THE PENETRATION OF LIGHT INTO PAPER AND ITS EFFECT ON HALFTONE REPRODUCTION

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ABSTRACT

In explaining how the tones of a halftone reproduction are related to dot area, the effect of the penetration of light into the paper is usually neglected. Measurements show that the light does not emerge from the paper at exactly the spot where it entered, so that some of the light which enters through a dot emerges through white paper. It is shown that this appreciably increases the density of the middletones, especially on uncoated papers, and multiple internal reflections from the paper surface increase it still further, so that the usual simple equation relating dot area to density is not accurate.

PAPER

The absorption of light by a halftone dot pattern seems simple enough at first sight, and quite a lot has been written during the last few years about dot size and halftone density.[1-3] The object of this paper is to describe some experiments which show that it is not as simple as we thought.

For instance, imagine that we have a checkerboard dot pattern printed on perfectly white paper, so that the ink covers exactly 50 percent of the paper area. Will this pattern absorb more or less than 50 percent of the light that reaches it? It ought to absorb less than 50 percent, because the black dots are not perfectly black. Anyone

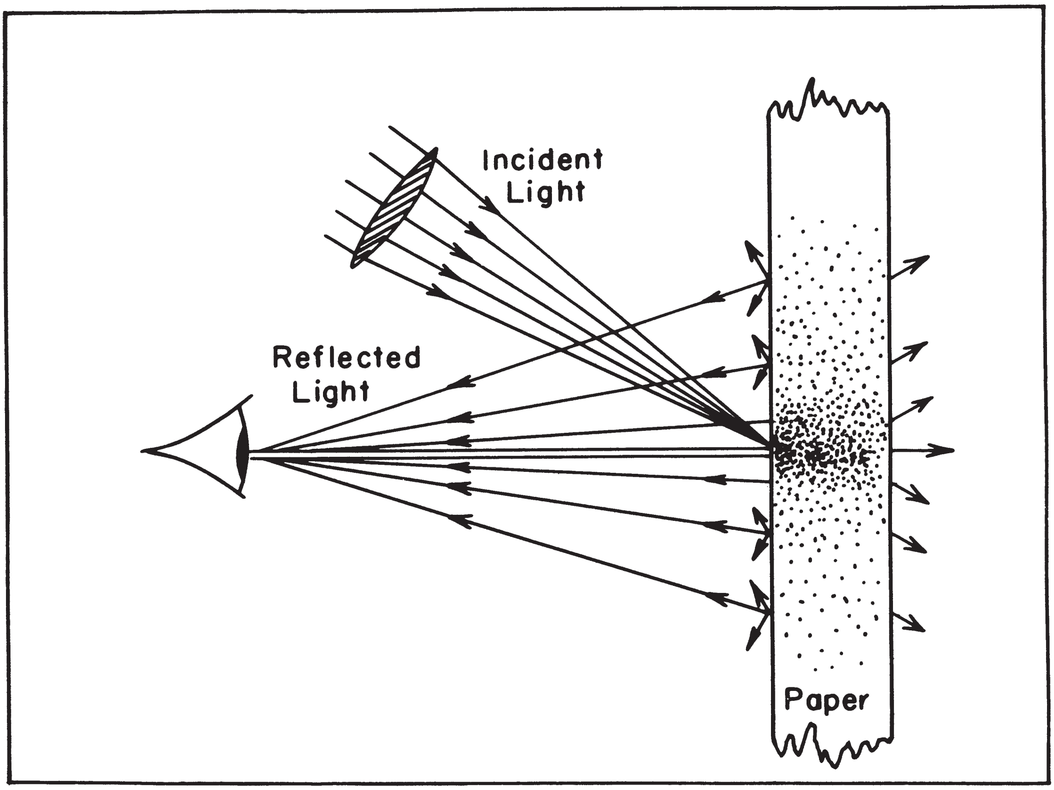

Figure 1. How a spot of incident light spreads to a patch of appreciable size before emerging from the paper.

who has measured it will know that such a pattern usually absorbs more than 50 percent -- that is, its reflection density is usually greater than 0.3.

This discrepancy has quite an appreciable effect on photomechanical tone reproduction. It has been suggested that this discrepancy may be caused by the penetration of ink vehicles into the paper between the dots. It is true that this may contribute to it in some cases, but it seems likely that the penetration of light into the paper may be the chief reason. This is illustrated in Figure 1, which represents a spot of light projected onto the paper spreading out into a patch of considerable size.

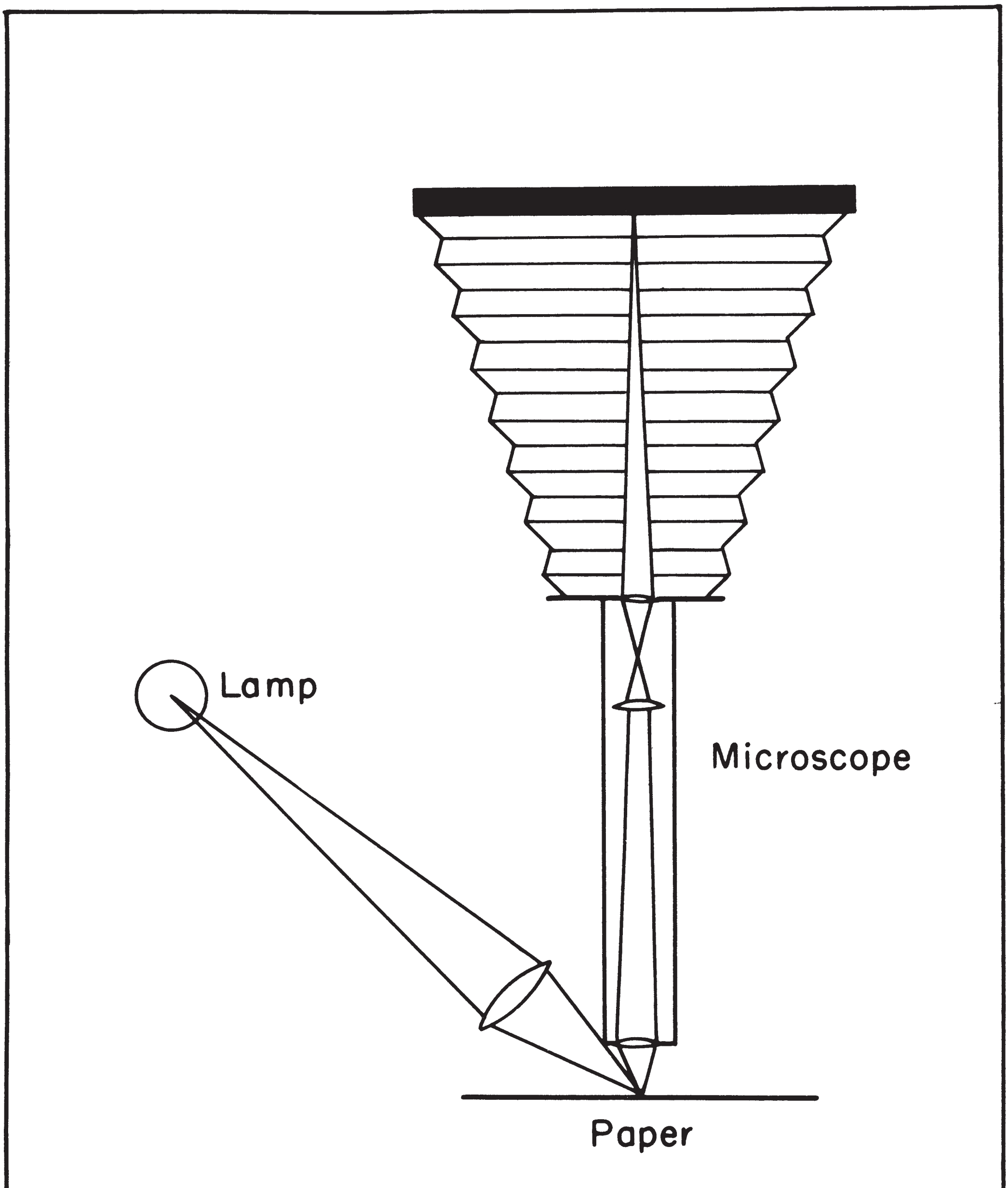

Figure 2. Diagram of photomicrographic apparatus used for measuring spreading of light in paper.

The distance over which the light spreads may be roughly indicated by the well-known fact that if you place a piece of paper on a dark surface it appears blacker than on a light surface. The black surface shows through the paper. This must mean that an appreciable amount of the light passes all the way through the paper, which is usually about 3 or 4 mils thick. This thickness is comparable to the distance between halftone dots. Since the light is diffused by the paper, it is likely to spread sideways to about the same extent that it penetrates through.

Therefore, some of the light which enters a halftone pattern through a space tries to come out through a dot, and is absorbed instead of being reflected. The experiments described here show that this is the principal reason why a 50 percent dot pattern often absorbs more than 50 percent of the light.

Some measurements on the extent of this spreading of light in various kinds of paper were made by projecting a lamp filament on the paper and making a photomicrograph of the image, as shown in Figure 2.

A photomicrograph of uncoated paper made in this way is shown in Figure 3.

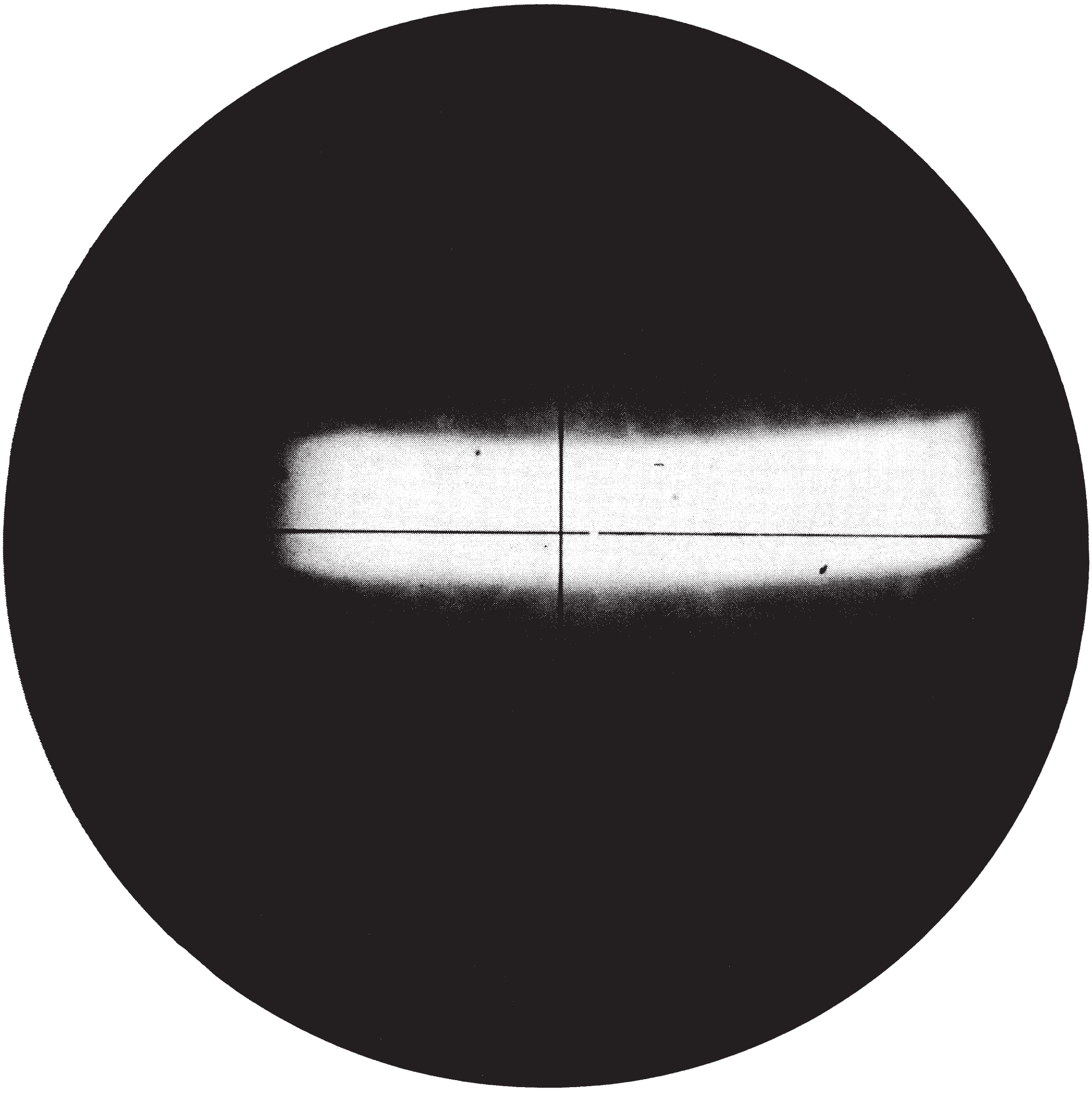

Figure 3. Photomicrograph of image of lamp filament projected onto uncoated paper (50X).

Instead of a sharp-edged image of the lamp filament being observed, the light is seen to spread appreciably beyond the boundary of the image.

Figure 4 shows a comparison of different kinds of paper made in this way. To make sure that the spreading of light was due to the paper rather than the optical system, a tarnished aluminum mirror was included, and this gave a very sharp edge, with very little spreading of light, as shown in the central strip of this illustration.

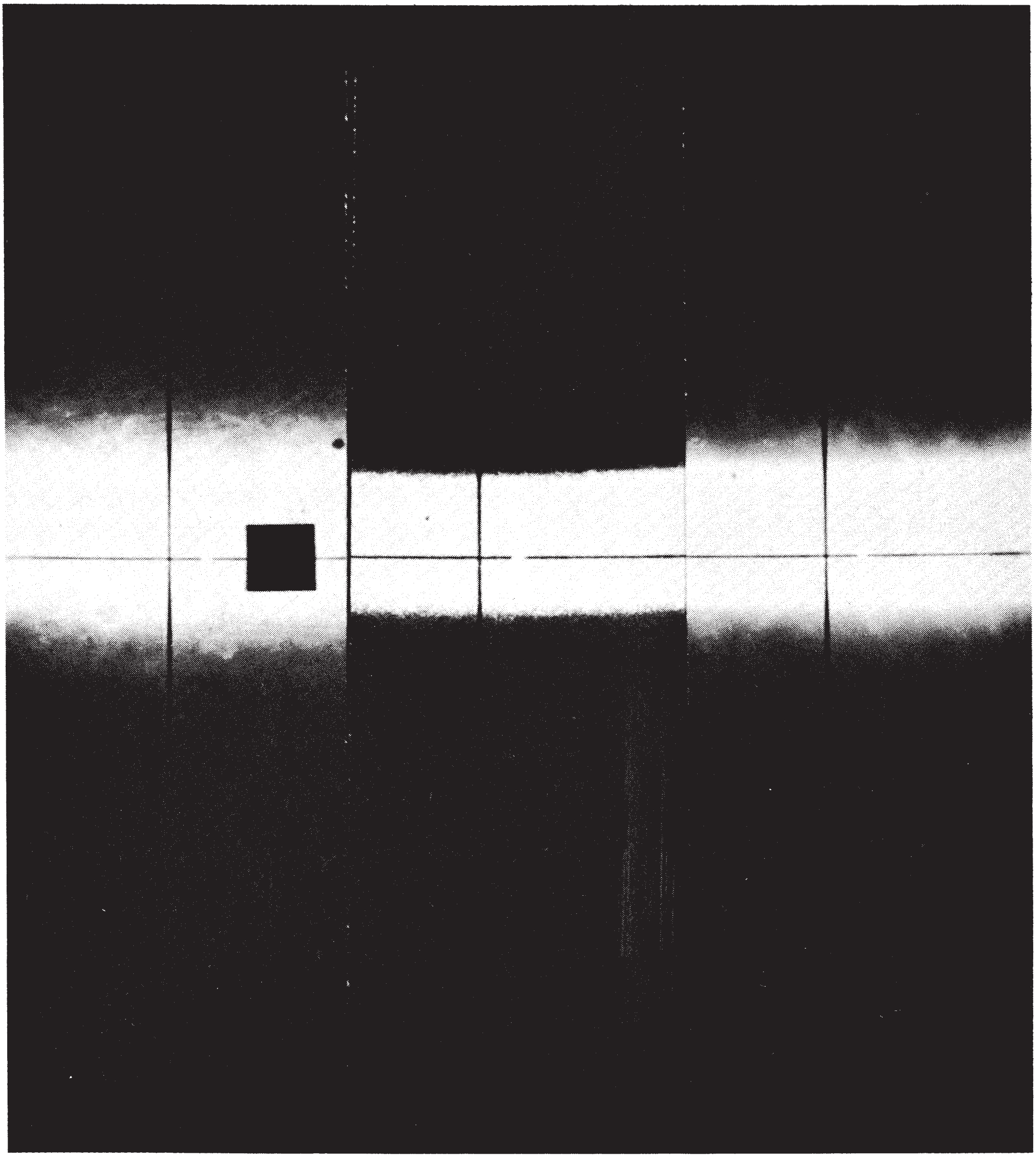

Figure 4. Photomicrograph of image of lamp filament projected onto (left) uncoated paper, (center) tarnished aluminum mirror, (right) coated paper (50X). The small black square indicates the relative size of a 50% dot made with a 150-line screen.

Microdensitometer traces of these photomicrographs have been plotted to show the actual amount of light-spreading. Even with the coated paper this is quite appreciable. With a checkerboard pattern and using a 150-line screen, between one-fourth and one-half of the light which enters the paper through a clear opening will probably emerge through a dot, and vice versa. The effect on the tone value of a halftone pattern can be indicated by considering the extreme case where the dots are so black that they absorb all the light that reaches them.

It will also be assumed, in this extreme case, that the paper is so translucent that the dot pattern is completely diffused before the light emerges from the paper. Considering a checkerboard pattern again --- that is, a 50 percent dot --- 50 percent of the incident light will strike the black dots and will be absorbed, as shown in the upper part of Figure 5, a shadow of the dot pattern being produced in the interior of the paper.

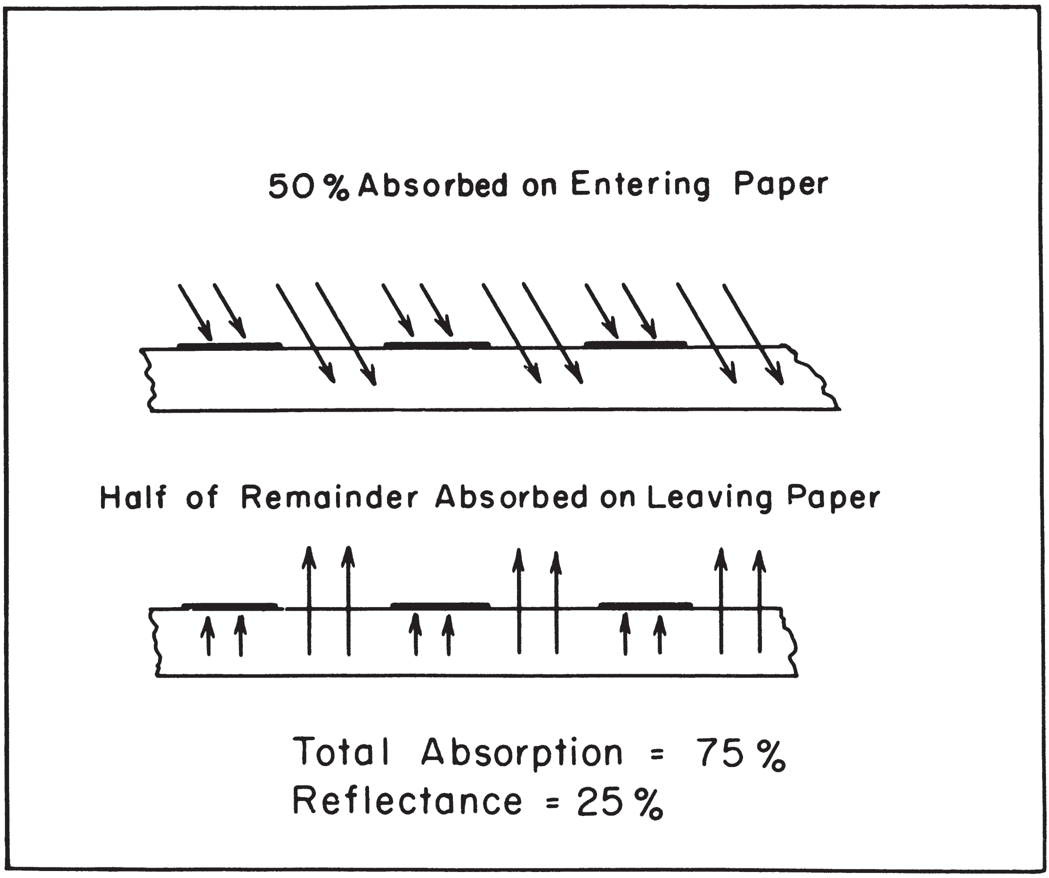

Figure 5. Absorption of light on entering and emerging from paper.

The remaining 50 percent will be diffused by the paper, so that it loses its dot structure, and half of it will be absorbed on the way out, as in the lower part of Figure 5. Only 25 percent of the original light will escape from the paper, so its reflection density will be 0. 6 instead of 0. 3. In practice, this would occur only with extremely fine screens, but there is a tendency in this direction with ordinary printing. A halftone pattern on opal glass, however, shows the effect very well.

Table 1 shows some results made with different screen rulings and different types of paper. In these examples, the halftone pattern was on stripping film and was stripped onto the paper.

Table I

Screen Ruling	65	133	133	150*
Dot Area	64.5%	76.6%	45.1%	61.1%
Transmission Density	0.45	0.63	0.26	0.41
Reflection Density:				
On aluminum	0.52	0.74	0.32	0.44
On coated paper	0.60	0.94	0.47	--
On uncoated paper	0.64	1.08	0.47	--
On opal glass	0.97	1.35	0.61	0.97

* Parallel-line screen.

In each case, the white paper, with clear film over it, was taken as 100 percent reflectance, and a correction was made for the surface reflectance of the stripping film.

Opal glass and grained aluminum represent the two extremes. In the case of the opal glass, where the dot pattern was almost completely diffused, the density was over twice that obtained with the grained aluminum.

It was expected that the reflection density of the halftone stripped onto grained aluminum would be equal to the transmission density before stripping, whereas a halftone stripped onto opal glass, which diffuses the dot pattern almost completely before the light emerges, would have twice the density if the theory were correct. Halftones on paper should have intermediate values. Actually, after correction for the effect of surface reflection, the reflection densities were slightly higher than was expected. The grained-aluminum discrepancy turned out to be chiefly due to the fact that the stripping film emulsion was thick enough so that the edges of the dots cast a shadow on the metal surface, and it could be eliminated by using a parallel line screen with lines parallel to the incident light. The high value obtained on the opal glass was due to another effect which will be discussed later.

In any case, these results effectively spoiled the simple equations which have been used in the past to represent the relationship of dot area to the reflection characteristics of the halftone.

The simplest of these equations is

$$\text{Absorption} = A_s a,$$

where A_s is the percent absorption of the solid ink, and a is the dot area.

In terms of light reflected rather than absorbed, the following equation can be used:

$$\text{Reflectance} = 1-a(1-R_s),$$

where R_s is the reflectance of the solid ink.

For practical purposes, we are more interested in density than percent absorption, so we can rewrite the same equation in the following form:

$$D = -\log\left[1-a(1-\text{antilog } -D_s)\right],$$

where D_s is the density of the solid ink.

These equations are equivalent to those published by Murray in 1935,[4] which have been used ever since as indications of the relationship between dot area and density.

What changes must be made in these equations to fit the new results? In the extreme case, where the support is completely diffusing, like opal glass, a fairly simple relationship might be expected to hold. Consider the events in four stages. Suppose one unit of light reaches the paper. Some of this (s) is reflected by the surface; 1 - s is not.

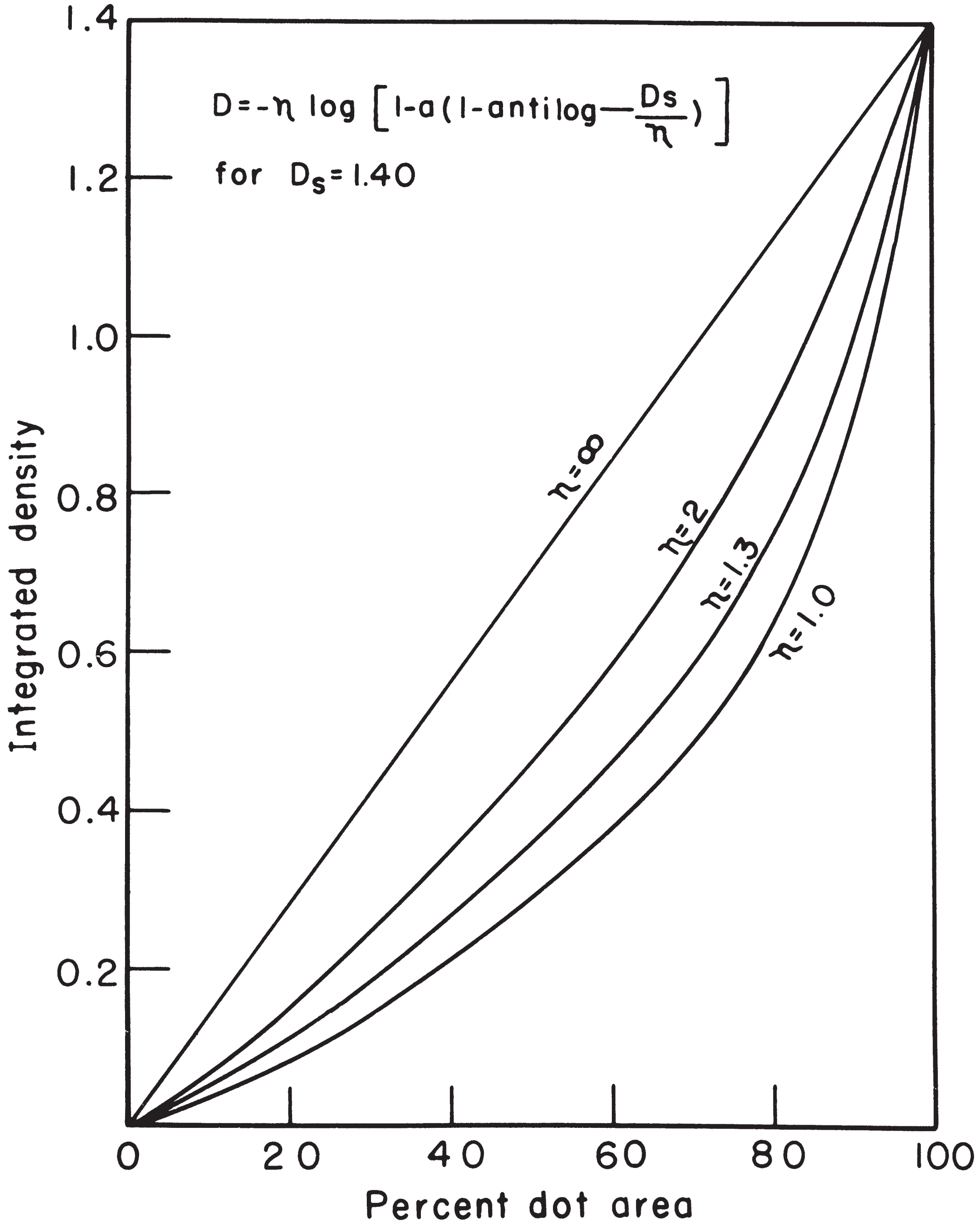

Figure 6. Relationship of density of dot area, calculated from the new equation, for various values of n.

This is transmitted through the dot pattern, and in so doing a fraction of it proportional to the dot area is absorbed, $a(1-T_s)$, where T_s is the transmittance of the ink film, and the remainder, $1-a(1-T_s)$, reaches the paper, where a fraction is absorbed by the paper and the remainder, R_p, is reflected. However, before it amerges, it has to take a second trip through the dot pattern, which again absorbs $1-a(1-T_s)$ of it. The fraction of the incident light which emerges is found by multiplying all these effects together and adding the surface reflectance to the result, so that the total reflectance of the halftone pattern is

$$\text{Reflectance} = s + R_p(1-s)\left[1-a(1-T_s)\right]^2.$$

We can simplify this slightly by leaving out R_p, since the reflectance of the paper cancels out if its density is taken as zero, which is usually done.

The value of s, the surface reflection, depends on the gloss of the paper and the ink. It is never greater than 0.04, and, if the surface is very glossy, it can be disregarded. If the value $a = 1$ is substituted in the equation, it is found that $R_s = T_s^2$, and the equation reduces to the following:

$$R = \left[1-a(1-R_s^{1/2})\right]^2.$$

In terms of density, the equation is

$$D = -2\log\left[1-a(1-\text{antilog } -D_s/2)\right].$$

This equation is not rigorously true for several reasons. Surface reflection always plays a part; the internal reflections affect the result; the paper does not completely diffuse the dot pattern; and it is not certain that the small dots carry as heavy a layer of ink as the solid, or that it is uniform over the area of the dot. However, in spite of these deficiencies, it does correspond closely to actual density measurements, at least for fine-screen work; and, with one slight modification, namely, the use of a different factor, it fits the observed facts still better, the equation being

$$D = -n\log\left[1-a(1-\text{antilog}-D_s/n)\right].$$

In simple terms, the only difference between this and the Murray-Davies equation mentioned previously is that the density is divided by two (or whatever factor is appropriate) before the calculations are made, and the final result is multiplied by the same factor.

Figure 6 shows the relationship of density to dot area calculated from this equation, for an ink density of 1.4, and for various values of n. Where $n = 1$, it corresponds to the old equation. If n were equal to ∞, density would be proportional to dot area, so that a straight line would be obtained.

The best values of n in this formula for various screen rulings, with coated and uncoated paper, are given in Table 2.

Table II

Screen Ruling, (lines per inch)	Value of n	
	Coated	Uncoated
65	1.3	2.0
150	1.8	--
300	3.0	--

A low value of n indicates that the spreading of light in the paper is small compared with the dot size, so it is lowest for coated papers and coarse screens.

Using these values of n in the formula, the observed densities were plotted against the calculated values, as shown in Figure 7, for 150-line offset printing on coated paper. The agreement is seen to be excellent for a value of n = 1.6. The upper curve corresponds to the old equation, or to the new equation with n = 1.

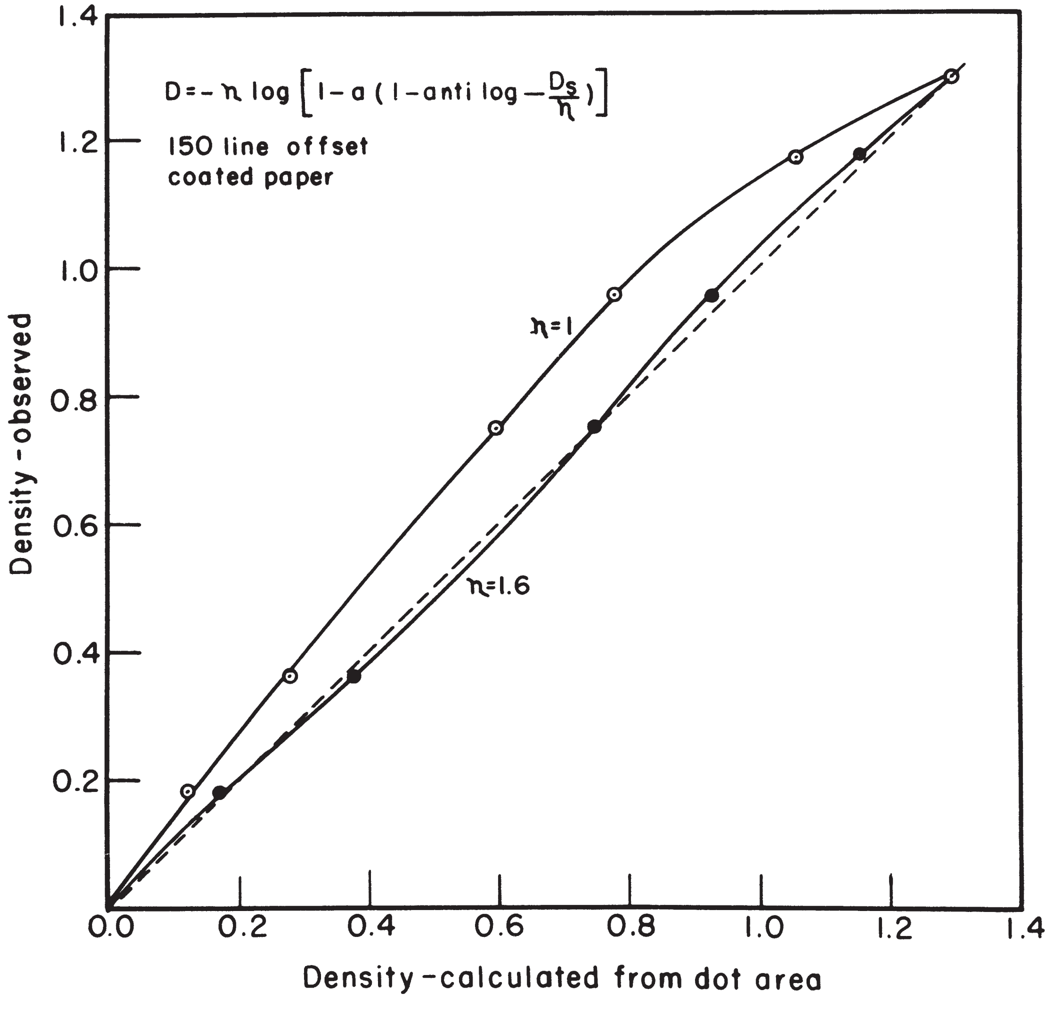

Figure 7. Observed vs. calculated density for old equation (n = 1) and new equation (n = 1.6).

In photoengraving, there is a complicating factor which affects the density, especially in the shadows. Some of the ink is squeezed over the edge of the dot, resulting in a thinner layer of ink over most of the dot area. The density reading is lower than it would be if the ink were spread over the surface uniformly. Thus, in taking the step where the shadows are just plugged up solid, a pattern of small black dots is seen on a slightly lighter background. This can readily be observed with a magnifier in any halftone illustration printed by letterpress. Although this must be counted as a solid in dot area measurements, its density is slightly less than that of the true solid produced by a plate having no dot structure. This slightly lower density is, however, more representative of the average ink density throughout the halftone scale.

If the density of the first solid step is used for the maximum density, the equation gives better agreement up to that point in the tone scale.

It should be pointed out that throughout this work we have been referring to the dot area in the printed reproduction, not that in the printing plate. The printing plate nearly always has a smaller dot area than the reproduction, but the dot spreading during the printing process is very variable. It must be taken into account in any attempt to understand the complete photomechanical reproduction process, but it does not enter into this work, which starts with the printed sheet.

Now that a formula has been given which works well in practice, the previously mentioned multiple internal reflection phenomenon will be discussed. We had previously believed this to apply only to continuous-tone images.

This new factor is due to the fact that a large part of the emerging light is reflected back into the paper by the paper surface, as was described by Williams and Clapper[5] at the Optical Society Convention in 1950. It is due to the difference in refractive index between the paper and the air, and occurs to those rays which are emerging at an oblique angle. These oblique rays are totally reflected internally.

Because of this, an appreciable amount of the light may be reflected several times before it finally emerges from the paper. This gives it extra opportunities of striking a halftone dot and being absorbed, and would account for the fact that the halftone tint on opal glass gave a density over twice as high as that predicted from the dot area.

The mathematical treatment of this phenomenon is rather involved, so no attempt will be made here to write an equation for it. However, its effect is similar to that caused by penetration of light into the paper, and the formula already given allows for it satisfactorily.

It should be emphasized, however, that the new equation is not theoretically rigorous, because of the multiple internal reflections and other factors. Although it was based on theory in the first place, it should be regarded as an empirical formula because of these other complications. It does, however, fit the observed facts quite well.

These phenomena have very pronounced effects in color work, even in a single color. The equation applies equally well to a colored ink, and enables us to calculate more accurately the amount of red, green, and blue light absorbed. The practical effect is that halftone tints appear more like a continuous-tone tint than they would if there were no penetration of light into paper. The same ink printed in a fine screen shows a definitely purer color than the same ink printed in a coarse screen, where these effects are negligible.

The general conclusion from all this is that the relationship between dot area and halftone density is not nearly so simple as it appears. The discrepancies described here represent only one of the many factors that affect photomechanical tone reproduction, but they are by no means negligible, especially in the lithographic field where uncoated papers are so commonly used.

Acknowledgments. The authors wish to thank the Photomicrography Department of these laboratories for making the photomicrographs of images projected on paper.

Rochester, New York
April 11, 1951.

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   No. 304 Optical Density
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DISCUSSION

QUESTION: Well, then, you say in the example there, there wasn't time to go into the calculation of that, but if you make some calculations for the red, green, and blue absorption of light based on those equations you would find that that would be your conclusion. Is there a difference in the degree of absorption?

J.A.C. YULE: What happens, is that the absorption of the most strongly absorbed color is increased more by this effect than the absorption of the other colors and that makes the color look purer.

HULL, R.R. Donnelley & Sons Co: Are you able to obtain sufficient contact with your screen to get good diffusion measurements on your paper when you strip your film?

YULE: Well, that was actual optical contact, we stripped it using a stripping film cement and the contact I believe was very good and that is indicated by the fact that when we stripped it down to the grained aluminum, the densities were just about as low as they ought to be.

HULL: Can you do that with practically any paper?

YULE: You probably couldn't do it on very rough paper.

McWHORTER, Goss Printing Press Co: I gathered from what you said that this effect was mostly pronounced on news print as compared to an enameled paper, as you know the engravers in newspaper engraving plants pull a proof on enameled stock and say, "Look what a good job I've done", and then when they print on the news print, it doesn't look so good. I think you pretty well described why. I wonder if you can tell me some rather simple photographic step we could use to drop out the middle tones in the photographic engraving process so that we could put this information to use right away?

YULE: I'm afraid there are other complicating factors besides this in the case of news print. The maximum density of the ink printed on news print of course is much lower and I think that is a more important factor in this case. Actually, although the paper is of a type which would allow more penetration of light, with news print you use coarse screens and that largely makes up for this fact. These effects that I've been describing, they are not so great as on coarse screen work.

G. HAMMER, Forbes Litho Co: In the operation called half tone blowup, I believe its either black and white or in color; I think it has been a general practice for the trade to consider that the enlarged dot pattern is going to reproduce lighter in color value than the fine screen dot pattern from which it was made unless something else compensates for it. That is described by some of the workers in the trade saying when you enlarge half tone image if it is printed with the same paper, with the same strength ink in it, with a much coarser screen, the white paper seems to gain upon the dots giving you less color saturation. It would seem here as if you would have something that might be considered an explanation for that, would you say?

YULE: I think this would account for that quite well.