min) on newsprint machines and reached 750 m/min (2500 ft/min) on fine paper machines. **Table I** indicates average maximum speed in 1985, growth rate of speed between 1950 and 1980, and expected maximum speed by 1990. Reality has already surpassed the predictions. The projected speed of the No. 11 newsprint machine in Kvarnsveden will be over 1300 m/min (almost 4500 ft/min).

Major contributors to this relentless progress include mechanical developments, improved headbox design, improvements in processing technology and control, more efficient drainage devices, and innovations such as two-sided drainage. The rate of speed increase is often restricted, however temporarily, by limitations in water removal, by the market pressure to increase or at least maintain quality, and by the usual side effects of speed increase, such as deteriorating formation and decreased machine availability caused by an increase in the number of web breaks and other process disturbances (e.g., deposition). Experience indicates that ingenuity always overcomes these hurdles.

An increase in machine speed enhances two major factors affecting sheet formation, namely turbulence and shear. These, in turn, influence fiber dispersion and flocculation. This paper examines the effects of increased machine speed on drainage, formation, and retention. The focus of this discussion is the interplay of the hydrodynamic and chemical factors associated with the various mechanical developments on the wet end that have been introduced in pursuit of higher machine speeds and greater productivity.

Figure 2 shows how machine width and speed affect production costs (*1*). In the search for higher productivity, machine builders have already reached the economically justifiable limit of machine width (around 10 m). The limit for machine speed, however, is still out of sight, and that is why a discussion on the effects of speed on drainage, retention, and paper quality is always timely and justified.

Marton, a consultant and an adjunct professor at SUNY-ESF (Syracuse, N.Y.), lives at 10705 Meadowhill Road, Silver Spring, Md. 20901.

Formation and fiber flocculation

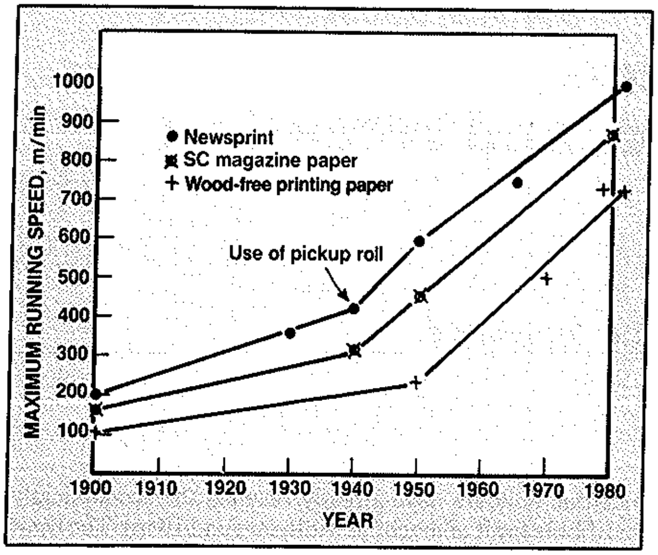
Higher machine speeds usually increase turbulence and shear, both of which play an important role in keeping fibers dispersed. Turbulence denotes the presence of irregular eddy currents in which the forces responsible for momentum and material transfer are randomly oriented. Turbulence facilitates an isotropic distribution of fibers in the forming web. The intensity and scale of turbulence are dependent both on flow velocity and machine design characteristics; the magnitude of the effects also depends on the flow regime.

At rather low fluid velocities, Jokinen and Ebeling (*2*) observed only a 25% decrease in flocculation after a fourfold increase in velocity. In turbulent flow, flocs of substantial strength can form in the course of mechanical flocculation, and floc size diminishes with increasing flow velocity (*3*). This latter concept of reducing floc size with high-intensity turbulence has found widespread use in headbox design. However, high-turbulence headboxes also are prone to produce a sheet with grainy formation. In the headbox, eddy currents create the turbulence; on the wire, turbulence is achieved through the upward pressure pulses generated by the drainage devices.

Turbulence generally improves paper formation by reducing floc size. The resultant floc strength determines the level of shear needed to attain and maintain floc dispersion. Local variations in fluid velocity generate the shear forces, which are unidirectional. An increase in machine speed always increases shear.

Figure 3 shows the effect of various wet-end components on shear in a high-speed (2500 ft/min) machine system (*4*). The highest shear stresses on the fiber wall develop in the fan pump and on the pressure screen. Shear stress nearly doubles when machine speed doubles. Figure 3 also shows that the dynamic drainage jar (DDJ) of Britt and Unbehend (*5*) provides a better simulation of the shear conditions on a high-speed machine than the traditional drainage testers.

1. Development of maximum machine speed for newsprint, supercalendered magazine, and wood-free printing grades, 1900–1980 (*1*)



I. Machine speeds for three paper grades

	Present maximum running speed, m/min	Speed growth rate 1950-1980, %/year	Estimated maximum running speed in 1990, m/min
Newsprint	1100 - 1200	2 - 2.5	1250 - 1300
Supercalendered magazine paper	850 - 950	2 - 2.5	1050 - 1100
Wood-free printing paper	750 - 850	3 - 3.5	950 - 1000

Source: JAAKKO POYRY estimates (1).

Both turbulence and shear decay swiftly. The rate of decay depends inversely on the scale of variation in fluid velocity. The old rectifier-roll headbox generated large-scale turbulence and formed large flocs that could travel all the way to the wet line on the wire. Small-scale shear and microturbulence in hydraulic headboxes disperse the fiber flocs, but the forces decay within a few centimeters of travel down the table.

The development of dewatering elements and the setup of the fourdrinier table were directly influenced by increasing machine speeds. Cross-machine direction (CD) shake was a satisfactory tool for redispersing the flocs on slower (≤ 500 ft/min) machines. On faster machines (≤ 1300 ft/min), table rolls assured higher-intensity and larger-scale turbulence. At higher speeds, however, it became difficult to control stock activity (jumping) with table rolls.

Foils, invented by Burkhard and Wrist in the 1950s, allow a gentler vacuum action but increase the danger of sheet sealing if the turbulence is too low. The scale and intensity of turbulence on the foils also increase with machine speed. At machine speeds exceeding 2000 ft/min, the control of turbulence becomes difficult and formation starts to deteriorate. Kallmes (*6*) recommends a turbulence-free environment and proposes pure shear formation by using serrated slice and forming showers together with proprietarily designed, rather quiet foils. Paper machine speeds were increased further by revolutionary developments in dewatering brought about by the emergence of twin-wire and hybrid top-wire formers. In top formers, the bottom half of the sheet is formed on standard foil blades. The stock-web sandwich is then subjected to a strong, fine-scale, machine-direction (MD) shear force in the entrance nip of the top former. This high-intensity shear redisperses the remaining stock suspension, which improves formation. Top-wire machines consistently show formation improvements after conversion. Roll formers usually exhibit relatively higher first-pass retention than stationary blade formers; the latter provide better small-scale turbulence and somewhat better formation (*7*).

Control of flocculation/deflocculation and improvement of formation on modern high-speed machines is mainly in the hands of the machine designers. The wet-end chemist also has some tools to influence the formation of web structure, although to a lesser extent. Chemical additives are being used increasingly to speed up existing machines in lieu of mechanical modifications. One can apply, for instance, deflocculating agents (very-high-molecular-weight gums or anionic polyacrylamide resins (PAM)) to lubricate the fibers. The recent introduction of network-forming dual-component additives shows promising results in creation of a uniformly small floc structure (*8*). The use of these additives is examined in greater detail in our discussion of dewatering and retention.

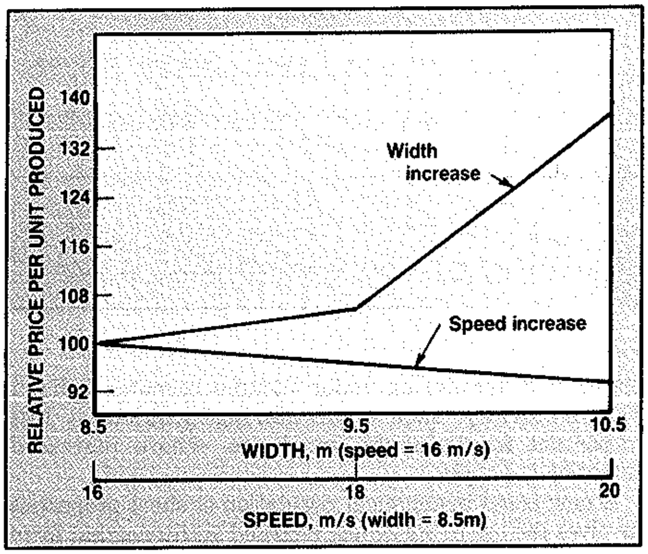
Drainage

An increase in machine speed mandates improvements in water removal at the limiting sections of the machine. In the forming section of older and slower machines, table rolls drain off most of the water. The application of table rolls is limited at higher speeds by the possibility of stock jumping and deteriorating formation (*9*). The water-removal capacity (Q) of a table roll is (a) proportional to roll diameter (D) and some function of velocity (V^m, where $0.2 < m < 2$ for different pulps) and (b) inversely proportional to the square of specific filtration resistance (R_0).

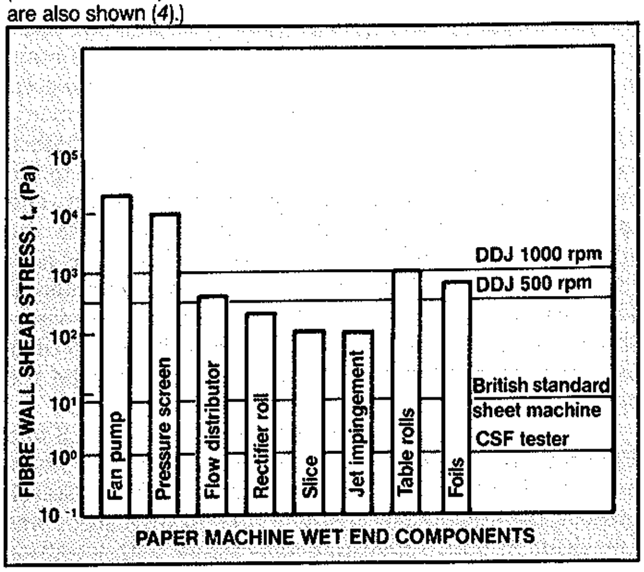
$$Q = D \cdot V^m / R_0^2 \quad (1)$$

The vacuum action increases with the square of velocity. At speeds exceeding 2800 ft/min, pressure reduction would equal 1 atm and water would boil. Even at lower speeds, the table rolls generate strong pressure waves and pull water so hard that a large portion of fillers and fines is removed from the wire side of the sheet. A foil creates a milder vacuum action that is about half as strong. Modern machines are equipped with simple or complex foils and a series of low- and high-vacuum wet-suction boxes. Optimum water management on single-wire machines was discussed recently by Hansen (*9*), and the

2. Relative price of paper machine per production unit as a function of machine width and speed (Data are based on 100% utilization of capacity on a machine producing 45-g/m² newsprint (*1*).)



3. Maximum shear stresses on the fiber walls for various wet-end components of a paper machine operating at 2500 ft/min (760 m/min) (Shear stresses produced in some commonly used laboratory testers are also shown (*4*).)



important role of forming fabrics was discussed by Lewyta (*10*) and Johnson (*11*). While a single-wire fourdrinier is still the choice of most producers of filled thin papers, hybrid formers are increasingly installed to increase dewatering on offset papers and board.

Twin-wire formers are the most efficient design for water removal on tissue, newsprint, and linerboard machines, with a potential four-fold increase in dewatering capacity. However, a certain weakness can develop in the center of the final sheet, and retention is reduced because of the decreased filtration thickness on only half of the sheet (*12*).

An important consequence of two-sided drainage is the improved distribution of filler and fines in the sheet. Ash content in the top side decreases, while ash on the wire side increases (*13*). This affects surface strength and makes linting and vessel-segment picking more uniform on both sides. The sheet becomes, in all properties, less two-sided and generally prints better.

Retention

Retention of fillers and fines is a result of multiple process steps proceeding mainly in the headbox and on the wire. Pertinent events also occur back in the stock-preparation stage, where the chemical environment is established.

Increasing machine speed usually decreases retention unless proper countermeasures are taken. Higher speed increases the dispersing action of shear and turbulence. Depending on the hydrodynamics and the applied retention aids, the shear resistance and dispersability of the flocs and aggregates can vary over a wide range. Floc size and floc strength are mostly influenced by the acting hydrodynamic forces, but colloidal and chemical forces also can make significant contributions to the flocculation-deflocculation-reflocculation steps.

Selective shear flocculation is the primary mechanism for deposition and retention of small particles on the fibers in the headbox, according to van de Ven and Mason (*14*). Under high-shear conditions, the nearly equally sized filler-filler or fiber-fiber particles do not flocculate readily, while two particles of different size form a stable pair, with the small particle orbiting the large one at least until high shear is sustained. After the shear has ceased, high-molecular-weight, long-chain-length polymers are needed to stabilize the fiber-particle pairs by bridge formation. In this picture of headbox retention mechanism, colloidal and ionic forces (electrostatic repulsion/attraction, van der Waals forces, and zeta potential) play a subordinate role. Retention suffers if the shear force exceeds a critical limit (1-10 nN), where C-C bonds in polymers can rupture or the force of attraction between particle and fiber is disturbed. Shear forces existing in the headbox or in its approach system are comparable with these rupture forces (*15*). The bonds between particles of equal size are more easily broken than bonds between particles of unequal size. Hence, high shear in the headbox favors heterocoagulation over homocoagulation. Filler particles must be attached to the fibers right in the headbox to attain efficient filler retention (*14*).

Van de Ven extended his theory to include retention of particles on the wire (*16*). Small, still-dispersed filler particles (<10μm diam.) are not retained in the fiber mat during drainage. The larger pulp fines can be captured in the pores of the fibrous web, with a deposition rate ranging from a few to 100%.

According to this view, the success of filler retention on high-speed machines is predetermined by the hydrodynamics of the headbox and the efficiency of the applied bridging polymer. However, experiments with small rosin-size particulates indicate that colloidal and chemical interactions that precede the headbox also can play a significant role in the attachment of small particles to fiber (*17*).

The rosin-size retention experiments were carried out in a DDJ, where no filter pad is formed during high-shear stirring. Thus, filtration contributions can be excluded. Two commercial rosin sizes—a dispersed rosin acid emulsion and a fully saponified liquid rosin soap size—were used at two stirrer speeds (400 rpm and 1000 rpm). As sizing agents, 1% size and 2% alum were added in reverse order to fractionated coarse hardwood fiber. The chemical environment and the contribution to the electrostatic attractive or repulsive forces were adjusted by applying alum and cationic starch and by increasing the pH. After 10 min of high-speed stirring, the fiber fraction was separated and the amount of attached rosin determined. Selected data (*17*) are presented in **Table II.**

In this first step of simulated sizing, the small anionic particles of dispersed size attach themselves, through a cationic mediator, by electrostatic attractive force to the anionic active centers of the fiber surface. Alum, and specifically the applied cationic starch, promote the attraction, while higher pH enhances ionization of both rosin and fiber COOH groups and increases the repulsion. The data show that increasing shear rate may promote either detachment and dispersion or attachment to fiber by shear coagulation and deposition, depending on the balance of the opposing forces.

In the presence of 0.3% cationic starch at pH 4.8 and 1000 rpm, the portion of size that remained on the fibers increased to almost 80% of the size applied. With no starch present, the attachment of size to fiber at high shear was cut about in half, suggesting that sizing with emulsion rosin sizes at high machine speed may require a cationic promoter in addition to alum. Increased pH enhances the contribution to repulsive ionic forces and reduces the attachment of rosin. Reduction of shear rate at 400 rpm showed a beneficial final effect by decreasing detachment and increasing shear deposition only in the poorly balanced sizing system without cationic starch. In the presence of starch, the effects are reversed.

Soap size and alum form small-particle-size, cationic, aluminum–rosinate complexes that do not require additional cationic promoters to adhere to the anionic fibers. The deteriorating effect of a pH increase is more dramatic because of the strong ionization of the aluminum–rosinate complex.

In fine paper furnishes with high filler and fines content, the situation becomes more complicated. The high-surface-area particulates accumulate a considerable portion of the added chemicals, and the final sizing efficiency depends both on the degree of size attachment and on the efficiency of retention of the size-loaded fillers and fines on the wire.

The complex nature of reactions necessitates better and more fundamental knowledge on the formation and behavior of flocs, on their redispersability, and of the colloid and surface chemistry involved both in hetero- and homo-flocculation of fibers and filler/fines particles. Many papers have been published on flocculation since the appearance of Robertson and Mason's work in the mid 1950s (*18*), and numerous instruments have been constructed to carry out these studies. An ingenious laser optical instrument was developed (*19*) for estimating and characterizing fiber flocculation on-line in a side stream of the paper machine. Britt and Unbehend also devised a rather simple laboratory test for redispersability of flocs (*5*) by measuring the effect of additives on retention of fines at two stirrer speeds in a DDJ. These and other pertinent studies indicate that floc strength and fines retention increase in the order: alum $<$ polyethyleneimine $<$ cationic starch $<$ PAM $\leq$ dual polymer system.

Successive application of two unlike-charged polymers (polyelectrolytes), such as cationic starch and anionic PAM, creates tenacious flocs and assures good retention even under high shear. However, the flocs usually are large and formation suffers. Additionally, the web becomes too porous and dewatering under vacuum becomes difficult (*20*). Naturally, such a dewatering problem is less important for twin-wire machines, where increased retention is sought.

II. Retention of rosin size on papermaking fibers*

	pH	Cationic starch, charge	Applied size recovered from fibers, % 400 rpm	1000 rpm
Dispersed size	4.8	-	59	43
	4.8	+	69	78
	5.8	+	...	57
Liquid soap size	4.6	-	...	68
	4.6	+	...	73
	5.8	-	...	16

*Dynamic drainage jar, 2% alum, 1% size, 0.3% starch, reverse addition (17).

A new trend in chemical regulation of sheet properties involves the use of oppositely charged additives that form easily reversible flocs that can engage in network formation (*21*). Two such additive systems are already in commercial use. One system (*22*) recommends addition first of a good film-forming and high-molecular-weight cationic potato starch before the stock-chest, and introduction of a colloidal anionic SiO_2 sol later, just before the headbox. In the other system (*8*), a combination of cationic PAM and bentonite (montmorillonite) is used. It is claimed that in this "superflocculation" process, reversible microflocs create a dynamic interconnected structure with high permeability, which assures retention, favors dewatering, and enhances formation. The initial experiences are promising, but the cost of chemicals is rather high. Nonetheless, further increases in machine speed will require chemical fine-tuning of the wet end.

Disturbances

An increase in the speed of a paper machine often creates undesirable side effects that reduce the machine's availability.

Web breaks

One major problem on high-speed machines is an increase in the number of web breaks. Web breaks frequently occur on paper machines with open draws. Since a paper machine is a constant draw and not a constant-tension device, the web must withstand the generated tension to counter the adhesion forces and other effects required to strip the wet web from a roll (*23*).

The stripping force (S) is related to the work of adhesion (W) and web speed (V), as seen in Eq. 2 (*24*):

$$S = W / (1 - \cos\phi) + m V^2 \qquad (2)$$

where

S = tension in the paper required to strip it from the surface, g/cm

W = work required to overcome the web-to-surface adhesion, erg/cm²

V = web speed or speed of stripping, cm/s

ϕ = web's take-off angle from the roll

m = wet web mass, g.

At high speeds, W becomes independent of speed, and the second term dominates. Examples with couch solids at 20% for 30 lb/3000 ft² newsprint production at 1800 ft/min are provided in the literature (*23*). The expression mV^2 is 25 N/m, whereas W is around 3–9 N/m, depending on ϕ at the couch. Thus, adhesion force adds only 11–26% to the total tension.

As water is removed in the press, the mass of the wet web (m) is reduced. At the same time, the work of stripping (W) increases. After the third press, the sheet reaches 40% consistency, mV^2 = 12.5 N/m, and W = 18 N/m. Thus, the adhesion contribution starts to dominate (60% of the total stripping force). Press picking and load-elongation properties of the stock influence the outcome. At any rate, the mV^2 term strongly increases with machine speed, and the danger of wet web breaks increases unless proper countermeasures are taken.

Deposition

Another frequent disturbance in the paper machine system is the deposition of suspended impurities. These impurities include inorganic material, wood extractives, hydrophobes derived from sizing and defoamers, and recycled latex. It is not generally recognized that deposition of the suspended impurities, especially hydrophobes, is promoted by shear coagulation. Shear is a simple function of machine speed, as seen in the conventional hydrodynamic expression of fluid shear rate,

$$\dot{\gamma} \simeq U^n / d \tag{3}$$

where

U = linear velocity profile (n = 0.5–1)

d = gap between the two parallel surfaces in relative motion.

Increasing the machine speed or the proximity of the surfaces (to each other) increases the danger of shear coagulation.

Papermakers usually combat pitch with alum. It is understandable that alum is also the main tool used against white pitch, which is a deposit of latex and other hydrophobes (*25, 26*). An earlier investigation of white pitch formation (*27*) indicated that the chemical environment (alum, cationics) can sensitize the recycled and resolubilized latexes of polyvinyl acetate or styrene-butadiene and that high shear coagulates them. Earlier, the use of table rolls in slower machines, the high turbulence and water flow, wider gap, and lower shear prevented deposition of white pitch under the wire. Under such conditions, the depositable materials tended to attach themselves to the less-turbulent areas on the machine, such as in the presses or on drier drums.

On fast machines (≥ 1500 ft/min), foils are substituted for table rolls. The gap between fabric and blades is usually smaller, with a consequent increase in shear that enhances coagulation and deposition of the dissolved latex, especially if the white water chemistry further sensitizes it. The usually applied polyethylene strips on foils are poorly wetted, and their mutually hydrophobic nature promotes pitch accumulation on the blades and on the Uhle boxes. Deposition can be alleviated by modifying latex composition, substituting high-surface-energy ceramic blades, switching to a better fabric design, and effective con of wet-end chemistry.

It is safe to predict that these and other shear-rela problems will occur with more frequency as mach speeds are increased. We can increase the availability a productivity of our high-speed paper machines throu better control of wet-end operations. This can be achie by increasing the use of on-line instrumentation and thoroughly understanding the chemical and physi reactions that take place in the wet end.

Literature cited

1. Poyry, J.,A Review on the Future of Paper, Jaakko Poy Oy, Helsinki, 1984, p. 127.
2. Jokinen, O. and Ebeling, K., Paperi Puu 66(5): 317(1985).
3. Kerekes, R.J., J. Pulp Paper Sci. 9(7): TR68(1983).
4. Tam Doo, P.A., Kerekes, R. J., and Pelton, R. H., J. Pulp Pape Sci. 10(7): J80(1984).
5. Britt, K.W. and Unbehend, J. E., Tappi 63(4): 67(1980).
6. Kallmes, O. J. and Radcliffe, J. P., 1987 Papermaker Conference Proceedings, TAPPI PRESS, Atlanta, p. 211.
7. Sinkey, D. and Wahren, D., IPC Publication No. 18C Appleton, Wis., June 1986.
8. Langley, J. G. and Litchfield, E., 1986 Papermaker: Conference Proceedings, TAPPI PRESS, Atlanta, p. 89.
9. Hansen, V. E., 1985 Wet End Operations Seminar Proceed- ings, TAPPI PRESS, Atlanta, p. 1.
10. Lewyta, J., 1987 Papermakers Conference Proceedings, TAPPI PRESS, Atlanta, p. 337.
11. Johnson, D. B., Pulp Paper Can. 87(5) T185(1986).
12. Ebeling, K., Paperi Puu 65(3): 173(1984).
13. Marton, J., Das Papier 35(10A): V38(1981).
14. van de Ven, T.G.M. and Mason, S. G., Tappi 64(9): 171(1981).
15. Pelton, R. H., Tappi J. 67(9): 116(1984).
16. van de Ven, T.G.M., Pulp Paper Can. 85(3): T58(1984).
17. Marton, J. and Kurrle, F.L., J. Pulp Paper Sci. 13(1): J5(1987); and 1985 Papermakers Conference Proceedings, TAPPI PRESS, Atlanta, p. 197.
18. Robertson, A.A. and Mason, S. G., Pulp Paper Mag. Can. 55: 263(1954).
19. Linhard, F., Horn, D., Eisenlauer, J. and Hemel, R., Wochbl. Papierfabr. 115(8): 33(1987).
20. Britt, K. W. and Unbehend, J. E., 1986 Papermakers Conference Proceedings, TAPPI PRESS, Atlanta, p. 129.
21. Lindstrom, T., Svensk Papperstid. 90(1): 24(1987).
22. Moberg, K., PIMA (9): 24(1985).
23. Rutland, D. F., Jones, A.Y., Shallhorn, P.M., Tichy, J. and Karnis, A., Pulp Paper Can. 78(4): T99(1977).
24. Mardon, J., Appita 15(1): 14(1961).
25. Schalin, O. and Palsanen, J., Wochbl. Papierfabr. 109(11): 407(1981).
26. Laufman, M., Wochbl. Papierfabr. 115(9): 371(1987).
27. Marton, J., Huang, D.K., *et al.*, Binder Performance in Coated Paper, Report TPR-77, TAPPI PRESS, Atlanta, 1979.

The generous permission of Jaakko Poyry to reproduce two of the figures and one table from Reference 1 is gratefully acknowledged.

Received for review Oct. 2, 1987.

Accepted Nov. 12, 1987.

Presented at the 1988 Papermakers Conference.