THE DEVELOPMENT OF PRINT DENSITY AND PRINT THROUGH IN NEWSPRINT

J.H. De Grâce and J.E. Dalphond*

ABSTRACT

Samples of the same newsprint were calendered to different roughnesses and porosities. Solid images were printed under constant press conditions with different amounts of a non-drying, oil-based ink. Print density decreased with increasing roughness and porosity. The reduction was caused by the non-uniform thickness of the ink film as it filled the surface depressions of the paper, and by the distribution of pigment in the z-direction of the paper. The condition worsened as vehicle oil penetrated further into the sheet. More ink was required by the rougher sample to attain the same print density as the smooth sample. Therefore, more pores were filled by vehicle oil and the rough sample suffered a greater loss of sheet opacity, and had a higher print through. Extraction of the vehicle oil from the prints showed that oil penetration caused over 60% of the print through of the samples. Print through first decreased with time, then increased, and finally decreased again due to sheet compression and recovery during and after printing, and to the penetration and redistribution of vehicle oil in the sheet. The literature on the effects of the structural properties of newsprint on the optical properties of solid prints is examined.

INTRODUCTION

Two properties often used to describe print quality are print density (PD) and print through (PT). For any paper, a high PD achieved with the lowest amount of ink and with minimal PT is desirable.

Much research has been done on the factors that affect the optical properties of prints. The present work provides further insights into how the structural properties of

---

*Pulp and Paper Research Institute of Canada newsprint affect the optical properties of images printed with non-drying, oil-based inks. Print density and print through values were measured just after the moment of printing, and the development of these properties with increasing amounts of transferred ink was followed. The changes in PD and PT that occur through post-nip ink penetration were monitored over a period of time after printing. Finally, the relative contributions of the ink pigment and of the vehicle oil to PD and PT were examined and related to the structural properties of the samples.

CONCEPTS

INK TRANSFER

Newsprint is compressed as it passes through a printing nip (Watanabe and Amari, 1982). This results in a temporary smoothening of the surface, and in a temporary reduction of the average size of the fibre interstices (pores) of the sheet, in and after the nip. In the nip, ink on the printing plate comes into contact with the surface of the paper, and is partially hydraulically impressed into the pores near the surface. As the sheet emerges from the nip, the non-impressed ink film splits between the plate and the surface of the paper. Simultaneously, ink penetrates into the paper through aspiration as the sheet recovers from its compressed state and the pores enlarge to their original size.

During sheet compression in the nip, the thickness of the ink film on the printing plate required to contact and transfer to all of the exposed fibre surface depends on the smoothness of the surface contour - the printing roughness - while the compressed pores determine in great part the amount of ink that is hydraulically impressed into the paper - the printing porosity. A rough surface leads to over-inking in the low areas and in a non-uniform thickness of the transferred ink film. This situation has an adverse effect on the optical properties of the print (Weidenmuller, 1975).

INK DISTRIBUTION

Ink pigment and vehicle both penetrate the sheet together in the nip (Levlin and Nordman, 1967). After printing, ink is drawn from the surface until the pores have regained their original dimensions. With non-drying inks, penetration continues through capillary action. The liquid vehicle that is not retained by the capillaries formed between the solid pigment particles (Fetsko and Zettlemoyer, 1962), or that does not adhere to the fibres, is drawn away from large ink-saturated paper pores by the stronger capillary forces of smaller pores (Tollenaar, 1953) and of the fine capillary system formed by the fines fraction in the paper. The depth of ink penetration is generally non-uniform due to the effects of paper formation (Madsen and Aneliunas, 1968). Further, pigment particles tend to be left behind as the vehicle continues to penetrate into the sheet (Coupe and Smith, 1956). As a result, the ink pigment and the vehicle are usually distributed differently in the sheet.

For a given ink, the porosity of the non-compressed sheet largely determines both the amount of ink that remains at the surface - the ink holdout of the paper - and the depth of penetration and distribution of ink components within the sheet.

MODIFICATION OF INK AND PAPER OPTICAL PROPERTIES

Opacity of the ink layer and print density

Print density (PD) is measured as the reduction in the amount of light that is reflected back from the image, due to the absorption of light by the ink. (By definition, the lower the reflectance, the higher the print density.) This depends upon the extent to which ink covers the surface of the paper and on the opacity of the ink film. Incomplete coverage of solid image areas on the paper by ink produces a speckled print, and also reduces the average PD value. Full optical coverage (OC) (equation 4, Experimental) is achieved when there is sufficient pigment to cover the entire image and to make the ink film continuously opaque.

For a given amount of pigment, the opacity of the ink layer is a function of the three dimensional distribution of pigment particles within the paper. Ideally, the pigment should be distributed uniformly over the paper surface without any penetration into the pores of the sheet.

A layer of pigment of uneven thickness is less efficient than a uniform layer of the same quantity of pigment in optically covering a substrate (Fetsko and Zettlemoyer, 1962, and Ruckdeschel, 1978). The uniformity of pigment distribution depends on the roughness of the uncompressed sheet. During post-nip penetration, sheet formation controls the uniformity of ink vehicle drainage from the paper surface into the pores, and this also affects the evenness of the ink film remaining on the surface. Furthermore, continued vehicle drainage also causes the remaining pigment layer to follow the surface contour of the paper more closely, further reducing the smoothness of the ink film itself.

As ink penetrates into the sheet, some of the light-scattering interfaces at the paper surface are recovered. Some pigment particles are also carried along with the vehicle, reducing their concentration at the surface. This results in further decreases in the optical density of the ink film (Lin and Kan, 1970). Figure 1 shows the PD values for different amounts of ink transferred to a smooth, non-porous plastic sheet and to a relatively rough, porous sheet of newsprint. The maximum equilibrium PD value obtained for the plastic after full ink coverage (O.C. = 98.7%) shows the actual tinctorial strength of the ink as the maximum optical density of 2.35 is approached. The PD curve for the newsprint illustrates the combined effects of sheet roughness and porosity on reducing the tinctorial strength of the ink.

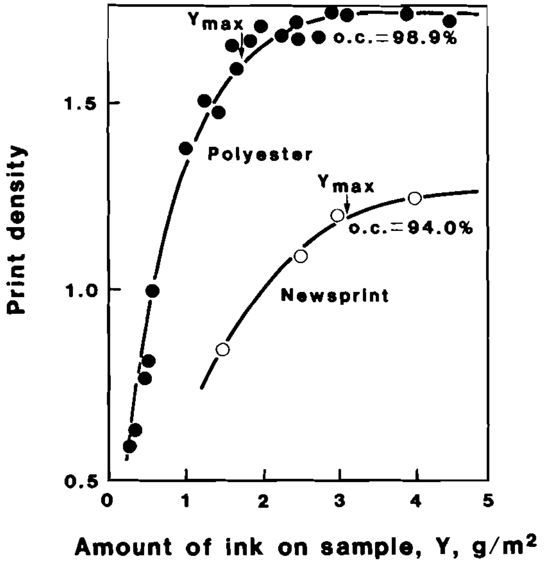

Figure 1. The difference between print density for a smooth, non-porous plastic sheet (polyester), and for a relatively rough, porous sheet of newsprint illustrates the adverse effects of roughness and porosity on the tinctorial strength of the ink.

All of these events combine to decrease the average gloss and optical density of the printed area, while local variations in the value of these properties produce a mottling in the print.

Opacity of the paper and print through

The opacity of a sheet of paper largely determines the degree of visibility of a printed image on the reverse side of the sheet. Print through is the property most commonly used to describe newsprint quality.[1] It is measured as the undesired reduction in the original reflectivity of the paper on the reverse side of the print. Three additive components contribute to PT of non-drying, oil-based inks (Larsson and Trollsas, 1973):

If the ink film remains on the paper surface without penetrating, PT depends on:

1. The optical density of the print, and the intrinsic opacity of the paper, or direct show through. Under those conditions, this basic PT component is also the least PT value possible.

When the ink penetrates into the sheet, further increases in PT occur due to two additional components:

2. The penetration of pigment into the pores of the sheet.

3. With non-drying, oil-based vehicles, there is a loss in the opacity of the paper as a result of the separation of the vehicle oil from the pigment, and the further penetration of the oil into the pores of the sheet.

When the paper is illuminated on the reverse side of the print, light that is transmitted through the ink-free layer of the sheet reaches pores containing vehicle oil. When a pore that is sufficiently large to interact with the incident light (Roeher, 1966) is saturated with a liquid of the same refractive index as the fibres, the light-scattering air/fibre interfaces forming the pore are destroyed, and the

---

[1] The term direct show through, or simply show through, is used when a sheet of the same paper is placed over the print, or when the reverse side of a printed sheet where no ink has penetrated (e.g., a "Xerox" print) is observed. Show through depends on the optical density of the print and on the intrinsic opacity of the sheet. The more common term print show through, or simply print through (PT), is used when ink penetrates into part of the printed sheet thickness and the reverse side of that sheet is observed. The rarer term strike through is used when the ink physically penetrates to the other side of the sheet.

opacity of that part of the sheet is thereby reduced. More of the light is transmitted through this layer, eventually reaching the pigment-containing layer of the sheet. Part of the light is absorbed by the ink pigment in the pores and on the surface. Therefore, less light is reflected back from the paper on the reverse side of the print.

While opacity is a fundamental property of paper, it has been demonstrated (Pauler and Bristow, 1986) that opacity may not always be a good predictor of the print through of oil-based inks on filled papers. The present work also shows that the same may be true for a newsprint calendered to different average pore sizes even when light-scattering power and opacity have not changed.

EXPERIMENTAL

The samples were printed under constant press conditions and with a single ink. Only the amount of ink on the printing plate and the structural properties of the newsprints were varied.

The events that take place during the transfer of ink from the printing plate to the paper determine the initial values of print density (PD, equation 2) and of print through (PT, equation 3). Print density was measured 74 ms after printing and PT 86 ms after printing - the minimum interval after printing possible with our experimental setup (Appendix). Changes in PD and PT with time were monitored up to 72 hours after printing.

THE SUBSTRATES

Printing was done on samples of the same newsprint conventionally calendered in the Paprican laboratory calender to different roughnesses and porosities. Physical properties of the samples most related to their printing properties are shown in Table I.

INK TRANSFER CONDITIONS

Printing was done with a 4-color GFL rotary proof press and GFL SCAN standard testing ink. The ink, press, and the printing procedures have been described elsewhere (SCAN P35:72, 1972). Ink was transferred to the papers from a full tone solid image on a GFL phosphor-bronze plate at a nip pressure of 3.6 MPa, and at a printing speed of 4.6 $m.s^{-1}$. At that speed, the dwell time of the paper and

Table I

Paper Properties

Newsprint Sample	Basis Weight	Caliper	Parker Print-Surf		R_∞	R_o	Light Scattering Coefficient	LSC/unit thickness*	Printing Opacity
			Air Permeability	Roughness					
			P_{20}	S_{10}					
	$g.m^{-2}$	µm	$ml.min^{-1}$	µm			$cm^2.g^{-1}$	$µm^{-1}$	%
1	47.7	96	802	6.69	60.5	57.7	530	0.0263	96.0
2	47.7	67	358	3.31	59.3	56.6	516	0.0367	94.5

*LSC/unit thickness = light-scattering coefficient x basis weight/caliper.

ink in the printing nip was 0.97 ms. The amount of ink applied to the printing plate was varied between 0.5 and 15.0 $g.m^{-2}$. The ink transfer data were converted into fractional transfer values (FT, the amount of ink transferred to the paper, Y, divided by the initial amount of ink on the printing plate, X).

$$FT = Y/X \tag{1}$$

Curves were fitted to the pooled FT data obtained during the PD and PT experiments, using a modified version (Mangin, Lyne, Page and De Grâce, 1982) of the Walker-Fetsko ink transfer equation (Walker and Fetsko, 1955). The maximum fractional ink transfer values were then calculated for FT_{max}, X_{max}, and Y_{max}. The PD and PT values at FT_{max} (PD_{max} and PT_{max}) were then interpolated. The ink transfer properties of the samples at FT_{max} are shown in Table II.

PAPER OPTICAL PROPERTIES

The optical properties of the newsprint samples were determined from reflectance values obtained with an Elrepho photometer and a FMY-C visual efficiency filter (545 nm).

The light-scattering coefficients were calculated from the Kubelka-Munk equations. The printing opacity of the samples was calculated according to TAPPI T-519 os-78. The optical properties of the samples are shown in Table I.

PRINT OPTICAL PROPERTIES

The print density (PD) and print through (PT) values were calculated from reflectance values according to the SCAN standard P36:77:

$$PD = \log R_\infty/Rp \tag{2}$$

and,

$$PT = \log R_\infty'/Rp' \tag{3}$$

where,

R_∞ and R_∞' are the reflectance values for the blank paper on the printed side and on the reverse side respectively.

Table II

Printing Properties

Newsprint Sample	X_{max}	Y_{max}	FT_{max} Y_{max}/X_{max}	OC_{max}	PD_{max}	PT_{max}	$PT_{e\ max}$
1	10.64	6.56	0.62	93.5 (74 ms)	1.16 (74 ms)	0.102 (86 ms)	0.052 (3 s)
					1.08 (5 min)	0.108 (5 min)	-
					1.05 (24 h)	0.152 (24 h)	0.052 (72 h)
2	5.00	3.08	0.62	95.0 (74 ms)	1.16 (74 ms)	0.126 (86 ms)	0.043 (3 s)
					1.03 (5 min)	0.108 (5 min)	-
					1.00 (24 h)	0.134 (24 h)	0.043 (72 h)

( ) Time after printing.

Rp and Rp' are the reflectance values of the solid print on the printed side and on the reverse side of the print respectively.

The optical coverage (OC) values of the samples were calculated from (De Grâce and Mangin, 1984):

$$OC = 1 - [(Rp - Ri)/(R_\infty - Ri)] \quad (4)$$

where Ri is the reflectance value of a thick layer of the same ink. The Ri value for a thick film of GFL ink is 0.0045 (optical density, OD = 2.35).

The on-press measurements of Rp, and Rp', were made with a MacBeth on-line densitometer with a 536 nm filter. The setup and the time schedule for the measurements are shown in the Appendix. The differences in reflectance values between the MacBeth and the Elrepho were found to be negligible. The effects of the different backgrounds used during the measurement of Rp and Rp' were negligible when the printed ink film was opaque.

The optical properties of the prints at FT_{max} are shown in Table II.

THE CONTRIBUTIONS OF INK PIGMENT AND VEHICLE OIL TO PRINT THROUGH

Two additional sets of prints were made under the same conditions as described above. These prints were extracted with petroleum ether (Larsson and Trollsas, 1973) to remove the vehicle oil. One set was extracted 3 seconds after printing, and the other set was extracted 72 hours after printing. No pigment particles were detected in the extract. Therefore, it was concluded that there was no significant displacement or loss of pigment due to the extraction process. The reflectance values of the reverse side of the oil-free prints (Rp'_e) were measured, and the print through values (PT_e) were calculated in the same way as for PT (equation 3). The PT_e values of the samples at FT_{max} are shown in Table II.

RESULTS AND DISCUSSION

PAPER PROPERTIES, AND INK TRANSFER AND PRINT PROPERTIES

The ink transfer values show how much ink has been received by the paper. We believe that after less than 100 ms past the nip the newsprint sheet profile and pore structure have not fully recovered from their compressed state. Therefore, the initial optical properties of the prints measured less than 100 milliseconds after printing can serve to indicate how the ink was distributed in the compressed paper at the moment of transfer.

Optical coverage by ink

An indication of how the ink was distributed on the surface of the samples during transfer was obtained through calculation of optical coverage (OC, equation 4) at 74 ms after printing. The development of OC as a function of increasing amounts of transferred ink, Y, is illustrated in Figure 2 for two samples of the same newsprint calendered to different roughnesses and porosities. The OC values increased as ink transfer increased with the amount of ink on the plate. The ink also covered more of the image area as the thickness of the ink film on the plate was increased, and as deeper surface depressions in the paper were contacted (Walker and Fetsko, 1955).

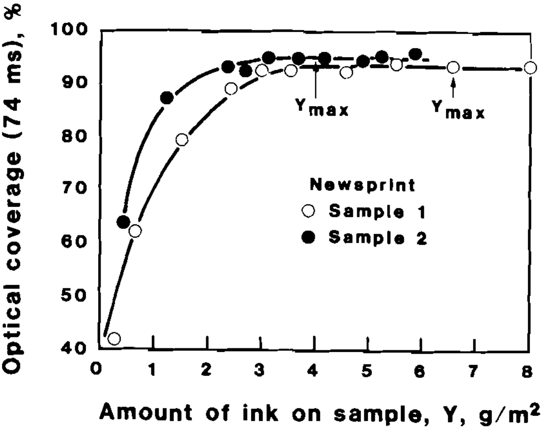

Figure 2. The increase in optical coverage by ink 74 ms after printing with increasing amounts of ink was slower for the rougher, more porous newsprint sample 1. At Y_{max}, more ink was required by sample 1 to reach the same optical coverage as the smoother, less porous sample 2.

The rate of coverage of the rougher sample 1 was slower than for sample 2, and sample 1 had lower OC values than sample 2 until Y_{max} was reached. This is mostly due to the deeper surface depressions of sample 1 (S_{10}, Table

I). Also, more ink (Y_{max}, Table II) was required by sample 1 to reach similar OC_{max} values. At Y_{max}, optical coverage (OC_{max}) was calculated to be 93.5% for sample 1, and 94.0% for sample 2 (Table II). This difference is not significant within the experimental limits.

Past Y_{max}, OC increased at a slower rate with increasing amounts of ink. It has been proposed (Walker and Fetsko, 1955) that, once Y_{max} has been reached, the fraction of the total amount of transferred ink that can be hydraulically impressed into paper during transfer reaches a maximum that remains constant even when more ink is added to the printing plate. Therefore, as the maximum amount of hydraulically impressed ink is approached, more of the total amount of ink that is transferred is due to the splitting of the free, non-impressed ink film between the printing plate and the surface of the paper. After the maximum in hydraulic impression is reached, further increases in the total amount of ink transferred occur solely through splitting of the free ink film. Further, the fraction of the total amount of ink that is transferred through splitting decreases as the thickness of the free ink film increases (De Grâce and Mangin, 1988). All the above lead to a diminishing rate of increase in the total amount of ink transferred (Y).

Nevertheless, OC increased past the maximum in impressed ink, although more slowly, because the increasing ink film thickness on the paper surface filled more of the surface depressions of the paper. This compensated for surface roughness, which decreases the efficiency of the pigment in optically covering the paper surface. From this, it follows that any increase in roughness necessitates that more ink be transferred to the paper to achieve a desired OC value.

Print density

As shown in Figure 3, print density (PD) at 74 ms developed more slowly for sample 1 and reached a lower equilibrium value than sample 2. The rate of increase in PD is particularly diminished after Y_{max}. Print density depends on optical coverage. Accordingly, the development of PD and the differences between the respective PD values of the two samples result from the same reasons given for optical coverage.

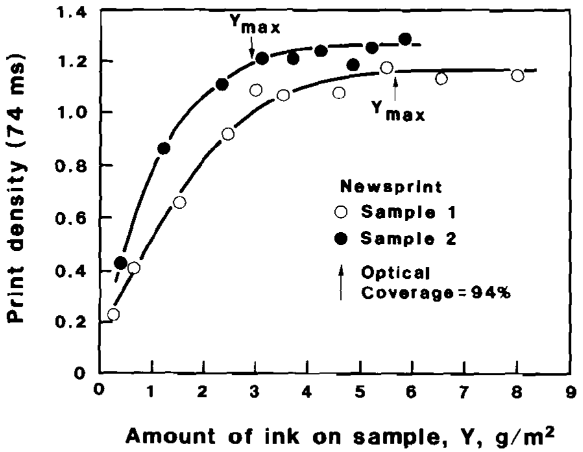

Figure 3. Print density 74 ms after printing increased more slowly for newsprint 1, and more ink was required by the rougher, more porous sample 1 to reach a similar print density as sample 2 at Y_{max}.

Effect of Surface Roughness on Print Density

When the image area is totally covered by ink and the ink thickness on the surface of the paper increases, the ink film becomes opaque. Therefore, past Y_{max} ($OC_{max} > 90\%$), the adverse effect of surface roughness on optical coverage by the pigment is more important in determining PD than is the effect of pigment distribution in the z-direction of the sheet. Furthermore, the reduction of PD by paper roughness is enhanced by the post-nip penetration of vehicle, since the ink film will then closely follow the surface contour of the non-compressed paper.

Print through

In Figure 4, the rate of increase in print through (PT) at 86 ms, as with that for PD, was lower for sample 1. As Y increased, sample 1 reached a lower equilibrium PT than sample 2. The differences in the PT values are due to differences in pore structure. The more calendered sample 2 has the same number of pores as sample 1, but the average pore size is smaller, and, therefore, these take less ink to fill. Furthermore, it is assumed that both samples also have the same extent of air-cellulose fiber interfacial area since they have similar light-scattering coefficients in the presence of air (Table I). However, the thinner sample 2 has a higher air-fiber interfacial area per unit thickness, and therefore, higher light-scattering power per unit thickness (Table I). In the presence of the same quantity of vehicle oil in the two samples, more light-scattering interfaces were lost in sample 2, resulting in higher PT values in that sample during and immediately after printing.

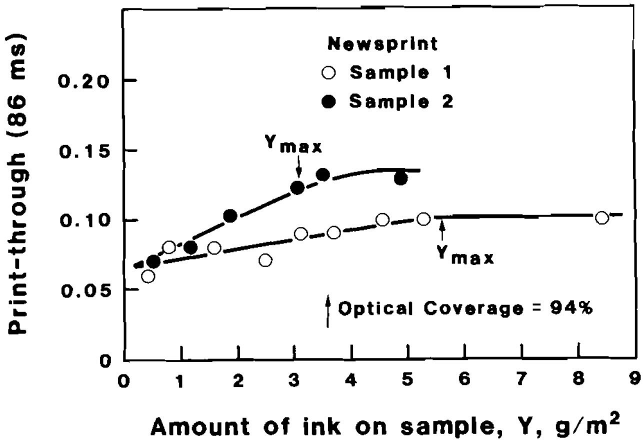

Figure 4. Print through obtained 86 ms after printing increased at a slower rate for newsprint sample 1. At Y_{max}, the print through of sample 1 was lower than that of sample 2 because the smaller pores of sample 2 were saturated at lower amounts of vehicle oil. The levelling off of the curves indicates that the maximum amount of ink that can be hydraulically impressed into the sheets has been reached.

Maximum in the Amount of Ink Impressed into the Paper

The levelling off of the PT values after Y_{max} obtained 86 ms after printing (Figure 4) is further evidence of a maximum in the amount of ink that can be hydraulically impressed into the sheet. Since the initial value of PT is greatly dependent on the amount of hydraulically impressed ink, PT tends toward a constant value as the amount of ink impressed into the sheet becomes constant. After the maximum amount of ink is impressed, any further increases in PT are marginal and could only result from increases in the amount of ink transferred to the surface of the paper through free ink film splitting. Therefore, the rate of increase in PT levelled off for the same reasons given for OC and for PD. This is also supported by the correspondence between the points where the OC, and PD curves (74 ms), and the PT curves (86 ms) level off (Figures 2, 3, and 4).

It should be emphasised that this correspondence is not seen for PT values obtained at longer times after printing, due to the masking effects of post-transfer vehicle oil penetration into the sheet (Figures 6a and 6b).

POST-TRANSFER INK PENETRATION AND PRINT PROPERTIES

Figures 2, 3, and 4 illustrate the effects of the ink transfer properties of the newsprint samples on the initial values of print density and print through. The changes in PD and PT at Y_{max} (OC ~ 94%) due to ink/paper interactions during post-nip ink penetration were monitored between 74 ms and 72 hours after printing for PD, and 86 ms and 72 hours for PT. The sequence of events described below was repeatable, and occured at other Y values and with other newsprint samples.

The development of PD_{max} and PT_{max} with time has been divided into three stages, and is shown in Figure 5.

STAGE I

Effects of passage of paper through a printing nip

Print density I

The PD_{max} values (Figure 5; Table II) obtained 74 ms after printing, were the highest, and were the same for both samples. This is attributed to a smoothening of the surface and a decrease in the average pore size of the compressed sheet as it passed through the printing nip. This effect diminished as the sheets recovered from their compressed state. During recovery, the surfaces resumed their original roughness, and ink penetrated into the sheets through aspiration. We surmise that these events led to a roughening of the surface of the ink film, uneven ink film thickness, the recovery of light-scattering interfaces, and a reduction in the tinctorial strength of the ink as pigment was distributed in the z-direction. These factors combined to lower PD. The PD of sample 2 decreased at a faster rate than that of sample 1, due to a higher rate of ink penetration into the smaller pores of sample 2.

Print through I

The PT_{max} of both samples (Figure 5; Table II) were higher 86 ms after printing than after three seconds, and sample 2 had the highest value. In view of the results of the model experiments presented in the next section, the high PT values obtained 86 ms after printing are attributed to a reduction in intrinsic sheet opacity due to compression and vehicle oil penetration, and to pigment penetration.

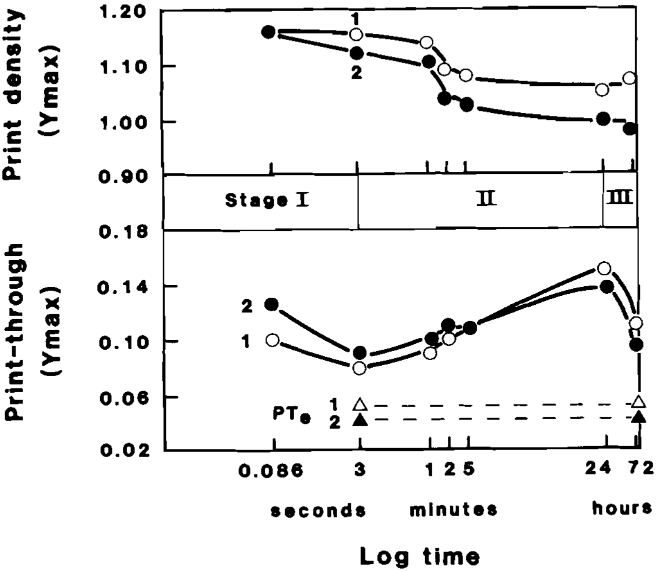

Figure 5. Print density and print through at the Y_{max} values of newsprint samples 1 and 2 as a function of time. Print density decreased as ink vehicle penetrated into the sheets, exposing light-scattering interfaces at the surface, and causing the pigment to follow the surface contour of the papers more closely. Print through first decreased (I), and then (II) increased to a maximum value, and (III) decreased again. The trends are due to sheet compression and recovery effects (I), and to vehicle oil penetration (II) and redistribution (III) into the sheets. The constant PT_e values (oil-extracted prints) indicate that pigment penetration ceased prior to 3 seconds after printing.

Effect of Sheet Compression on Intrinsic Paper Opacity

As stated above, the higher print through (PT) values at 86 ms are due in part to a reduction in paper opacity while the sheet is in the compressed state (Lyne and Madsen, 1965). In a model experiment, the reflectance of the paper itself was measured before and 86 ms after passage through the printing nip at the same speed and pressure used during printing. The reflectance values of the paper alone were 57%

and 56% before the nip, and 86 ms after the nip respectively. These values are not significantly different.

In a second model experiment, the sheet was covered with a solid black "Letraset" film that provided intimate contact with the paper surface, without significant penetration of adhesive. The "Letraset" background had a reflectance value of 1.6% which is equivalent to a print density (PD) of 1.55. The reflectance values measured on the reverse side of the paper from the background before the nip, and 86 ms after the nip were 53% and 51% respectively. These corresponded to direct show through values of 0.032 for the uncompressed sheet, and 0.048, at 86 ms after the nip - a 50% increase in PT due to sheet compression. That is, the PT component due to direct show through increased as a result of the lower opacity of the compressed sheet. With this background, the opacity of the paper was calculated to be 94.7% before, and 89.4%, at 86 ms after compression in the nip.

Effect of Sheet Compression on Paper Opacity in the Presence of Vehicle Oil

The high PT values obtained at 86 ms were also due to additional reductions in the intrinsic opacity of the sheet brought about through the presence of oil in the compressed pores. We propose that since the average pore size was smaller while the sheet was still compressed shortly after printing, the pores were saturated with oil sooner than they would have been at their normal size. Also, the reduction in the thickness of the sheet by compression resulted in a greater number of pores per unit thickness. Therefore, more light-scattering interfaces were lost in the thinner sheets at the same depth of oil penetration. This created an increased loss of sheet opacity and a greater PT. Therefore, sample 2 had a higher PT value than sample 1 at 86 ms due to its smaller average pore size and lower initial caliper.

As the sheet was recovering from its compressed state, the pores began to enlarge to their original sizes, and vehicle oil was drawn in from the sheet surface. The decrease in PT observed for both samples between 86 ms and three seconds indicate that the enlarging pores could accommodate the additional amounts of oil, so that the sheets also simultaneously recovered some of their original opacity.

STAGE II

Effects of post-nip penetration of vehicle oil

Print density II

In Figure 5, it is seen that after three seconds past the nip, the PD of both samples continued to decrease, with sample 1 now showing higher PD values than sample 2. As will be shown later, pigment penetration into the sheet ended prior to three seconds after printing. Therefore, post-nip changes in PD are associated with vehicle penetration, as explained previously. The higher PD values of sample 1 are due to the higher Y_{max} value of that sample (Table II).

Print through II

Until 3 seconds after printing, the expanding pores could accommodate the additional oil drawn in through aspiration. However, the pores continued to fill with oil by capillary action. As a result, as shown in Figure 5, PT began to increase again, but the PT of sample 1 was now higher than that of sample 2. More vehicle oil penetrated into sample 1 because of its higher Y_{max} value, and so the extent of pore saturation was greater than that of sample 2.

Due to the concomitant but opposite effects of pore size recovery and vehicle oil penetration on the PT values obtained between 86 ms and three seconds, it is not possible to determine from these data when the sheets had fully recovered from their compressed state, and the effects of sheet opacity and ink penetration into the sheet could not be separated in the period up to 3 seconds after printing.

STAGE III

Effect of vehicle oil redistribution within the sheet

Print density III

It is seen in Figure 5 that print density continued to decrease at a continuously diminishing rate as vehicle was drawn from the surface, until the final reflectances were measured 72 hours after printing. As penetration continued, the free vehicle on the paper surface became depleted. PD then stabilized.

Print through III

After 24 hours, print through appeared to have reached a maximum value (Figure 5). Since no reflectance measurements were made between 5 minutes and 24 hours, the exact point at which the maximum PT occurred could not be determined.

Beyond 24 hours, the PT of sample 1 remained higher than that of sample 2, but decreased for both samples until the lowest measured values were reached 72 hours after printing. This decrease in PT is attributed to a redistribution of vehicle oil. Vehicle oil was drawn away from larger pores by the stronger capillary forces of smaller pores. As vehicle penetration from the paper surface ceased, light-scattering interfaces were recovered in the large pores. Furthermore, it may be that some of the oil migrated into pores that were too small to scatter the illuminating light (Roeher, 1966) to begin with, and so the presence of oil in these pores did not affect the opacity of the sheets.

INK PIGMENT AND VEHICLE OIL, AND PRINT PROPERTIES

Separation of the Pigment from the Vehicle and its Effects on Print Density and on Print Through

The $PT_{e\ max}$ values (Table II, Figure 5) were obtained from two different sets of prints that were extracted with petroleum ether three seconds, and 72 hours after printing. In general, PD increased by about 5% after the extraction. In the absence of vehicle oil, the amount of light reflected off the printed area was reduced (loss of gloss). In the absence of vehicle oil, the PT_e values could only be due to the presence of pigment on the surface and within the sheet and to the intrinsic opacity of the sheet. Since the values obtained at these different time intervals were the same, it is concluded that pigment penetration ended prior to three seconds after printing. This implies that pigment penetrated into the compressed pores through hydraulic impression in the printing nip, and perhaps also through aspiration (Levlin and Nordman, 1967) as the sheet emerged from the nip and recovered its original thickness and porosity. It is concluded that the changes in PT with time past three seconds are solely due to the penetration of the vehicle oil. Since pigment penetration did not continue beyond three seconds, vehicle penetration must also be the cause of the changes in PD with time.

Relative Contributions of Ink Pigment and Vehicle Oil to Print Density and Print Through

In Figures 6a and 6b, the print through (PT) values obtained 24 hours after printing, and after extraction of the vehicle oil (PT_e), are shown for samples 1 and 2 as a function of the amount of ink on the paper. The PT values obtained 24 hours after printing resulted from the additive contributions of the intrinsic paper opacity, the penetration of pigment into the sheet during printing, and the component due to a loss in the opacity of the paper from the continued penetration of vehicle oil after printing. The lower PT_e values are due solely to the intrinsic paper opacity and to pigment penetration, which did not continue after printing.

The difference between PT and PT_e values gives the decrease in sheet opacity due to the presence of vehicle oil. At their respective Y_{max} values, the contributions to PT_{max} due to the combination of opacity and pigment, and to the reduction in sheet opacity by the vehicle oil, are similar for both samples: 35% opacity/pigment, and 65% vehicle oil for sample 1, and 31% and 69% respectively for sample 2. Therefore, vehicle oil penetration had about double the effect on the PT of both samples than those of initial sheet opacity and pigment penetration.

Note that for both samples, the PT_e values reached an equilibrium value at a point that corresponds to those in Figures 2, 3, and 4 at 86 ms after printing. While not shown here, the print density (PD) data after 24 hours also reached equilibrium at the same ink content in the paper, but at lower PD due to vehicle oil penetration. These findings further support the view proposed earlier that equilibrium in the optical properties of prints occurs when the maximum amount of ink has been hydraulically impressed into the sheet.

However, the PT values obtained 24 hours after printing (Figures 6a and 6B) increased as the amount of transferred ink (Y) was increased, and still had not reached equilibrium at the highest values of Y. Increases in Y resulted in greater post-transfer oil penetration from the paper surface, leading to increasing loss in sheet opacity and greater PT.

SUMMARY

During printing, press parameters, and ink and paper properties combine to determine the amount of ink that is

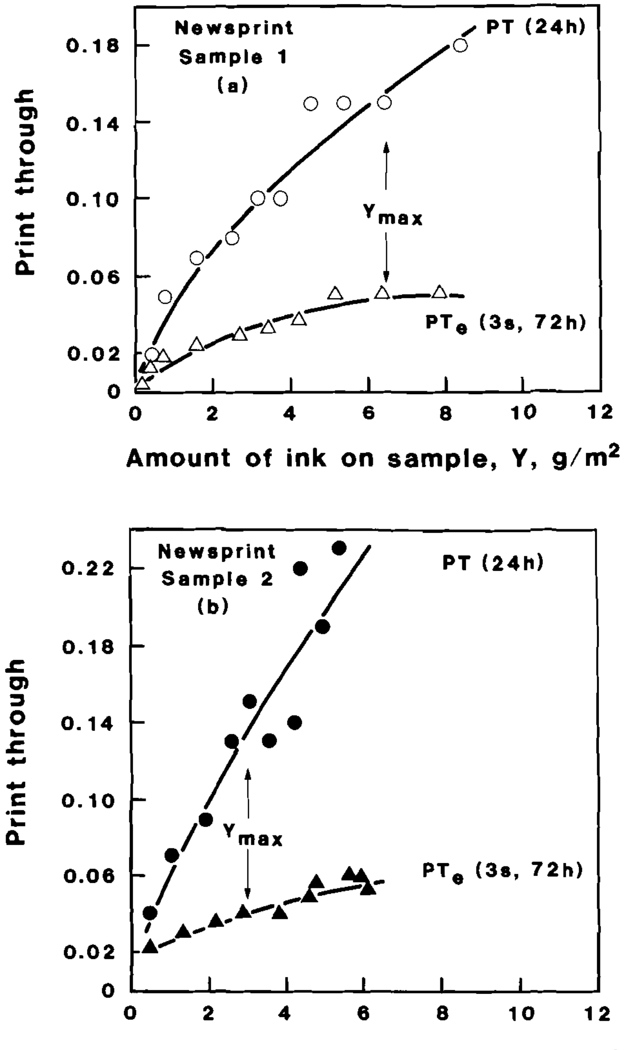

Figure 6 (a and b). Print through (PT) obtained 24 hours after printing as a function of the amount of ink on newsprint samples 1 and 2, and the PT_e values of the sheets extracted for vehicle oil. The higher PT is due to the presence of oil which contributed 65% and 69% to PT at Y_{max}, for samples 1 and 2 respectively. (The point at which the PT_e curves level off coincides with those in Figures 2, 3, and 4.)

transferred to the paper, and the distribution of ink pigment and vehicle on the surface and within the sheet. With non-drying, oil-based inks, post-transfer ink penetration also affects ink distribution. However, penetration continues through capillary action, and therefore, does not depend on the printing press conditions, but on ink and paper properties.

Ink penetration affects the optical properties of the ink itself as well as that of the paper. Print density (PD) and print through (PT) depend upon these optical properties. Therefore, PD and PT develop through a dynamic process of ink penetration into the paper in the printing nip, and during a period of time thereafter. In general, the ink that remains on the paper surface affects mostly PD, to a degree that depends on the surface roughness of the paper. The fraction of penetrated ink mostly affects print through, the extent of which depends on the quantity of ink in the sheet and on the average pore size of the paper. For oil-based ink, the reduction in sheet opacity by vehicle oil can cause over 60% of the print through in newsprint.

Newsprints that confine pigment to a smooth surface will be the most efficient in achieving high print density with a minimum amount of ink. However, if smoothness is accompanied by a reduction in average pore size (e.g., from excessive calendering), even that minimum amount of ink can be sufficient to saturate the pores with vehicle oil and produce a high print through. With that constant amount of ink, a rough newsprint with a larger average pore size would have a lower print density, but would also have lower show through because fewer pores would be saturated by the vehicle oil.

However, it is more relevant to commercial printing to compare different papers at the same print density. At constant print density, the rougher newsprint could have more print through, since it requires more ink to attain the same print density.

The printing quality of newsprint can be increased through improvements in its structural properties which can be effected during the papermaking operations (Crotogino and Gratton, 1987). For example, novel calendering techniques are used to improve sheet finish by modifying the surface contour, and by changing the pore structure near the sheet surface to minimize ink penetration into the paper.

When printing with oil-based inks, print through can be reduced by minimizing the adverse effect of vehicle oil on paper opacity. Filler pigments (e.g., clay, or TiO_2) are frequently added to higher quality papers. By increasing light-scattering, print through is reduced. However, it has been shown (Pauler and Bristow, 1986) that pigments of a much smaller size distribution can be added to the furnish to form a structure that contains pores too small to affect the light-scattering power of the sheet, but having sufficient volume to absorb significant amount of vehicle oil. Since the decrease in light-scattering power is small, print through is minimized.

Attempts to predict the print through properties of paper before printing are often made by light-scattering and opacity measurements, or by measuring the permeability to a flow of air - properties that are largely a function of the porous structure of the paper. Therefore, these methods can achieve some measure of success in predicting print through. However, when opacity is decreased by vehicle oil, print through also greatly depends upon the capacity of the pores to accommodate the vehicle oil without losing too much sheet opacity.

Sheets modified by fillers or in other ways can also be evaluated for their printing quality by the methods employed in this work.

CONCLUSIONS

The following conclusions were drawn as a result of this work.

1. When the ink film on the paper surface is opaque, the reduction in the optical coverage by ink caused by surface roughness causes a greater reduction in PD than the distribution of pigment in the z-direction of the sheet.

2. The effect of paper roughness on PD is enhanced through vehicle penetration into the sheet because the surface pigment more closely follows the surface contour of the paper.

3. The existence of a maximum in the amount of ink that can be hydraulically impressed into the sheet during printing is shown by the levelling off of the print through curve with increasing ink levels obtained 86 ms after

printing. This is not seen when print through is measured at longer times after printing, due to the masking effects of post-transfer ink penetration into the sheet.

4. At a constant amount of ink, the print through of a more calendered sample of the same newsprint was higher, due to its smaller average pore size and higher pore concentration per unit sheet thickness. This resulted in a faster saturation by vehicle oil and a greater loss in sheet opacity than for the less calendered sample. However, at constant print density, more ink was required by the less calendered sample, leading to more print through.

5. Print through is high at the nip exit due to sheet compression, but decreases as the sheet recovers part of its original opacity. Post-nip vehicle oil penetration then causes print through to increase to a maximum value. Print through finally decreases as the vehicle oil is drawn into smaller pores and light-scattering interfaces are recovered in the larger pores.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. B.D. Jordan for his helpful discussions. Dr. J. Aspler is thanked for his help in reviewing the text.

LITERATURE CITED

Coupe, R.R., and Smith, A.H.
1956. "Penetration of Ink into Paper and its Relevance to Print Quality", Journal of Oil and Colour Chemists' Association, vol. 39, no. 8, pp. 579-608.

Crotogino, R.H., and Gratton, M.F.
1987. "Hard-Nip and Soft-Nip Calendering of Uncoated Groundwood Papers", Pulp and Paper Canada, vol. 88, no. 12, pp. 208-216, T461-T469.

De Grâce, J.H., and Mangin, P.J.
1984. "A Mechanistic Approach to Ink Transfer - Part I: Effect of Substrate Properties and Press Conditions", Advances in Printing Science and Technology, vol. 17, pp. 312-332, W.H. Banks, Ed.

De Grâce, J.H. and Mangin, P.J.
1988. "A Mechanistic Approach to Ink Transfer - Part II: The Splitting Behaviour of Inks in Printing Nips", Advances in Printing Science and Technology, 19, W.H. Banks, Ed.

Fetsko, J., and Zettlemoyer, A.C.
1962. "Factors Affecting Print Gloss and Uniformity", TAPPI, vol. 45, no. 8, pp. 667-681.

Larsson, L.O., and Trollsas, P.O.
1973. "Print Through as an Ink/Paper Interaction Effect in Newsprint", The Fundamental Properties of Paper Related to its Uses, Transaction of the Cambridge Symposium, vols. 1 and 2, pp. 600-612, F. Bolaru, Ed.

Levlin, J.E., and Nordman, L.
1967. "On the Penetration of Ink into Paper", Advances in Printing Science and Technology, vol. 4, pp.33-55, W.H. Banks, Ed.

Lin, T.P., and Kan, H.K.
1970. "Calculation of Reflectance of a Light Diffuser with Non-uniform Absorption", Journal of the Optical Society of America, vol. 60, no. 9, pp. 1252-1256.

Lyne, M.B., and Madsen, V.
1965. "Further Laboratory Studies of Penetration in the Press Nip During the Printing Moment", TAGA Proceedings of the 17th Annual Meeting, pp. 104-117.

Madsen, V., and Aneluinas
1968. "The Effect of Formation on Print Quality", TAPPI, vol. 51, no. 7, pp. 309-314.

Mangin, P.J., Lyne, M.B., Page, D.H. and De Grâce, J.H.
1982. "Ink Transfer Equations - Parameter Estimation and Interpretation", Advances in Printing Science and Technology, vol. 16, pp. 180-205, W.H. Banks, Ed.

Pauler, N., and Bristow, J.A.
1986. "Opacity is not always a Direct Guide to Print Through - Effects of Special Pigment", Advances in Printing Science and Technology, vol. 18, pp. 432-438, W.H. Banks, Ed.

Roeher, W.W.
1966. "Measurement and Reduction of Ink Strike Through in Newsprint", TAPPI, vol. 49, no. 6, pp. 255-259.

Ruckdeschel, F.R.
1978. "The Effect of Toner Surface Structure on Colour Gamut", Colour Research and Application, vol. 3, no. 4, pp. 169-176.

Tollenaar, D.
1953. "Exchange of Liquid Between Paper Pores", Applied Science Research, section A3, pp. 451-461.

Walker, W.C., and Fetsko, J.M.
1955. "A Concept of Ink Transfer During Printing", American Ink Maker, vol. 33, no. 12, pp. 38-44, 69-71.

Watanabe, K., and Amari, T.
1982. "Dynamic Compressive Modulus of Paper", Report on Progress in Polymer Physics in Japan, vol. 25, pp. 409-412.

Weidenmuller, J.
1975. "Factors affecting the printability of lightweight newsprint, Part I, International Research Association for Newsprint, Darmstadt.

Anonymous
1972. SCAN P35:72, "Test Printing of Newsprint in the GFL Rotary Test Printing Press", Scandinavian Pulp, Paper and Board Testing Committee.

APPENDIX

The installation for the on-press measurement of print density (PD) and print through (PT) directly after printing with the 4-colour GFL rotary press is shown in Figure 7a. Only one inked printing plate was fastened to cylinder A.

To measure PD, the paper sample on cylinder B was printed by bringing cylinders A and B into contact in the standard fashion for one impression. Optical density (OD) values were measured as the printed area on the paper passed the densitometer head 74 ms after printing.

To measure PT immediately after printing, cylinder B was brought into contact with cylinder C, onto which a two-sided adhesive paper was fastened. This transferred the paper to cylinder C with the reverse side of the print facing the densitometer measuring head. An elliptically-shaped area (Figure 7b) was cut out from the adhesive paper to eliminate the penetration of adhesive into the sheet being tested. The cut-out area also served to reduce the stress put on the sheet and prevent its tearing as it transferred to the adhesive paper. Finally, the cut-out area allowed the printed area to pass between cylinders B and C without being submitted to another nip pressure. The OD values of the reverse side of the print were then measured 86 ms after printing.

Further PD and PT readings were then taken every 1.25 seconds for 2 minutes, then one reading was taken after 5 minutes, 24 hours, and 72 hours. The prints were protected from light between the readings taken after the first 5 minutes.

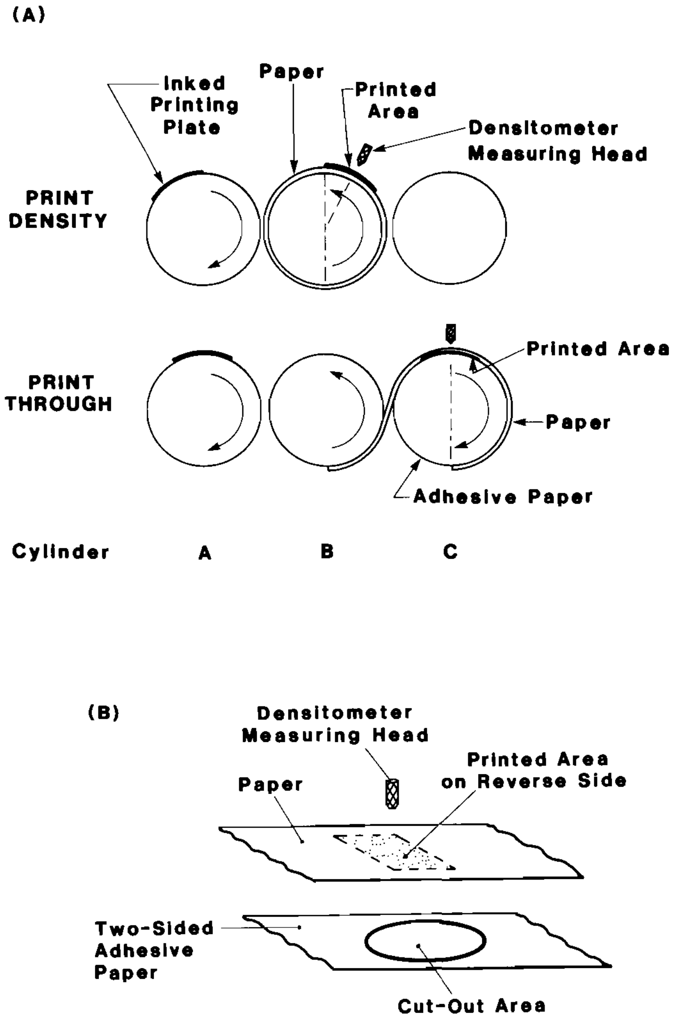

Figure 7(a and b). Installation for the on-press measurement of print density and print through.