# HIFI Color Printing within a Color Management System

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## Introduction

About five years ago the concept of high fidelity color[1-4] was introduced in the graphic arts community as a reaction to digital color reproduction systems such as video and the internet. Graphic arts manufacturers, suppliers and providers unified their forces to develop new technologies for making print more vivid, more convenient and economical. However, each provider has its own interpretation to reach this goal and as a result there is no clear difference between conventional offset and Hifi color printing. Because also with conventional offset techniques very pleasing images can be obtained, the main criterion for Hifi color printing is related to the quality of the printing process and hence we assume that Hifi color printing corresponds to high quality printing.

One way to increase the image quality of offset systems is obtained by expanding the gamut with additional inks. However the workflow of such a process is different from the conventional CMYK offset process. Quite a lot of technical issues have to be solved such as what is the gamut increase of processes with more than four inks, how can we model such processes and make profiles, what about screening and is the ICC profile specification flexible enough for such print processes? The aim of this presentation is to discuss these technical issues in the case of a Hifi print process based on the Hexachrome™ ink set of PANTONE®.

## Image Quality

The image quality of color reproduction devices is influenced by quite a lot of factors such as the paper, the ink set, the basic resolution of the printer, screening and color management. For a given offset system, however, most of these parameters are fixed, and hence the image quality can only be enhanced by optimizing the last two rendering parameters.

Screening is a technique to simulate several gray or color shades for devices with a limited number of gray or color levels such as binary black and white printers. With this technique a compromise is found between the number of shades for each color that can be reproduced and the resulting image resolution. In general the higher the image resolution the less number of shades can be used and vice versa to obtain the same quality.

Color management on the other hand is responsible for the transformation of colors to the device color values, also referred to as the transformation between device independent to device dependent color spaces. Here different approaches are possible depending on the kind of images, the input and output devices and the preferences of the user. This transformation to device color values should be colorimetrically correct e.g. neutrals should remain neutral, preserve detail both in the low lights as in the high lights, reproduce powerful images, and no artifacts or banding should be present.

In general the best image quality is obtained with devices with a high resolution and a large dynamic range, both in gray values as in color saturation. This range, also referred to as the gamut of the device, should be large enough so that images from any source can be reproduced exactly. In general however, the gamut of color reproduction devices is too small to reproduce all the colors of the most common input devices. One of the tasks of a CMS is to map the out of gamut colors onto printable colors in such a way that the visual difference between the out of gamut color and the corresponding in gamut color is as low as possible. The gamut mapping strategy determines to a large extent the resulting quality of the color management system. Consequently we assume that the image quality of a Hifi color system is increased if its color gamut is enlarged significantly.

## Hifi Color Workflow within a CMS

To enlarge the gamut of the CMYK offset process, three fundamentally different approaches have been used. To expand the gamut with the conventional CMYK inks, each ink is printed twice to obtain higher densities. In general, higher densities correspond to more saturated colors but the most saturated colors darken if their densities increase. To overcome this problem more saturated CMYK inks can be used. In this way images can still be printed on offset presses with four stations, but because we are working with a non standard ink set, the inks will be more expensive. A final solution is obtained by extending the CMYK inks with additional inks. A typical example is the Kuppers ink set.[5] In this case the CMYK inks are extended with a red, green and blue ink. With this ink set the secondary colors are obtained with one ink instead of overprinting two inks and hence these secondary colors will be more saturated and lighter.

In our Hifi color approach, the gamut is expanded by making use of additional inks based on the Hexachrome™ ink set. Hexachrome™ is the Hifi system developed by PANTONE® in which six inks are used,[3] i.e., cyan (C), magenta (M), yellow (Y) and black (K) extended with an orange (O) and a green (G) ink. In this system also the primary colors cyan, magenta and yellow have been changed, for example to obtain deeper blues.

To support the Hexachrome™ Hifi workflow a CMS should be used. The basic functions of such a CMS allows to scan, to proof and to print images properly. However, no good results are obtained if the corresponding guidelines from scanning to proofing and printing are not respected. Separations in general assume that a number of conditions are respected and in the case of a more complex print process such as Hexachrome™ this is even more important. Therefore it is necessary that with a CMS guidelines containing the preferred workflows of at least more complex reproduction systems are given.

## Color Gamut of Ink Processes Terminology

### Terminology

The independent variables with which a printer can be addressed to reproduce a given color are called inks or colorants. If there are n colorants, the printer is called an n-ink or n-colorant process. For simplicity, the values of the colorants or simply the colorant values are normalized between 0 and 100 %. If they are represented in an n-dimensional space or colorant space, all the physically realizable colorant combinations are contained in a n-dimensional cube or colorant cube.

The behavior of a color printer is described by the printer model. This is a transformation from colorant space to color space. The domain of the printer model is the colorant cube, the range is the gamut of the printer, a three-dimensional volume in color space. We suppose that the printer model is a well-behaved function, e.g. it is a continuous function in the colorant domain.

### Color Gamut Representation

In most cases the gamut is represented in the xy-chromaticity diagram. For a CMY or CMYK printer this is done by taking the convex hull of the xy-chromaticity coordinates of the primary colors, i.e. 100% cyan, 100% magenta and 100% yellow, together with the chromaticity coordinates of the secondary colors, i.e. red (overlay 100% magenta and 100% yellow), green (overlay 100% cyan and 100% yellow) and blue (overlay 100% cyan and 100% magenta). This results in a hexagon obtained by drawing lines between the colors red, yellow, green cyan, blue, magenta and red.

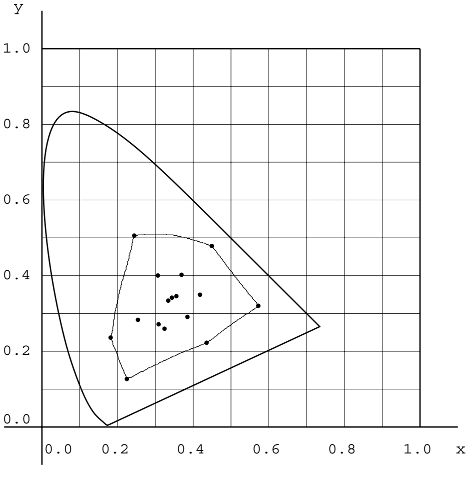

*Figure 1. Gamut in the xy-chromaticity diagram of the Hexachrome™ CMYK process*

A more accurate representation is obtained if all the colorant combinations are transformed to XYZ by making use of the printer model and projecting these colors in the xy-chromaticity diagram. This is shown is Figure 1 for the CMYK process of Hexachrome™ . Here the outline is close to a hexagon. The gamut of the Hexachrome™ process is given in Figures 2 and 3. This gamut is obtained by taking the union of respectively 3 and 5 4-ink processes. In Figure 2 the gamut is based on the processes CMYK, OMYK and CGYK. In Figure 3, the gamut is based on the processes CMYK, OMYK, CGYK, COMY and CGMY.

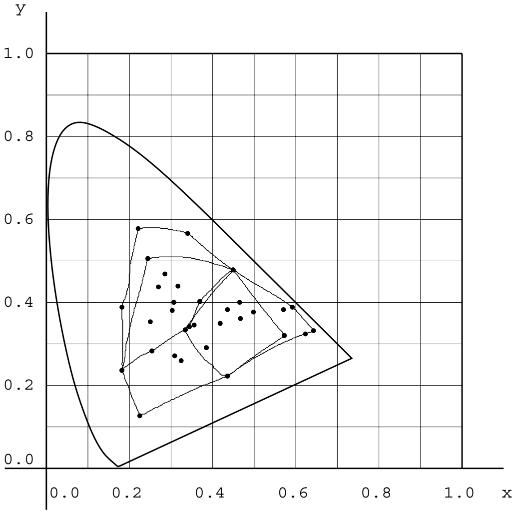

*Figure 2. Gamut in the xy-chromaticity diagram of the Hexachrome™ processes CMYK, OMYK and CGYK*

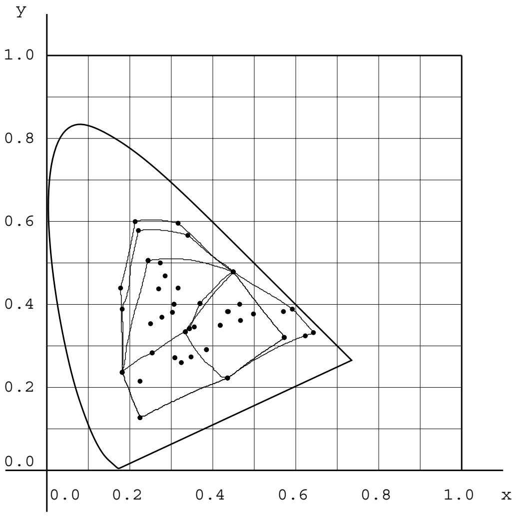

*Figure 3. Gamut in the xy-chromaticity diagram of the Hexachrome™ processes CMYK, OMYK, CGYK, COMY and CGMY.*

The representation of a gamut in an xy-chromaticity diagram gives only a broad idea about the color range, because colors are specified with three more or less independent values and hence the color gamut of a reproduction device is a volume in a three dimensional color space such as XYZ or CIELAB.

A more detailed representation of a gamut is obtained by intersecting the gamut in a psychovisual space such as CIELAB at different lightnesses and hue angles and counting the number of colors per cross section. Hence a good gamut representation is obtained with two graphs, one that specifies the number of colors per lightness cross section and another graph that relates the number of colors per hue intersection.

## Color Gamut Calculations

As indicated in the previous sections, the gamut of a color reproduction device should be represented in a device independent color space. If the relations between color and colorant values are continuous functions and if the domain of the physically achievable colorants is connected in colorant space, the resulting gamut in color space is also connected and the transformation of the colorants of an ink process with more than two inks results in a volume in color space. Such a gamut is completely determined if its boundaries are known in color space. In the three-dimensional color space these gamut boundaries are two-dimensional surfaces. Due to the continuous relation between color and colorant values, there should be 2-dimensional surfaces in colorant space that are mapped on the gamut boundaries in color space by the printer model. These surfaces in colorant space are called colorant boundaries.

In previous article 6 we indicated that different kinds of boundaries have to be taken into account depending on the printer model and the number of colorants of the ink process. For a 3-ink process there are two kinds of boundaries, i.e., physical boundaries due to limitations of the ink process and natural boundaries due to the color mixing of the inks. The gamut of a 3-ink process is obtained by taking the envelope of these surfaces transformed to color space by the printer model.

We also showed that the concept of physical and natural boundaries can be extended for 4-ink processes, but that another kind of boundary has to be taken into account. We called this a hybrid boundary because it can be seen as a mixing between physical and natural boundaries. Evaluation of different 4-ink processes indicated that natural boundaries are very rare and hence the gamut can be obtained as the union of the gamuts of the 8 extracted 3-ink processes of the 4-ink process.

For n-ink processes with more than 4 inks, it is possible to show that more than three kinds of boundaries exists that determine the gamut boundary. However from a practical point of view, no more than four inks will be used to obtain a color. Hence the reproducible gamut of an n-ink process can be obtained as the union of a number of 4-ink processes. To study the Hexachrome™ process 5 different 4-ink processes have been printed and modeled by making use of the IT8/7.3 target, i.e. CMYK, OMYK, CGYK, COMY and GCMY. The gamut of the CMYK process, the union of the CMYK, OMYK and CGYK, and the union of all five processes are shown in Figures 4 and 5. Here we see that the gamut of the Hexachrome™ process is extended significantly in the orange and green region compared to the CMYK process. If the gamut of the three 4-ink processes are compared to the gamut of all five 4-ink processes, there is a small gamut increase in the yellow region. However compared to the gamut of positive transparency and CRT display, there is still a large gap, mainly in the blue region.

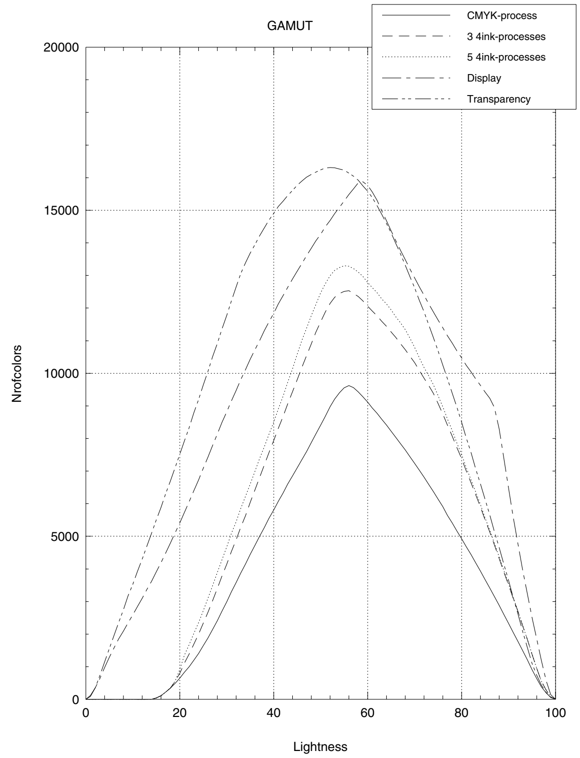

*Figure 4. Number of colors in gamut cross sections for different lightness values.*

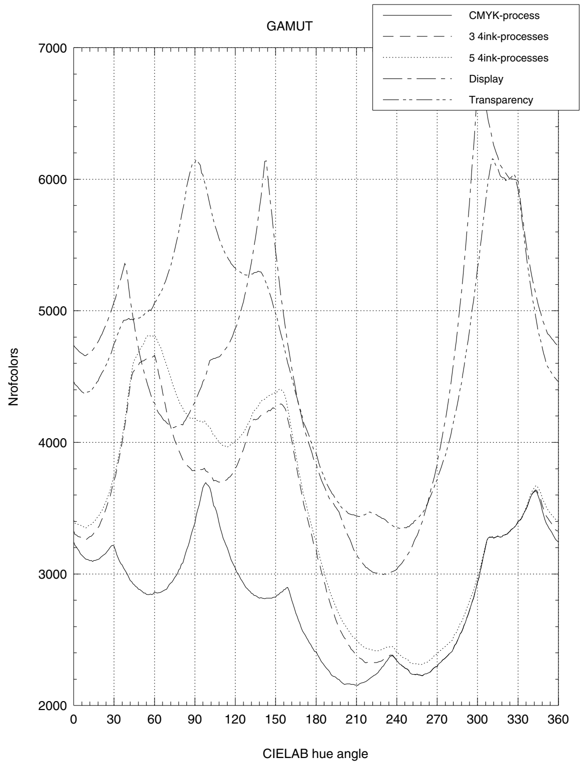

*Figure 5. Number of colors in gamut cross sections for different CIELAB hue values.*

## Color Separations

A printer model relates color values in function of colorant values. In case of color separations the inverse transformation is needed.

### 3-ink Process

For a 3-ink printer such as a CMY printer, the printer model relates color values in function of CMY values, i.e. for every CMY combination there is one set of color values. Intuitively one would think that also for the inverse transformation one set of color values corresponds to one set of colorant values. In general however for every color there is a finite number of colorant values with which this color can be reproduced. For a “well-behaved” 3-ink process such as most CMY processes there will be at most one set of colorant values inside the colorant domain for an in gamut color.

### 4-ink Process

In the case of a 4-ink process, typically a CMYK printer, there is no longer a one to one relationship between color values and colorant values. In general every color inside the color gamut can be reproduced with an infinite number of colorant values. Only colors at the gamut boundary are reproduced with in general one set of colorant values (or in special cases a finite number of sets of colorant values). To solve this problem an extra constraint on the colorant combination is needed. In most cases this has been a constraint on the black component because there is an exchange between CMY values on the one hand and black K on the other. Several strategies manipulating the amount of black have been used for several decades in the graphic arts and are known as GCR, UCR and UCA.

### n-ink Process

From a theoretical point of view, with an n-ink process such as Hexachrome™, colors can be reproduced with up to n colors. Due to printing limitations however colors cannot be printed with more than 400% dot percentage and apart from a small gamut enlargement there is almost no advantage in printing with more than 4 inks to obtain a given color. Hence the separation of an n-ink process will be based on a limited number of 4-ink processes. The choice of these 4-ink processes determines the gamut and should be in agreement with the separation strategy to avoid discontinuous separations or severe inversions.

## Screening

Offset presses are binary devices with a rather high resolution (1600 dpi or higher). The smallest dot a device can print is called a microdot. With a binary printer only a limited number of colors can be created, e.g. for a 4-ink process 16 (=$2^4$) colors can be obtained in overprinting the inks. To simulate several shades of colors, screening techniques should be used.

Suppose we have a binary black and white printer. To simulate several shades of gray values, larger dots are printed by activating a number of microdots in a given neighborhood. The size of the dot depends on the gray value we want to reproduce. If the dot structure is almost invisible or not disturbing the resulting gray value is obtained due to additive mixing of the black dots and the paper. By changing the size of the dots properly continuous tone information can be rendered. This kind of screening is called conventional screening or amplitude modulation because the size of the dots is changed but the distance between the dots is the same. In a second screening technique the microdots are randomly distributed in a given neighborhood, the size of the (micro)dots is the same but the average distance between the (micro)dots is changed. This kind of screening is called stochastic screening or frequency modulation.

In the case of color images the different components are screened and printed on top of each other. For conventional screening periodic patterns will be visible to the interactions between the screens. The high frequency pattern is called the rosette structure and is almost not disturbing at all. Lower frequency patterns (moiré) on the other hand are always quite visible and should be avoided as much as possible. For stochastic screening however no periodical artifacts are visible but graininess is introduced if several components are printed on top of each other.

Depending on the separation strategy the different components have to be screened properly. This can be both by making use of conventional and stochastic screening techniques. However in case of stochastic screening techniques details are better preserved in the low lights and the high lights and we have the impression that a larger gamut is obtained.

To investigate mechanisms that might influence the gamut size, three simple mathematical models are used with which the spectral behavior of 1-ink processes can be predicted quite accurately. The first model corresponds to the Murray-Davies model,[7] i.e.,

$$R(\lambda) = \alpha R_{100}(\lambda) + (1 - \alpha) R_w(\lambda)$$

with $R_w(\lambda)$ the reflectance curve of the paper, $R_{100}(\lambda)$ the reflectance curve of the 100 % patch $\alpha$ the dot area.

The second model is the spectral Yule-Nielsen model[7]

$$R^{1/n}(\lambda) = \alpha R_w^{1/n}(\lambda) T_{100}^{2/n}(\lambda) + (1-\alpha) R_w^{1/n}(\lambda)$$

with n the Yule-Nielsen factor. The third model can be seen as an extended Murray-Davies model because not only the dot area is taken into account but also the thickness of the ink layer. Mathematically this model can be described as follows :

$$R(\lambda) = \alpha R_w(\lambda) T_{100}^{2d/d_{100}}(\lambda) + (1-\alpha) R_w(\lambda)$$

with $T_{100}(\lambda)$ the transmission curve of 100% patch, $d_{100}$ thickness of ink layer of the 100% patch. In the IT8/7.3 target there is a step wedge for each ink with dot percentages 0, 3, 7, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, and 100. For each of these patches we optimized the parameters of the different models. The values are given in Figure 6 for the cyan ink process, both for conventional (Agfa Balanced Screening 175 lpi ABS in the left column) and stochastic screening (Cristal Raster 21µ CR right column). For the different models the reflectance curve of the 1-ink patches will be predicted and compared to the measured curves. As error measure the rms error between the reconstructed and measured reflectance curve is calculated.

In the top figures, the parameters of the Murray-Davies model are represented, in the middle figures the parameters of the Yule-Nielsen equations are shown and finally at the bottom the parameters of the extended Murray-Davies equations are given. In these figures the solid curve corresponds to the relative thickness of the patches compared to the 100 % patch, the dashed curve represents the area percentage and the dotted curve is the rms error (X 1000).

The error measure indicates that Murray-Davies is worse than the remaining other two models. The Yule-done Nielsen model and the extended Murray-Davies model predict the reflectance curves quite well although they are based on different physical processes. These results indicate that it is impossible to determine if the reflectance curve is mainly due to the Yule-Nielsen effect and some dot gain (constant thickness of the ink layers) or that the thickness and dot area change (Yule-Nielsen factor = 1). In fact it is not surprising that both models are more or less equivalent. Due to light scattering in the paper more light will emerge through the dot and as a result the dots will appear different, i.e. another size and in general thinner. Numerical calculations indicate that the Yule-Nielsen formula can be converted into the extended Murray-Davies equation with very small errors.

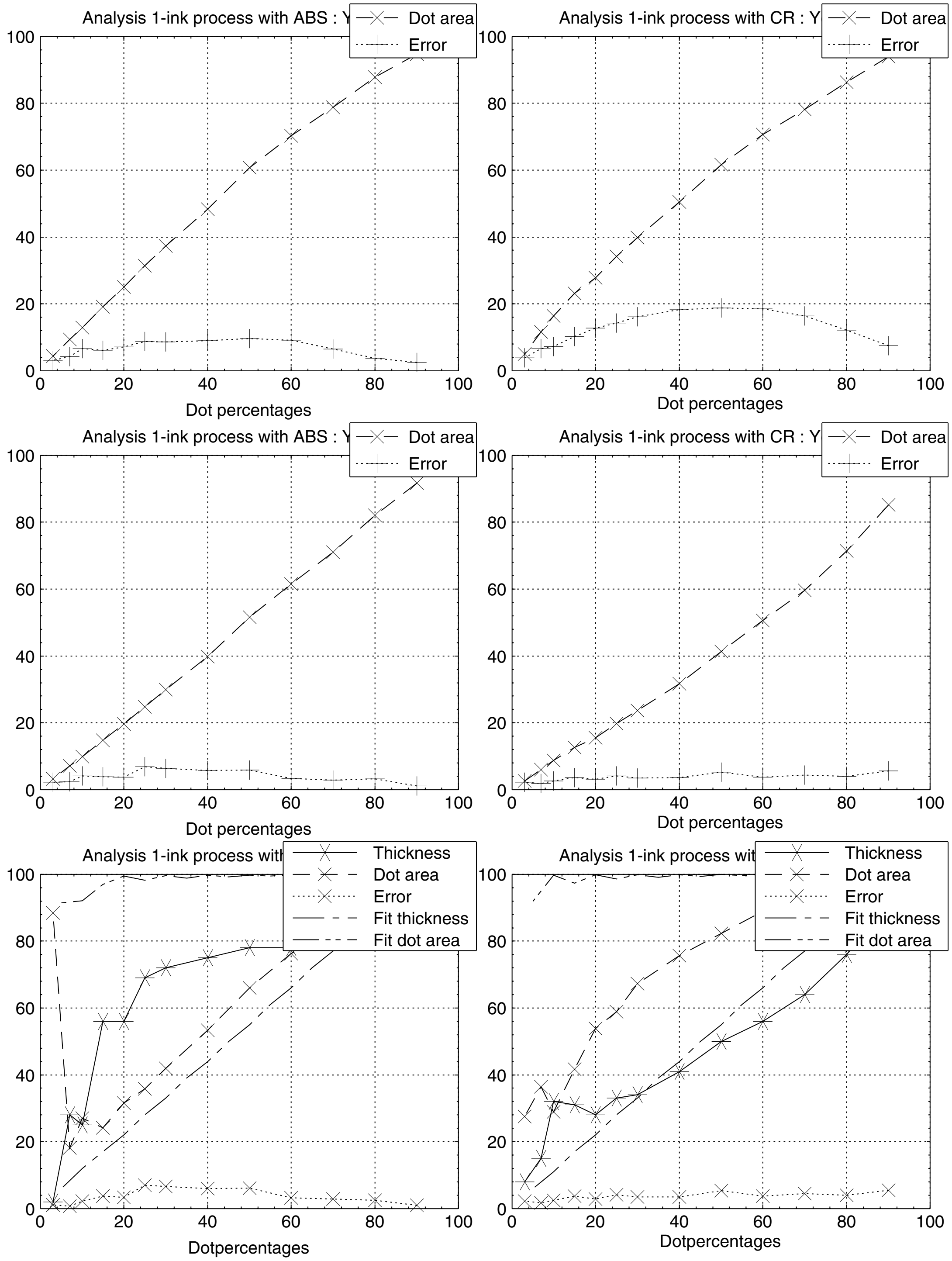

*Figure 6. Parameter values to predict the reflectance curves of 1-ink processes. In the top images the Murray-Davies formula is used, in the middle figure the Yule-Nielsen model and in the bottom images the extended Murray-Davies model is applied.*

We assume that the Yule-Nielsen factor is constant for a given screening and a given ink. Based on the step wedges we obtained for the CMYK inks 1.9, 1.6, 1.6 and 1.8 in the case of ABS and 6.4, 3.7, 4.7 and 1.8 for CR. Figure 6 shows that for ABS the dot gain calculated by the Murray-Davies formula is completely due to the optical dot gain. For CR the dot areas are smaller than the dot percentages but this is due to correction curves in the CR screens to map the dot gain of CR to the dot gain of ABS (see top figure).

The extended Murray-Davies equation indicates that the values of the thickness and dot area are different for both kinds of screening. The plots of the other inks show a similar behavior and hence we can say that these figures are characteristic for a given screening system. If we transform the Yule-Nielsen equations to the extended Murray-Davies model, there are still some significant differences between both curves. This is shown by the "Fit thickness" and "Fit dot area" curves. These curves are obtained by transforming the Yule-Nielsen equations with n-factor resp. 1.9 for ABS and 6.3 for CR to the extended Murray-Davies model. This indicates that thethickness of the ink layer still might change in function of dot percentage.

If the parameters of the extended Murray-Davies model really correspond to the dot area and thickness of the dots, the top figures indicate that with less ink a more saturated color can be obtained. Let's take for example the 60 % cyan ink patch. With ABS an ink amount of 0.56 (= 0.72 * 0.78) results in a less saturated color than in the case of the same patch for CR where an ink amount of 0.45 ( = 0.90 * 0.50) is needed. Because this more saturated color can not be obtained with ABS, the relationship between the thickness of the ink layer and the area percentage might be a cause of gamut differences for different screening systems. Indeed, this fixed relationship between both parameters is important because if the thickness of the ink layer is constant, and there would be only a difference in dot area, the gamuts would be the same because the same colors could be obtained with both systems but at different dot percentages.

## Hifi within the ICC Specification

With the ICC profile format as it stands today, basically it is already possible to create ICC profiles for Hifi color devices. Indeed, the color transformation table format, CLUT tables in ICC specification, do allow to set up input to output conversion tables where the number of channels in both input and output are completely arbitrary. A few considerations however do actually make the current ICC profile format less practical for characterizing Hifi color devices, or n-colorant devices as they are called by the ICC.

In a context where the colorants are not a priori known, it is necessary that an application somehow is able to find out the name of each colorant, has an indication of how the colorant appears and should know the order in which it has to consume or produce the channels. When an n-colorant process is well known one could of course think about defining a new color space. For example, it might be worthwhile to define a Hexachrome™ color space. However, one can not keep on defining new color spaces for each and every n-colorant process that is used by a group of people. Adding new color spaces also does not solve the general case.

The information about the colorants naturally belongs in the profile. First to make it easy to find this data, but more importantly because a profile is meaningless without if the names of the colorants are not known. An application or color management system must be able to find all necessary information in the profile.

The addition of colorant specification data to the ICC profile format is a fairly easy one. However, their is a second consideration to n-colorant spaces which might make a dramatic change in the ICC profile format necessary. For 4-colorant spaces the size of the profile necessary to have a good quality characterization is still manageable in many applications and device drivers. Taking only the A2B direction, this is the device dependent to device independent conversion table in an ICC profile, which is usually the most space consuming direction, requires approximately 100K. However for more colorants this size increases exponentially (186K for 6 colors; 1.2M for 7 colors; 8.4M for 8 colors for example). This could become prohibitive in some practical application where these profiles have to be used.

The easy way out of this problem seems to be to allow compression techniques on profiles. Standard data compression can be applied on profiles for example. However, this does not solve the problem because before a driver can use the profile, it has to decompress the profile which results in big memory usage again. Another solution is by specific techniques to make the conversion tables smaller. Depending on the technique used this might mean that the whole processing model of the ICC has to change, however we think that it is this solution the ICC has to go for.

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