POLYCHROMATIC COLOUR REMOVAL - REVOLUTION OR EVOLUTION?

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Abstract: The history of employing black ink as a substitute for the grey component of a three-colour reproduction is discussed and the development of both UCR and ´achromatic´ structure.

The criteria necessary to ensure that a colour match is obtained between a conventional reproduction and one produced with colour removal is defined, including the need for four colours in a limited range of tone values, together with the various mathematical models which will provide the effects.

The technique employed by Crosfield Electronics in developing Polychromatic Color Removal (PCR) is described together with the advantages of its application.

Introduction

The theory of Polychromatic Colour Removal is hardly new. At recent conferences it has been suggested that the first mention of it came from Tobias (1954). However, the first reference I am aware of comes from Yule (1940) in which he states that "if suitable corrected negatives could be made easily, the best results would usually be obtained by using the maximum possible quantity of black, and printing not more than two of the three subtractive colors at any one point. A brown, for instance, would be rendered by magenta, yellow, and black in suitable proportions. This will be called the ´first type of black printer´. This would have the great advantage that the neutrality of the grey scale would not be dependent on close control of the contrast of the three colour printers.

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On the other hand, such printers are difficult to make in practice; the author has, in fact, never seen a satisfactory print made in this way by photographic means, so that in practice something approaching the ´second type of black printer´, in which the black is only used to increase the range of neutral greys, is more commonly employed".

Thus we can see that the concept is one that has been around for many years and is hardly the revolution claimed by the more recent ´inventors´.

In the light of this it is interesting to ask why such an old concept is only now being properly applied and why the more limited form, commonly known as UCR, was never developed to its full potential. This has, I believe, arisen from two misconceptions and PCR could have been implemented many years ago had this been realised. Unfortunately the wide gap which sadly exists between theoreticians and practitioners of Color Reproduction precluded this.

The first misconception arose in the early development of colour scanners and was that UCR was somehow limited to the neutral axis only. This, I believe, had followed from the difficulties of making suitable negatives on a camera, as quoted by Yule earlier. Thus where UCR had been used it had only been applied in dense three colour overprints, i.e. near neutral. Believing this some scanner manufacturers spent a lot of effort defining ´neutrals´ in their colour space and applying UCR to those only. Inevitably this caused difficulties at the boundary between the neutrals and dirty colours.

The second misconception was that the separation of the colour space into chromatic and luminance components (to be reproduced by the coloured and black inks respectively) was necessary, a view which requires the spectral sensitivity of the colour separation system to be precisely defined. In fact this is quite incorrect and can only be provided by utilising two imaginary stimuli (inks) which lie on the alychne of the colour space. All real coloured inks have a significant luminance component. Obviously, knowing the chromatic and luminance components permits satisfactory colour removal to be calculated for real inks if the appropriate linear transformations are applied but it is not a necessary condition. This has been discussed at length by Johnson (1982).

In fact there are a number of theoretical approaches which can be applied to achieve the effect and these will be outlined in section 3. However, in order to understand them fully and particularly the development of PCR it is necessary to have a full understanding of the role of the Black printer. In two previous papers, Johnson (1984(a) and (b)), this has been discussed at some length but because it is important to a full understanding of the development of Polychromatic Colour Removal it will be reproduced here in section 2.

Prior to discussing the Black Printer it is interesting to briefly review terminology. The generic term ´achromatic structure´ has been widely used in Europe to describe the result; a term which is in my view, quite meaningless. More recently Sigg has suggested ´Grey Component replacement´ which is far more meaningful and very apt. It is to be hoped that this becomes more widely accepted. The various names coined by the scanner manufacturers have come about partly because of the unacceptability of the term achromatic structure and also to recognise the subtle differences between the techniques employed to obtain the result. However, they all fall under the generic term grey component replacement (as does conventional UCR).

The Black Printer and Grey Component Replacement (UCR/PCR)

The addition of black in colour reproduction has two quite distinct functions; (i) extending the gamut of colours in dark areas and (ii) replacing yellow, magenta and cyan with black ink (PCR/UCR). We know that whenever yellow, magenta and cyan print together the resultant colour has a grey component. This is an inevitable consequence of the theory of colour reproduction. The other process of colour reproduction which uses subtractive mixtures (i.e. photography) produces blacks which are sufficiently dense without the addition of blacks. Thus the addition of black in printing is purely to overcome limitations of the process, nothing to do with the limitations of the three colour theory.

Because of the printing inks used for three colour reproduction it is not possible to obtain a sufficiently dense black in reproductions, without addition of the black ink, by conventional printing. For this reason a black is added. However, a little thought shows that we only need to add black to increase the density of blacks already existing where yellow, magenta and cyan have reached their limit. Thus it is used to extend the gamut of dark colours. (Hence the use of skeleton blacks which are a practical approximation of this). This is the first of the two functions listed above.

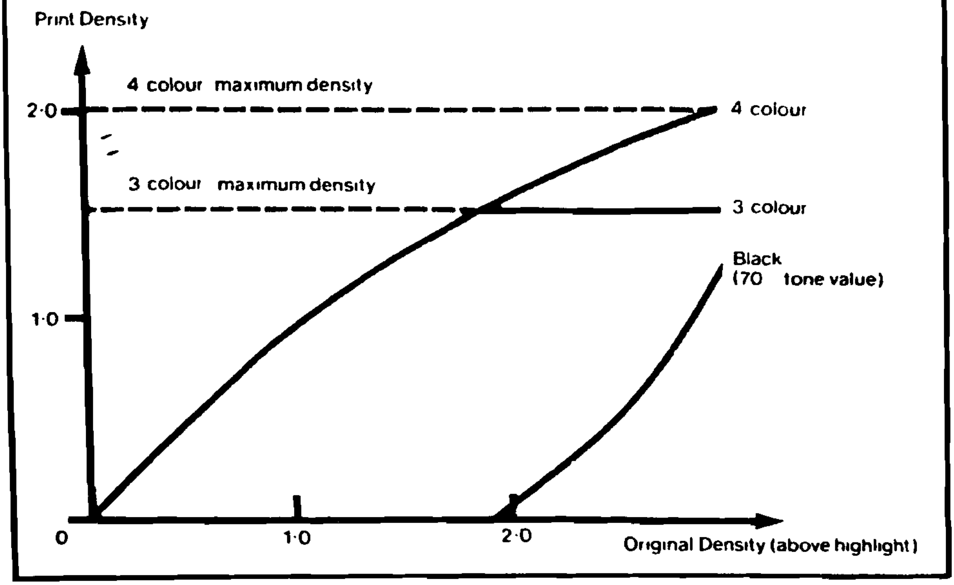
Figs. 1a and 1b show this graphically. 1a shows how black is added only when the three colour print has achieved its maximum density whilst maintaining a specific tone reproduction. 1b shows a more typical skeleton black which achieves the same tone rendering. (Note that this does in fact contain a small amount of UCR).

However, if yellow, magenta and cyan are being used to produce a grey it is natural to ask the question "can we remove this and replace it with the black ink (since we are printing a black anyway to extend the gamut)". The answer, of course, is "yes" and this is what the UCR and PCR are. This is the second of the two functions listed above and is quite separate from the first.

An important point, which many people fail to realise, is that the use of the term UCR should never have only been applied to neutral colours. All except the purest of colours contain three inks and hence a grey component. It has long been recognised that all (or some) of this can be replaced by black and for many people this has always been their understanding of the term UCR. Such people are amazed by the sudden "discovery" of the "new theory" of colour reproduction known as achromatic structure.

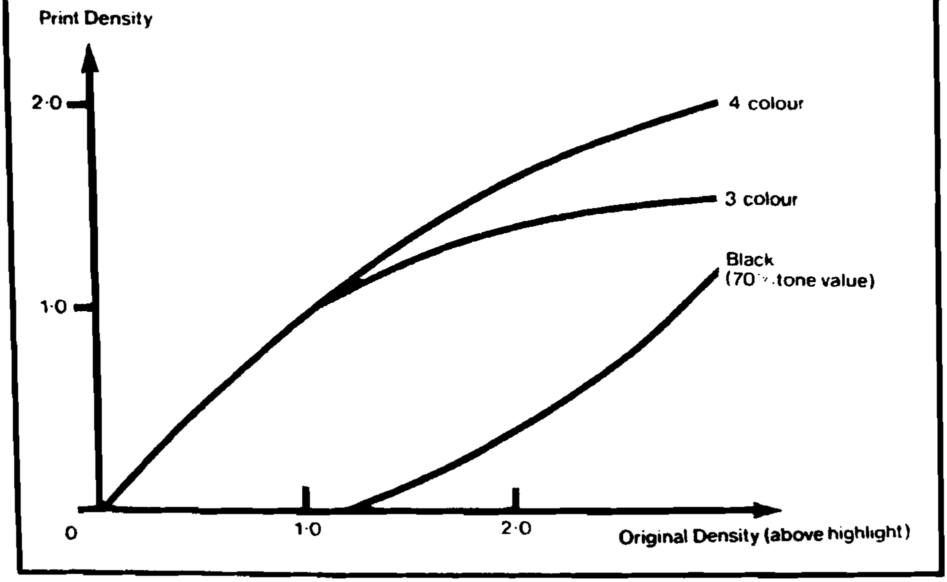
What is equally worrying is that many of the proponents of the achromatic structure seem to have lost sight of the primary function of the black ink; namely to extend the colour gamut. Thus they talk glibly of only having two colours and black in any one area. If this is done the maximum density achievable is lower than for a normal reproduction unless a dense black ink is used. This can hardly be considered desirable. Thus the application of PCR needs to be modified to take account of this. This is a trivial problem theoretically, and one that lends itself to a reasonably precise solution. What is surprising is that in much of the early information published about "achromatic structure" this was not seem to have been considered until the ´invention´ of ´Bunt´ addition to add to ´Unbunt-Aufbau.´

Figure 1a



Graph 1(a) shows the reproduction characteristic where the amount of black is kept to an absolute minimum and only prints when the 3 colour grey has reached its maximum.

Figure 1 b



1(b) shows the more common situation where black starts to print at a lower density and the 3 colour grey is reduced accordingly.

Figures 2a and 2b show two different ways in which PCR (or UCR) may be applied whilst retaining optimum tone reproduction consistent with the maximum density obtained by normal process colour. The former shows one of an almost infinite number of ways in which different levels of black can be combined with combinations of yellow, magenta and cyan whilst the latter provides the maximum colour removal possible which is consistent with these objectives and is that employed in Crosfield scanners. However, it should be noted that there is no unique solution to the problem; a number of combinations of black and colours will produce a similar result. We have employed that which provides the maximum removal in order to maximise the advantages given later.

Achieving Grey Component Replacement on a Scanner

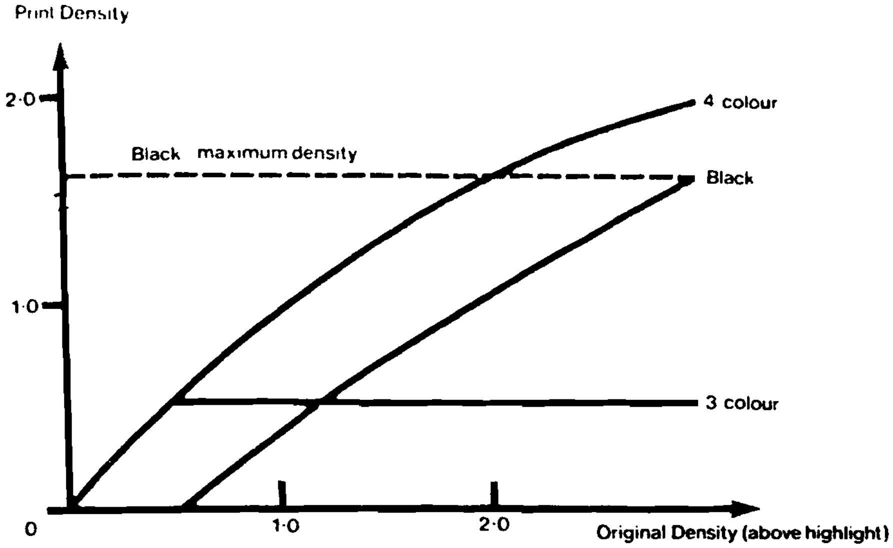
Because of the metameric nature of a grey component replaced reproduction, relative to a conventional one, the strict definition of a match between them is quite clear. It can only be correct for one viewing condition and under that condition the tristimulus values must be equal for all areas of the image. If one can be certain that this has been achieved then it will be impossible to tell the difference between a normal and a PCR set. It is fortunate that the degree of metamerism is not great but anybody who has viewed a normal and PCR set side by side under different illuminants will be aware that it is present. Thus the case for standard viewing conditions is further strengthened.

Because of this the obvious methods for obtaining PCR are based on colorimetric techniques. However, they are not necessary. It is possible to obtain a good colour match by careful definition of the grey component as will be described later. This has the significant advantage that colorimetry is not then required for the set-up; a tool available to very few printers.

There are various mathematical models which may be utilised to achieve the grey component removal required. Two of these are well known and require little introduction at this conference.

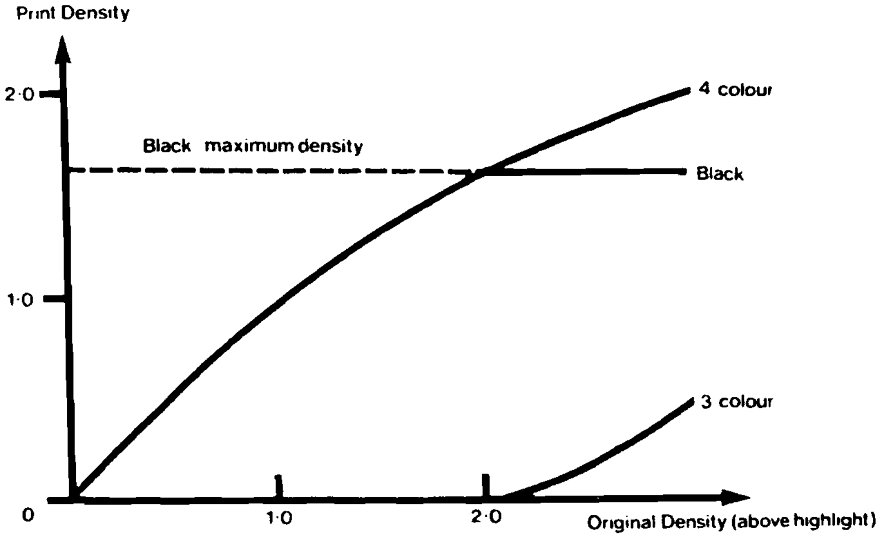
i) Neugebauer equations:- It was shown by Neugebauer (1937) that the tristimulus values of a colour can be written as a function of dot area. These equations are

Figure 2a



2(a) shows partial UCR limited to a specific value to maintain the 4 colour maximum density. If full UCR is applied then a special high density black is needed.

Figure 2b



2(b) shows Crosfield Polychromatic Colour Removal where the maximum black is applied, but 3 colour grey is also introduced to give the density differential in the shadows. Thus the 3 coloured inks are kept to an absolute minimum with all the attendant advantages.

based on the assumption that the colour produced by a halftone process can be described as an additive mixture of the individual inks and their overprints. The area of each is determined by assuming that the halftone dots are randomly distributed thereby giving the equation:

$$\begin{aligned} X = \; & (1 - c)(1 - m)(1 - y)X_w + c(1 - m)(1 - y)X_c + \\ & m(1 - y)(1 - c)X_m + y(1 - c)(1 - m)X_y + mc \\ & (1 - y)X_{mc} + cy(1 - m)X_{cy} + my(1 - c)X_{my} + \\ & cmy\ X_{cmy} \end{aligned}$$

where X is the tristimulus value of the colour; X_w, X_c etc. are the tristimulus values of the individual components and c, m and y are the fractional dot areas. Similar equations arise for Y and Z.

In order to overcome the errors in the Neugebauer equations, usually associated primarily with light scattering in the paper, Yule and Colt (1951) suggested raising the tristimulus values to the power 1/n, where n is dependent upon the paper. If n = 1 then the equations reduce to the basic equations above.

These equations are not easy to solve and may only be so by iterative means. A method for doing this was discussed in great detail by Pobboravsky and Pearson (1972). In their paper the authors considered the combination of 3 colours as well as 2 colours and black thereby giving two solutions to the problem one of which produced PCR (except for the necessary gamut extension described earlier).

For a general solution to the four colour problem additional terms have to be added; the value d for the dot area of the black and X_K, X_{KC} etc. for the tristimulus values. Obviously this makes the equations insoluble. In order to overcome this the restriction must be added that d x; the smallest of c, m, y (having taken account of grey balance). Then if d = mx a solution is possible albeit in two stages.*

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*Note the assumption that for equality of appearance d=x. This depends on the inks. We find that in practice a good approximation arises from d=ax but even this is not strictly accurate. What should be written is d=f(x)x. f may be determined by measuring the density (or luminance) of a scale of greys produced both by three colours and black.

Pobboravsky and Pearson (1972) achieved the solution described earlier by setting each of c, m, y and d to zero in turn and obtaining the three colour solutions, that with c, m, y and another with two of these and d. This is effectively setting m = 1.

Crosfield seriously considered using Neugebauer equations as a technique for achieving PCR. A recent study by Johnson (1985) showed when dot area is determined in an appropriate manner it provides a suitably accurate method of computing dot area. The reason it was rejected was the iterative solution required each time printing conditions change and the necessity for colorimetry since the grey component is never defined unless the equations are solved in two stages.

ii) Masking equations:- Rather than calculating the grey component replacement in the dot area domain an alternative approach is to remove the grey component in the original density domain. For this we could utilise masking equations, either first order as derived by Yule (1938) or higher order as suggested by Clapper (1962) which overcome some of the problems arising from additivity and proportionaltity failure.

The masking equations do not lend themselves readily to inclusion of a black. Obviously they could be rewritten to give:

$$D_r = C + mr^M + y_rY + K$$

where K is the density of the black. (It is assumed that the black has the same density through each filter). Unfortunately this would only give three equations with four unknowns and hence the solution is not unique.

However, if the density values D_r, D_g and D_b are equal for a neutral then a solution may be obtained by applying some specific restriction. Any colour will have a neutral component defined by its smallest density and by assuming additivity the value of K may may be determined.

For a given colour in the original let the neutral component be defined by $D_r{}^1 = D_g{}^1 = D_b{}^1$. Let n be the fraction of the neutral component to be printed by black. Then the equation above becomes:

$$D_r = C + m_r M + y_r Y + nD_r{}^1$$

with similar equations for D_g and D_b. We thus have the solution:

$$C = a_{11}(D_r - nD_r{}^1) + a_{12}(D_g - nD_g{}^1) + a_{13}(D_b - nD_b{}^1)$$

$$M = b_{11}(D_r - nD_r{}^1) + b_{12}(D_g - nD_g{}^1) + b_{13}(d_b - nD_b{}^1)$$

$$Y = c_{11}(D_r - nD_r{}^1) + c_{12}(D_g - nD_g{}^1) + c_{13}(D_b - nD_b{}^1)$$

$$K = nD_r{}^1$$

Additivity failure does make this analysis somewhat academic, a more complex analysis would be required to take account of this. Clapper (1962) discussed how this might be achieved by the second-order equations by dividing the colour space into zones in each of which only three of the four inks are varying and each with its own set of transformations. The number of zones and transformations depends upon the black printer ´rule´ applied.

From this discussion it is apparent that removing the grey component in original densities would be possible, but because of additivity and proportionality failure modification to the colour correction would be required. Crosfield also considered this approach but rejected it simply on the grounds of the existing signal processing path in the scanner.

The above discussion applies to the consideration of the black as a replacement for the grey component of the process inks; i.e. UCR. However, we need to recognise that the most important role of the black ink is to add density and thereby extend the gamut for the darkest part of the colour space. Obviously the limit to this is when both the black and the three colour grey have reached their maximum (i.e. 100 per cent dot of black and at least one of the three colours). Unless the additivity failure is very high, which is likely only when the black ink is very dark or intense, the region of colour space which will be produced by this combination will not be achievable by black ink alone. At this point a separate analysis is required.

In fact we now have a situation where at one point the solution to the four colour problem is unique and for regions of the colour space close to it the range of solutions is limited. This is easy to handle with the Neugebauer equations by noting that when c, m or y are greater than 1 then the restriction that $d = mx$ is removed. The solution is then obtained by maintaining the appropriate c, m or y at 1.

For the masking equations the solution is obtained in a similar way; when c, m or y have reached their limit the restriction on K is removed.

As stated earlier we considered both Neugebauer and Masking equations but because of existing signal processing and/or the need for colorimetry we rejected both. Instead we developed a technique which undertakes PCR following tone reproduction, colour correction and calculation of the black. Because the scanners are digital we have considerably more flexibility as to how and where such calculations are achieved. We have endeavoured to ensure that when applying PCR the operator has to make no editorial adjustments to the scanner unless non-standard printing conditions are encountered. This will become clear when the method applied is described. Thus the method used lets the operator set his scanner up exactly as normal for the work in hand and then having done this, with figures he is familiar with, can implement the desired level of PCR without any further changes, being assured that the result will match the normal reproduction.

The method applied is an extension of that described by Otschik (1981). This describes how to achieve the replacement of cyan, magenta and yellow by black but does not consider the problem of the additional black to extend the colour gamut. It is in this area that Crosfield have developed the idea further.

The method used breaks down into four steps, as follows:-

a) Removal of Grey Component - The grey component in any colour containing three inks is calculated from the grey balance conditions for those inks. The appropriate values are removed from each ink.

b) Replacement by Black - The density of grey removed in step (i) is replaced by the same density of black. The default values in the scanner are set to relate to that customers' inks printed under standard conditions. However, facilities are provided to enable the operator to modify the proportion of black where a different ink is used which is particularly dense or light.

c) Correction of Colour Values - The removal of the grey component in step (i) leads to a desaturation of colour for the two remaining components. This is quite predictable and follows from the unwanted absorptions of the inks and the halftone structure (additivity and proportionality failure). One way around this problem is to undertake the PCR in the original density domain, prior to colour correction, as described earlier. However, the advantage Crosfield has in their digital scanners is that relatively complex computations can be undertaken with ease and thus it is a simple task to correct the remaining colours to take account of the problem. In the report by Otschik mentioned earlier a correction curve was published which we found to be fitted by the equation:

$$y = 10^{x^2}$$

where y = correction factor and x = fractional area of black replaced. However, the appropriate curve for the customers conditions is set during installation and facililties have been provided to the operator to enable him to modify the correction for other stocks and/or inks.

d) Addition of Existing Black - In order to achieve the gamut extension which black is primarily there to produce it is neceesary to add the black ink values for normal printing to those calculated to replace the three colours when PCR is applied. Two problems immediately arise, additivity failure and limited maximum density.

A simple addition of the black ink values does not suffice; the phenomenon of additivity failure precludes the correct result by this means. In order to overcome this problem we note that additivity failure can be approximated by the equation:

$$y = (1-b/K)x+b$$

where K is the convergence point of the additivity diagram, b is the density of the replacement black and x is that of the original black. This follows directly from Yule (1967). Thus the value y gives the total black required.

For dark colours in the reproduction it is inevitable that the amount of black required will be greater than 100 per cent because of the limited maximum density. This is obviously impossible. Thus in such situations it is necessary to add a three colour grey to the reproduction in these areas. By applying the additivity failure logic above in reverse the amount to be replaced may be determined directly.

The default values in the scanner are such that the correct result is produced for standard printing conditions. However, if required the operator may increase or decrease the amount of black and/or three colour grey added by a simple factor. This is likely to be required for low quality substrates and non-standard inks. For standard printing conditions, however, no operator decisions are required; the calculations above are implemented directly the command to apply PCR is entered.

One way to get around the problem of limited maximum densities, without adding colour under black, is to print a more dense black ink. However, this imposes certain difficulties. At present I know of no sufficiently dense inks and furthermore this precludes a mix of PCR and conventional separations being printed together. There may also be gloss and printing limitations and so it seems likely that many printers will prefer to retain their normal black inks. The "Unbunt-Aufbau theory" has now had to be modified to recognise this rather obvious fact and the term "Bunt addition" has been added to the terminology. Conventional UCR and black printer theory has always recognised this fact and it is this that is implemented automatically in PCR as a direct consequence of the printing conditions.

Printing PCR

All the advantages of PCR are to the printer, there are none for the reproduction department. However, the advantages can be significant; they are

a) Reduced colour variation on the run - greater variation in inking level for the coloured inks is possible, without detriment to the reproduction, than for normal separations. Thus for the same levels of press control less colour variation occurs. On the other hand the black becomes more critical.

b) Lower ink costs - for a typical reproduction I estimate that approximately 40-50 per cent of the coloured inks will be saved and the black ink will be doubled. It does depend upon the relative costs of the inks but 20-25 per cent saving ought to be achievable, at least, for a firm not employing conventional UCR. However, the savings are not so significant where high levels of conventional UCR are employed already.

c) Lower energy costs - Associated with the reduced ink consumption is the saving in drying costs.

d) Reduced likelilhood of set-off - because less ink is printed coldset any non-heat set less likely to set-off.

e) Reduced ink acceptance (trapping) problems.

f) Increased sharpness - Since more information is in the black separation the resultant reproduction appears sharper particularly when small register errors occur.

All of these advantages have been proven in practice in lithograpy and are equally applicable to gravure. In my opinion by far the most important advantage is the first since many companies already employ some levels of UCR and will only obtain marginal cost savings. The quality advantage on the other hand can be significant.

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