HOW PAPER AND INK PROPERTIES INTERACT TO DETERMINE THE CHARACTERISTIC CURVE OF A LITHOGRAPHIC PRINTING PRESS UNIT

by: John MacPhee * and John Lind **

This is the third in a series of reports on a project that began as a study of the effect of paper on the characteristics of lithographic prints. It sets forth a hypothesis, based on experimental results, that explains why paper and ink, acting in consort, are the major factors that affect the tone reproduction characteristics of a lithographic printing press unit. Data from printing tests are presented to support the contention that paper properties are the primary determinant of the density range of the reproduction, while the second property of the characteristic curve, its slope, is determined primarily by the properties of the ink, through their effect on dot gain.

Background and Introduction

In mid-1989 a research program was undertaken at GATF aimed at quantifying the effect of paper grade on the characteristics of lithographic prints. The particular characteristics selected for study were print tonal properties. It was also decided to express these properties in terms of the press characteristic curve, that is defined as a plot of a function relating the tonal properties of a print produced by the press unit to the tonal properties of the film used to make the corresponding press plate. The effect of this objective was to focus the investigation on two properties of a press print: density range (maximum solid density referenced to the paper) and total dot gain (growth in dot size as measured with a densitometer relative to the dot size on film) since it is these two properties that determine the characteristic curve.

First Project Report. The first project report (MacPhee and Lind, 1990) suggested a new format for plotting the characteristic curve, as shown in Figure 1. The utility of this curve is that it provides a realistic portrayal of how the two determining variables, density range and dot gain, affect picture contrast, i.e., the slope of the curve or rate of change of the density of the print relative to the density of the original (as defined by the film).

The second result contained in this report was a catalog of how some of the more common press variables affect dot gain under typical conditions existing on a given sheetfed press.

* Baldwin Technology Corporation
** Graphic Arts Technical Foundation

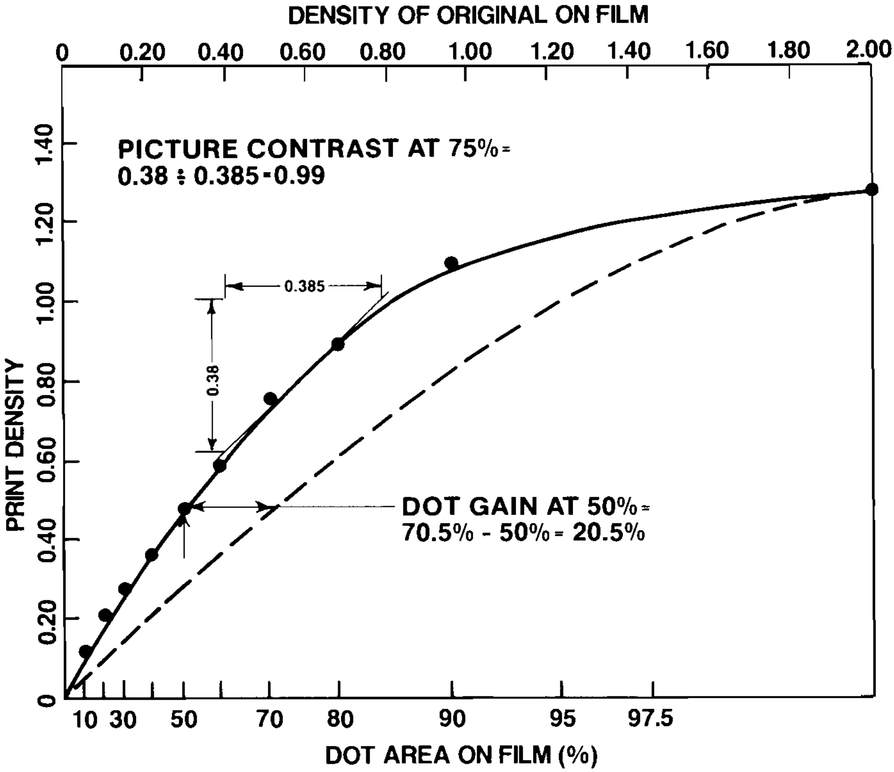


Figure 1 Format of press characteristic curve proposed in first project report.

Second Project Report. The second project report (Lind and MacPhee, 1990) presented the results of a series of press tests run under conditions whereby the same ink film thickness was printed on a variety of paper grades ranging from #1 coated to #3 uncoated, for two different sheetfed inks, cyan and magenta. Reporting was limited to dot gain and it was concluded that paper grade has a modest effect on mid-tone plate-to-print dot gain.

Objectives and Scope of this Report. The primary objective of this report is to answer the following two questions, that were raised in response to the earlier findings:

1. If the effect of paper on dot gain is modest, how then does paper exert the significant impact that it has on print tonal properties, and what paper properties are important in this regard?

2. How does the other major variable, ink, exert its important effect?

A secondary objective of this report is to extend the range of paper grades considered by including test data on newsprint.

The main body of this report comprises three sections covering the effect of paper, the effect of ink, and a proposed model of the paper-ink interaction. The last section lists some recommendations regarding additional studies and suggests how some improvements in print fidelity could be achieved based on the findings of this study.

The Effect of Paper

The earlier conclusion about the effect of paper grade on dot gain was reinforced by two additional series of press tests (J and N) carried out since, in which prints of magenta ink on newsprint were obtained. These press tests differed from those described in the previous reports in that ink film thickness on the prints was actually measured, in accordance with a procedure described elsewhere (MacPhee and Lind, 1991). Because of concern about picking, the same magenta ink was not used. Instead a special low tack sheetfed ink was formulated having the same pigment concentration as the ink used in the previous runs. Because it was not certain that this paper could be run on a sheetfed press, the first test series (labeled J) was run on a single width newspaper press. The second series (labeled N) was run on the same GTO press as was used in the earlier test series. The results of the latter tests, listed in Table I, strongly reinforce the findings of the previous tests in that dot gain on newsprint was 19.9% vs 15.2% on #1 coated paper at the same ink film thickness and the same screen ruling of 150 lines per inch (on the 120 line per inch target on the N-1 sheets, mid-tone dot gain was only 16.8, or 1.6% more than on the coated sheet finer ruled screen). This at first may sound incredible in that it flies in the face of conventional wisdom that states that dot gains on newsprint are much higher than on coated stock, even when much coarser screen rulings are used on the former. For example, SWOP specifies a total film to print dot gain of 24%, plus/minus 4% for a 133 lines per inch

Table I Results of Runs N-1 and N-2, Low Tack Magenta Sheetfed Ink

Run No.	Paper Grade	Number Of Sheets Run	Ink Consumed (gms)	Ink Film Thickness (gms/m^2)	Solid Density w Paper	Midtone Dot Gain, Plate to Print
N-1	Newsprint	1000	51.9	0.85	0.94	19.9
N-2	#1 Ctd	1000	50.7	0.83	1.18	15.2

screen on (coated) web proofing paper (Anonymous, 1988-1) whereas SNAP reports a typical result at recommended densities wherein mid-tone dot gain was 32% for an 85 line screen ruling on newsprint (Anonymous, 1988-2). This apparent divergence is however readily explained by the fact that the inks normally used in newspaper printing are much weaker or exhibit less holdout than typical sheetfed inks, as shown in Figure 2. As a result, much thicker ink films are needed to achieve the desired densities and it is the thicker ink film, rather than the paper that is primarily responsible for the higher gains that are experienced in real life newspaper printing. More will be said about this in the following section of this paper.

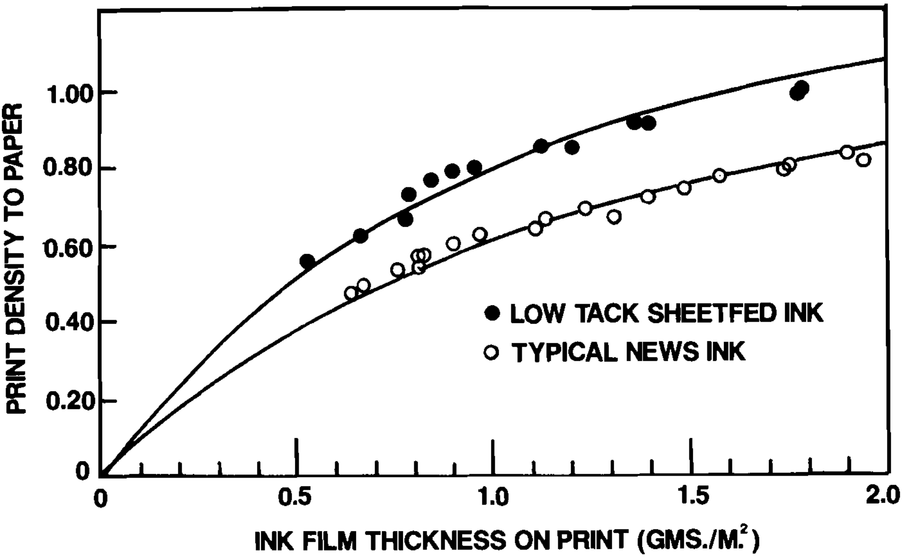


Figure 2 Plot of data obtained on IGT printability tester that shows a much lower ink film thickness was needed to produce a given density when printing with low tack sheetfed ink viz-a-viz typical news ink. For example, to achieve a density to the paper of 0.75, 1.5 gms/m² of the typical news ink is needed compared to only 0.8 gms/m² for the low tack sheetfed ink. Solid lines are best fit curves of Tollenaar equation (Tollenaar and Ernst, 1961).

In order to compare the data in Table I with the test results given in the second project report, correction factors must be applied to account for differences in ink tack and in solid densities. The corrected data is given in Table II along with the correction factors used and the data from the second project report. All of this data is plotted in Figure 3 in bar chart form. This updated plot shows that dot gain variation for the range of paper grades studied is a modest 7.5% ranging from a low of 12.6% for Run 0-2 on #1 coated paper to a high of 20.1% for Run B-1 on a #3 coated paper. The actual differences in gains were probably lower since run B-5 had the higher gain of the two runs on paper "C" while run 0-2 had the lowest gain of the three runs on paper "L".

TABLE II Data from second project report on runs made using magenta ink, updated to include runs using low tack ink (J-2, N-1 & 2). Ink film thickness is presumed to be constant on all prints.

Run No	Code ID	Ctd or Unctd	Grade No.	Data on Paper: Caliper (inches)	K/N Density	Smoothness *: Sh	PPS	Prof	Bright-ness	Solid Ink Density	Total Plate to Print Dot Gain: A50	A30
MR	C	CTD	#3	.003	0.16	48	1.40	0.89	67	146/132	17.6	18.2
O-1	J	CTD	#1	.007	0.08	3	1.32	0.45	87	143/137	15.3	14.3
O-2	L	CTD	#1	.005	0.09	4	0.99	0.69	86	144/137	12.6	11.6
O-3	H	UNCTD	#1	.005	0.37	120	4.35	2.69	93	97/93	19.7	20.1
O-4	I	UNCTD	#3	.004	0.43	155	5,71	3.27	76	96/86	19.4	19.6
O-5	A	CTD	#5	.004	0.18	31	2.30	1.45	66	144/130	14.9	14.4
O-6	K	CTD	#3	.003	0.11	4	1.06	0.52	82	142/134	14.6	14.0
O-7	B	M CTD	#5	.003	0.21	80	3.82	2.20	71	123/112	14.2	14.1
O-8	D	CTD	#5	.003	0.16	33	1.43	1.12	68	141/127	15.0	14.5
O-9	C	CTD	#3	.003	Reliable data not obtained because of feeder trips							
B-1	C	CTD	#3	.003	0.16	85	1.59	1.10	69	145/132	20.1	19.8
B-2	M	CTD	#1	.012	0.12	5	0.74	0.21	88	137/131	14.5	13.8
B-3	N	CTD	#1	.005	0.08	3	0.80	0.45	85	134/128	16.0	15.2
B-4	L	CTD	#1	.005	0.09	8	1.15	0.63	87	132/125	15.8	14.4
B-5	C	CTD	#3	.003	0.16	57	1.78	1.12	70	132/119	19.7	19.8
J-2	P	UNCTD	NEWS	.003	0.51	102	3.9	2.73	55	99/77	18.1	-
N-1	P	UNCTD	NEWS	.003	0.51	102	3.9	2.73	55	102/80	19.0	-
N-2	L	CTD	#1							137/130	14.3	-

Note: **Runs J-2, N-1, and N-2** used low tack ink which exhibited lower strength on press. To obtain the comparable dot gains and densities given above, the following correction factors were applied to the measured data to compensate for the differences in ink tack and film thicknesses relative to previous runs.

Run J-2: Subtracted 2.9% from mid-tone gain for higher tack effect.

Runs N-1 & 2: Added 2% to mid-tone gain for higher thickness effect.
Subtracted 2.9% from mid-tone gain for higher tack effect.
Added 0.08 to N-1 density and 0.19 to N-2 density for higher thickness effect.

* **Sh** = Sheffield, **PPS** = Parker Printsurf 10, and **Prof** = Surtronic Profilometer.

** Average for run as given in Table I.

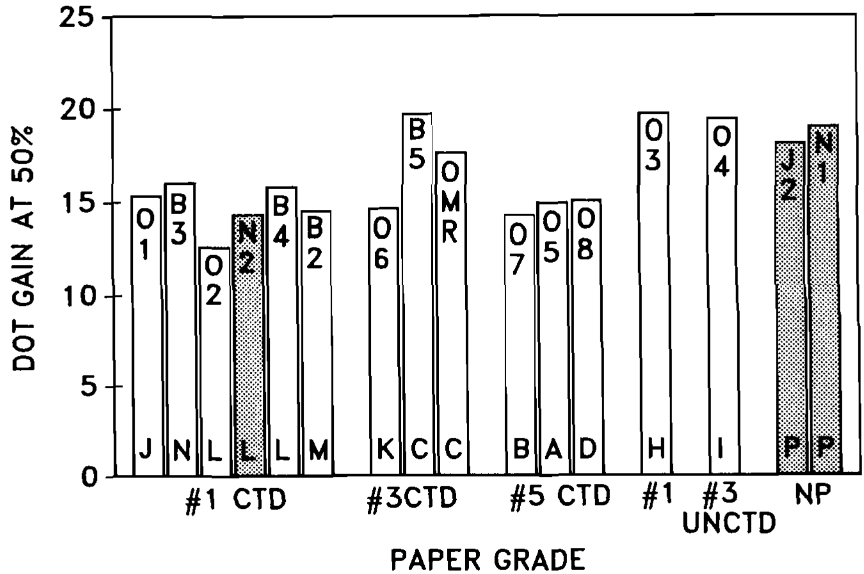


Figure 3 Bar chart showing the relatively small effect of paper on plate-to-print mid-tone dot gain at constant ink film thickness, magenta ink, and 150 line per inch screen ruling. Shading indicates runs with low tack ink.

If it is accepted that paper properties or grade per se have relatively little effect on dot gain, then it is quite logical to ask "through what print properties does paper exert its important influence?" The answer is to be found through an inspection of the test data in Table II: density range defined as solid density reading to the paper at some given ink film thickness. That is, density range varied by a factor of almost two: from a low of 0.80 for the newsprint in Run N-1 to a high of 1.37 for the #1 coated stocks in Runs O-1 and O-2. This is not surprising since the characteristic curve is governed by both dot gain and density range, i.e., if paper has little effect on dot gain, then it follows that it must exert a significant effect on density range, and indeed it does.

In order to learn how specific paper properties affect print density range it will be helpful to recall that print density range is determined by two quantities, identified in the definition given by Equation (1).

$$\left|\begin{matrix}\text{Print}\\\text{Density}\\\text{Range}\end{matrix}\right| = \left|\begin{matrix}\text{Solid Density}\\\text{Including}\\\text{Paper}\end{matrix}\right| \quad \text{minus} \quad \left|\begin{matrix}\text{Density}\\\text{of}\\\text{Paper}\end{matrix}\right| \qquad (1)$$

In general, it is taken that the first term on the right-hand side of Equation (1) is greater for papers having properties that cause the ink to lie on the paper surface. Such paper is said to have greater "holdout", which in turn is attributed to a lower relative absorptivity. Surface roughness is also thought to be a factor because measurements on a non-absorbing substrate have shown that a rougher surface gave rise to a lower density range (DeGrace and Mangin, 1983), which is to be expected for roughnessess on the same order as the film thickness.

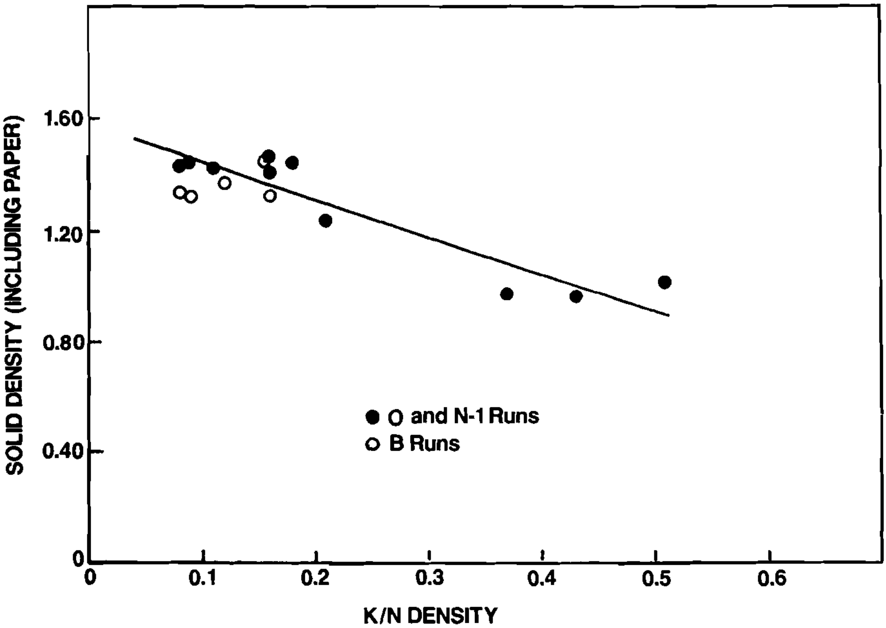


Figure 4 Plot of total print density versus K/N density. Best fit straight line shown is for R and N run data and has correlation coefficient of 0.94.

One method that is widely used as an indicator of paper absorptivity is K/N density (Preucil, 1963). Figure 4 is a plot of solid density including paper versus this measurement of the various papers listed in Table II. If the "B" runs are neglected (for reasons to be explained shortly) the remaining data can be fitted rather well to a straight line. This reasonably good correlation is consistent with the theory that print density including paper, for a given ink film thickness, is governed primarily by paper absorptivity.

As a matter of curiosity, print density including paper was also plotted as a function of surface roughness of the paper, as shown in Figure 5. (Although all three measurements of roughness given in Table II exhibited similar trends, the Surtronic Profilometer measurements were used in Figure 5 because they provide a direct absolute measurement of surface roughness.) Examination of the plot in Figure 5 and the corresponding data in Table II suggests that the density data for the "B" runs is suspect for two reasons.

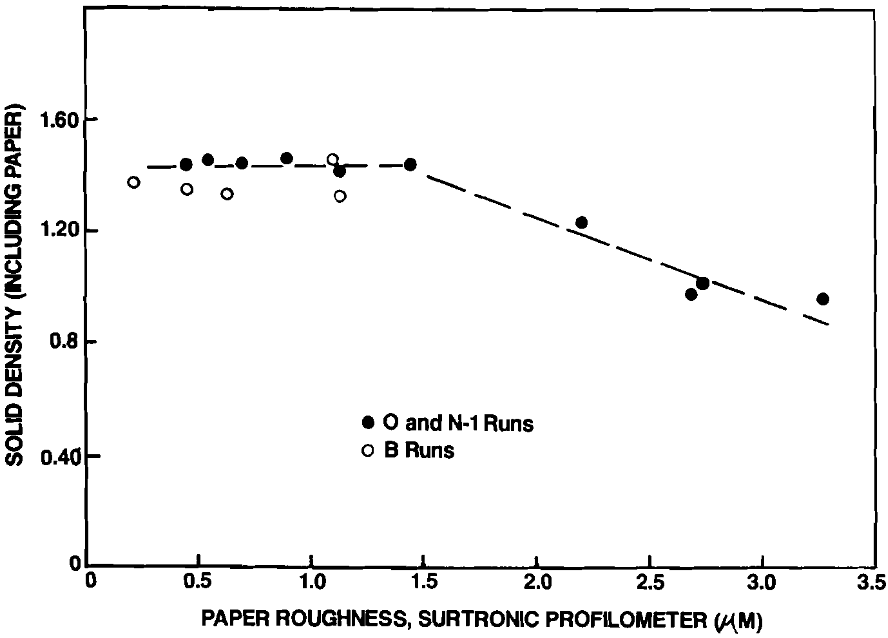


Figure 5 Plot of total print density versus paper roughness for constant ink film thickness.

First, the density for B-5 is 0.13 density units lower than B-1, run on the same paper. Second, all of the densities except B-1 lie on a line approximately 0.10 density units below the "O" run data for similar papers. Based on these observations, it was concluded that following the "B" run makeready (Run B-1) the ink feedrate to the plate decreased for some unknown reason, causing a drop in density on the subsequent runs (Run B-2, 3, 4, and 5). For these reasons, the "B" run density data have been neglected.

Examination of the remaining data in Figure 5 shows a trend whereby print density appears to be independent of roughness, up to a roughness value of about 1.5 micrometers, as measured by the Surtronic instrument. At greater roughnesses, density decreases in an approximately linear manner. However, this trend may be purely coincidental, i.e., no cause and effect relationship between density and roughness, since the surface roughness measurements of the papers tested more or less tracked the K/N density measurements. On the other hand, the break point in the curve is at a value (1.5 micrometers) that is on the same order of the ink film thickness on the print, i.e., the relationship suggested by Figure 5 makes sense. Re-examination of the data in Figure 4 reveals that it too may follow a discontinuous curve similar to the one shown in Figure 5. In any case, the data show that print density including paper is indeed a function of paper absorptivity and may also be influenced by roughness.

The dependency of the second term on the right in Equation (1) can be deduced from first principles: the fact that the density readings of the unprinted papers are measures of paper reflectance. Thus it is logical to expect that this density measurement will correlate very well with paper brightness and this is exactly the case as shown by the data in Figure 6.

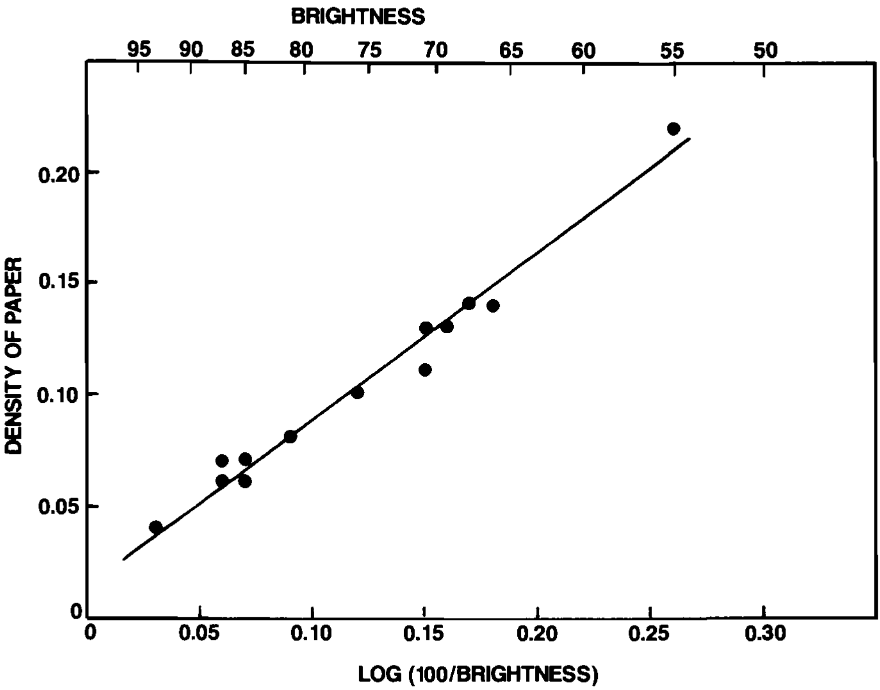


Figure 6 Plot showing relationship between paper density and brightness. Data points are for all papers listed in Table II. Best fit straight line has correlation coefficient of 0.98.

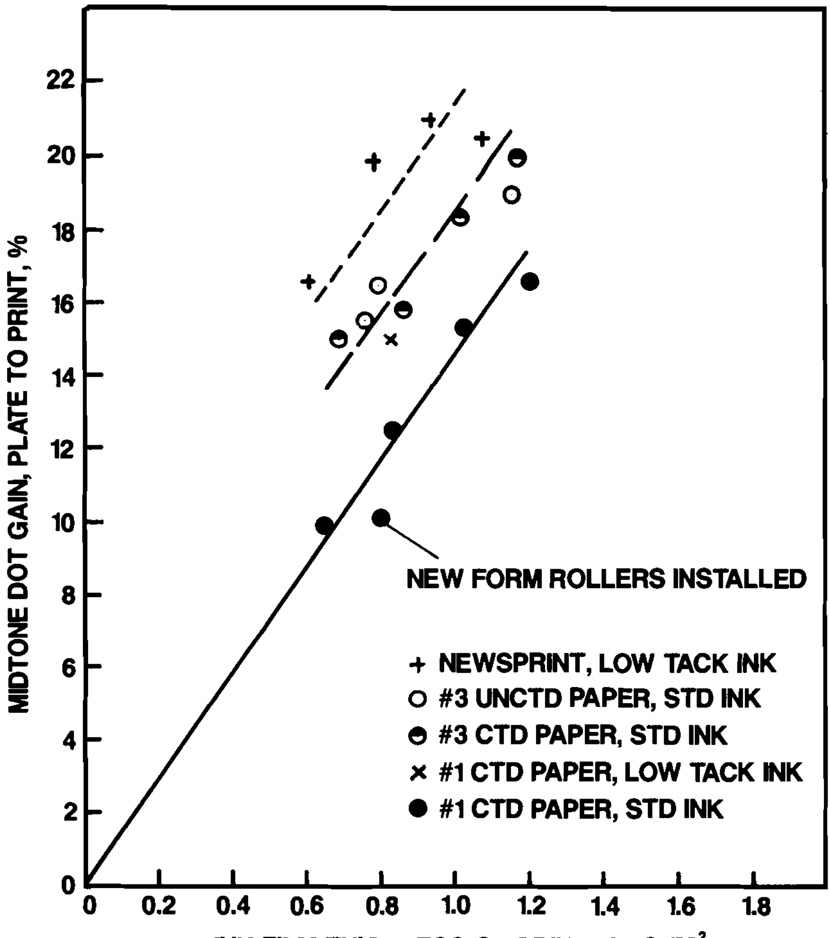
Taken together, Figures 4, 5, and 6 plus Equation (1) show that density range for a given ink and a given ink film thickness is dependent on two paper properties, K/N density and brightness, with the possibility that surface roughness may also be a determinant.

The Effect of Ink

Most printers are aware that on a given job two properties of ink, tack and film thickness, have a profound influence on tone reproduction, through their effect on dot gain. That is, it is axiomatic that dot gain increases when ink film thickness is increased and/or ink tack is reduced,and confirmation of this was provided by limited data that was presented in the first project report.

In order to provide a more comprehensive view of how ink film thickness affects dot gain, press tests were run to obtain data on how solid density and dot gain varies as ink film thickness is changed for four different grades of paper: #1 coated, #3 coated, #3 uncoated, and newsprint. The test procedure and the data on solid density is contained in a separate paper on this subject (MacPhee and Lind, 1991). The data on dot gain is listed in Table III and plotted in Figure 7. The curves in Figure 7 point up the strong dependence of dot gain on ink film thickness. At the same time, these curves provide further evidence that the effect of paper grade in this respect is modest.

The data in Figure 7 illustrates two other phenomena of interest: the effect of form roller hardness and the effect of ink tack. With regard to the former, the single measurement obtained when the form rollers on the press were replaced with a softer set, indicates that dot gain decreased 2%. More measurements should be made before this effect is taken as gospel, since another study (Takahashi, Fujita, and Sakata, 1986-7) concluded that dot gain only occurs in the transfer from plate to blanket. Figure 7 also displays additional limited data that confirms the previously stated relationship between ink tack and dot gain. That is, there is a detectable difference of 2.9% between the single point for the low tack ink (tack of 13 at 1,200 rpm) and the corresponding point on the curve for the standard ink (tack of 20 at 1,200 rpm) on #1 coated stock. If the newsprint data in Figure 7 is corrected by this amount, i.e., decreased by 2.9%, since the newsprint runs were with the low tack ink, then the effect of paper on dot gain deduced from the Figure 7 data is in the extreme about 5%. This finding is consistent with the observations made about the data recorded in Table I and the data plotted in Figure 3.



DOT GAIN VS INK FILM THICKNESS, 150 LPI SCREEN, MAGENTA SHEETFED INK

Figure 7 Dot gain vs ink film thickness, 150 LPI screen, magenta sheetfed ink. Plotted values of ink film thickness are those in Table III listed as best fit.

Table III Dot Gain Data from runs in which ink film thicknesses were measured.

Paper	Run Number	UGRA Solid Density to Paper	Dot Gain, Plate-to-Print		Ink Film Thickness (gms/m^2)	
			50%	30%	Measured	From Best Fit *
Newsprint	N-1	0.69	19.9	17.9	0.85	0.78
	N-4	0.83	20.5	18.6	-	1.07
	J-1	0.58	16.6	17.0	0.6	0.6
	J-2	0.77	21.0	21.5	1.0	0.93
#3 Uncoated	N-9	0.88	19.0	17.1	1.15	1.15
	N-11	0.74	16.5	14.9	0.81	0.79
	N-13	0.72	15.3	13.6	0.75	0.75
#3 Coated	DL-4	1.46	20.0	18.3	1.16	1.17
	DL-6	1.35	18.4	17.3	0.99	1.01
	DL-8	1.22	15.8	13.7	0.85	0.86
	DL-10	1.05	15.0	13.9	0.65	0.68
#1 Coated	DL-3	1.59	16.6	14.3	1.16	1.20
	DL-5	1.45	15.3	14.2	0.99	1.02
	DL-11	1.28	12.5	10.9	0.79	0.83
	DL-9	1.08	9.9	8.1	0.65	0.64
	DL-12	1.25	10.1	9.9	0.83	0.80
	N-2	1.11	15.2		0.83	0.67

* These values are taken from the best fit curves of solid density vs ink film thickness as shown in Figure 9 of the reference MacPhee and Lind, 1991.

Although the data presented in the two previous sections is very informative relative to separating the effects of paper and ink, it would be wrong to conclude that these effects are not inter-related. In addition, little or nothing has been said about two other ink properties that also affect tone reproduction: viscosity and strength. Conventional wisdom would lead to the conclusion that viscosity will indeed effect density in that a thinner ink will cause the pigment particles to penetrate more deeply into a given paper. Confirmation of this was provided by Bruce Blom who reported making many measurements, on uncoated paper, whereby lower densities at a given weight of applied ink were observed when ink viscosity was decreased, at a constant pigment concentration (Blom, 1991). The effect of strength, defined here as pigment concentration, can be deduced from the facts that film thickness required is governed by strength and that film thickness has been shown to affect both density range and dot gain. For example, a tinctorial strength test on the two inks used to obtain the Figure 2 data showed that the strength of the typical news ink was 40 percent less than that of the low tack ink. This indicates that the difference in density vs ink film thickness between these two inks is due primarily to their difference in strength, rather than (say) viscosity.

By considering all of the effects discussed in this paper, it is possible to formulate a model to explain how, on a given printing job, the properties of paper and ink interact to determine the tone reproduction curve of a printing unit. The model so formulated by the authors is shown in flow chart form in Figure 8. It should be noted that the concept of a transfer function used in this figure, that relates output to input, is a familiar one used by electrical engineers (Jay, 1977). Broadly speaking, this model postulates that paper is the independent variable in that its selection largely determines what ink is to be used. Thus ink, broadly speaking, is the dependent variable. Put another way, selection of the paper to be used pretty much determines tone characteristics since selection of an ink is governed pretty much by the paper. The way in which a given paper and a given ink affect the tone characteristics of the printing unit, and hence the print produced on it, is shown by the three transfer functions in Figure 8, which hopefully are self-explanatory.

One very important factor not reflected in this model is the cost of the two materials. This is especially pertinent with regard to ink because in practice the maximum tone reproduction performance achievable with a given paper is often sacrificed in exchange for a lower price for ink. Although this fact has been well known to (and lamented by) ink makers for many, many years, the authors were reminded of it by the excellent performance of the low tack sheetfed ink used by them on newsprint, as shown by the data in Table I, and by its performance viz-a-viz a typical news ink, as shown in Figure 2. Although the low tack sheetfed ink used here may not be a

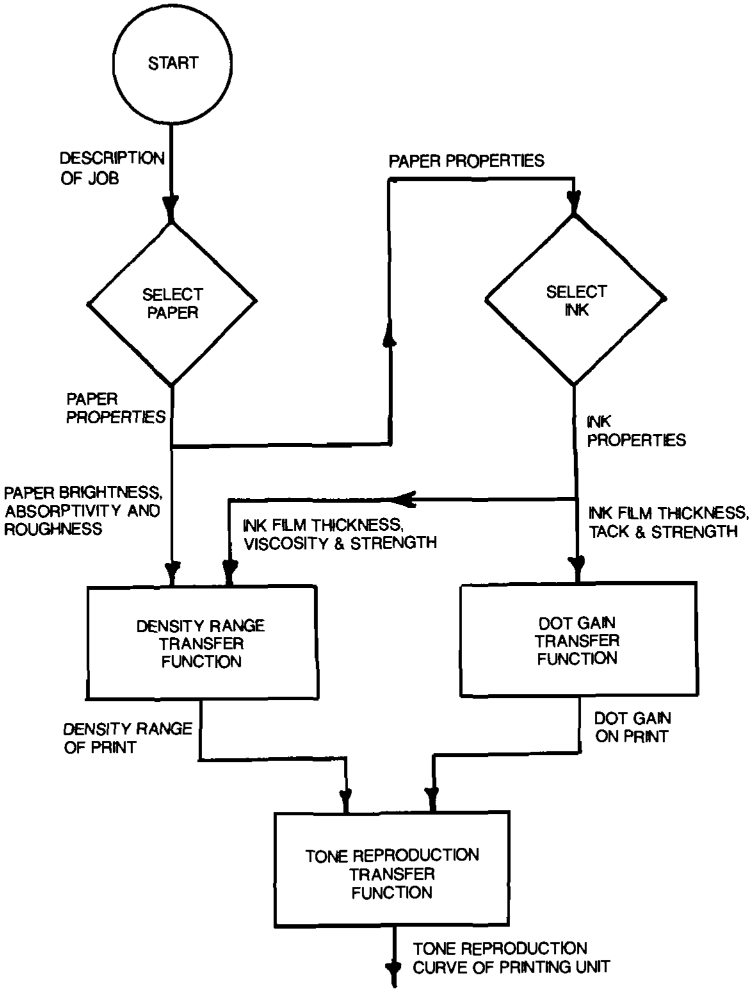


Figure 8 Flow chart that illustrates the primary ways that paper and ink interact to determine the tone characteristics of a printing unit. Diamonds represent a decision, made in consideration of inputs, that results in an output. Rectangles represent functions that govern relationship of output to input.

practical alternative for use on newsprint, there is no question that ink manufacturers could supply better performing inks for newsprint if users were willing to pay for the increases in costs necessary to do this.

Conclusions and Recommendations

Conclusions

The data presented in this and the two previous project reports provide a considerable body of information on how different grades of paper, and ink film thickness affect density range and dot gain in sheetfed printing, with a given magenta ink. More limited data was also presented to show the additional effects of ink tack, water feedrate, type of blanket, type of plate, printing pressure, plate-blanket squeeze, form roller hardness, and two different coatings. Although both density range and dot gain are affected by both paper and ink properties, it was found that density range is affected primarily by paper properties while dot gain is primarily affected by ink properties. The two most important paper properties are brightness and absorptivity (as measured by K/N density) although surface roughness also is important. The two most important ink properties are film thickness on the print and tack, although strength is also very significant. Thus tone reproduction is enhanced by using a paper with high brightness, low absorptivity and an ink with high tack and high strength. As everyone knows, other considerations such as pick resistance, ink-water compatibility, and scuff resistance often require that trade-offs be made in some of these properties.

Recommendations

A major question that remains unresolved is the importance of paper surface roughness relative to absorptivity in determining density range. To answer this it is recommended that additional tests be run on a group of (say) a dozen different papers having different values of these two properties. In addition, one pair of papers should have the same roughness values but significantly different K/N densities while a second pair should have equal K/N densities and significantly different roughness values. Also it is recommended that the procedure used for measuring ink film thickness (MacPhee and Lind, 1991) be employed in place of running books through the press without stopping, as described in the second project report. The reason for recommending this change is that the preferred procedure would eliminate any questions about whether a constant ink film thickness was maintained throughout the tests.

A second recommendation is that work should continue on searching for a measurement technique that will provide for a separation of mechanical and optical dot gain - to ascertain whether the small differences observed in dot gain due to paper property differences are caused by optical or mechanical effects.

References

Anonymous
1988-1, "Recommended Specifications Web Offset Publications", (American Association of Advertising Agencies, American Business Press, Magazine Publishers Association, NY) November, 1988, pp 14

Anonymous
1988-2, "Specifications for Non-Heat Advertising Printing", (Printing Industries of America, Non-Heatset Web Unit, Arlington,) 1988, pp 8

Blom, B.
1991, Personal communication

DeGrace, J.H. and Mangin, P.J.
1983, "A Mechanistic Approach to Ink Transfer Part I: Effect of Substrate Properties and Press Conditions", Advances in Printing Science and Technology (Pentech Press, London) pp 320

Jay, F.
1977, "IEEE Standard Dictionary of Electrical and Electronic Terms", (The Institute of Electrical and Electronics Engineers, Inc., New York) pp 278

Lind, J.T. and MacPhee, J.
1991, "A Study of Dot Gain in Sheetfed Lithography as a Function of Paper Grade", 1990 International Printing and Graphic Arts Conference. (Canadian Pulp and Paper Association, Montreal, and Technical Association of the Pulp and Paper Industry, Atlanta) Nov 6 - 8, 1990

MacPhee J. and Lind, J.T.
1991, "A New Graphical Format Which Illustrates the Different Ways in Which ink, Water, Paper, Plates, and Blankets Can Affect the Tone Reproduction Characteristic of a Given Printing Press Unit", TAGA Proceedings, pp 339

MacPhee J. and Lind, J.T.
1991, "Measurements of Ink Film Thicknesses Printed by the Litho Process", TAGA Proceedings

Preucil, F.M.
1963, "A New Method of Rating the Efficiency of Paper for Color Reproductions", Research Progress Report #60, (Graphic Arts Technical Foundation, Pittsburgh)

Taskahashi, Y.; Fujita, H.; and Sakata, T.
1986-7, "Ink Transfer and Dot Gain Mechanisms in Offset Printing Process", Graphic Arts Japan, (Japan Federation of Printing Industries, Tokyo), Vol, 28, pp 22-23

Tollenaar, D. and Ernst, P.A.H.
1961, "Optical Density and Ink Layer Thickness", Problems in High Speed Printing, Proceedings of 6th Conference of Printing Research Institutes, edited by W. H. Banks, Pergamon Press (London) pp 214