An Expanded Gamut Ink Set for High Speed Inkjet Printing on Flexible Films and Folding Cartons

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Abstract

Expanded gamut ink sets generally comprise up to three chromatic process color inks in addition to a standard cyan, magenta, yellow, and black (CMYK) set of inks. The main advantage of using a 5-, 6-, or 7-color ink set is the ability to significantly expand the number of available colors that can be reproduced over a basic CMYK ink set. For packaging applications this provides an option to accurately match important brand colors on press without the need to formulate specific spot color inks for each print job. In addition, it is also possible to minimize the total amount of ink used by substituting a single drop of one of the additional colors, e.g., blue, for two drops or layers of a standard CMYK ink set, e.g., cyan plus magenta. The choice of the specific color(s) of the added ink(s), as well as the order of laydown of the expanded gamut ink set, can have a measurable impact on the resulting color gamut. The choice of a pre- and post- treatments can also make significant contributions to the overall print quality and color gamut. This paper will describe the methodology and measurements that were used to select the specific nanoparticle pigment dispersions and ink colors that comprise the Kodak 7-color expanded gamut ink set which was recently showcased at drupa 2016 printing at 150 mpm on white BOPP label stock.

Background and Scope

Expanded color gamut printing (sometimes referred to as extended color gamut printing) is a color printing process that adds up to three additional process colors to the basic cyan, magenta, yellow, and black (CMYK) ink set. An early version of this process, referred to as the Küppers process, added red, green, and blue (RGB)

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inks to enable both a broader range of colors, effectively expanding the available color gamut of the printing process, while at the same time enabling more efficient ink usage of the printing process (1). Another version, known as the Pantone Hexachrome™ process, adds orange and green (OG) inks for similar reasons (2,3). More recently, many digital printers have found that by adding blue or violet (BV) inks to the Hexachrome™ set allows for better reproduction of the more saturated colors in this sector of the color space, for example, Pantone 286C (4).

The primary application space for expanded gamut printing is in packaging, where many brand identity or spot colors include dark or saturated reds, blues, and/or greens. Historically, these colors have been custom matched and printed as separate color separations on either flexographic or gravure analog presses. This has resulted in the need to maintain "libraries" of literally hundreds of spot color formulations and corresponding printing cylinders or sleeves. A significant amount of down time is also incurred when changing over from one job to the next, which becomes especially problematic as print runs and lead times become shorter. This can often result in more time spent changing over the press than actually printing each job. Therefore, a digital press with an expanded gamut process color ink set that is capable of accurately and consistently reproducing the vast majority of the Pantone color library, as well as non-Pantone specific brand colors, will streamline the process, eliminate waste, and minimize inventories.

Although the Kodak PROSPER CMYK pigment ink set, which is based on Kodak's long history of colorant chemistry and pioneering nanoparticle pigment dispersion technology, has already been shown to produce an exceptionally broad color gamut (5), we realized that for packaging applications this was insufficient to meet most customers' and brand owners' requirements. To this end, we began a research effort to explore which additional process colors when added to our base CMYK ink set would provide the greatest boost to our overall color gamut as well as to match the highest percentage of the current Pantone library for coated papers and films. This paper will describe the methodology and measurements that were used to select the specific additional nanoparticle pigment dispersions and ink colors that comprise the Kodak 7-color expanded gamut ink set which was recently showcased at drupa 2016, printing at 150 mpm on white BOPP label stock.

Materials and Methods

Inks. The water-based cyan, yellow, magenta, and black inks used for this study are commercially available under the tradename Kodak PROSPER Packaging Pigment inks (6). Aqueous nanoparticle dispersions of the following commercially available pigments were prepared using a proprietary milling process (7) that includes a proprietary polymeric dispersant (8): pigment red 254 (PR254, Irgazin Red L 3630, BASF), pigment orange 34 (PO34, Graphthol Orange RL-MX, Clariant), pigment green 7 (PG7, Heliogen Green D 8730, BASF), and pigment violet 23 (PV23, Hostaperm Violet RL 02, Clariant).

Model inks were prepared from these dispersions at a range of pigment concentrations for the initial 4+1 screening experiments (see below). Based on these results, a second generation of ink formulations were formulated for phase 2 of the 4+1 printing studies as shown in Table 1. Press-ready ink formulations were based on these results, and include commercially available ink addenda at levels appropriate for each ink, including humectants, stabilizers, binders, surfactants, defoamers, conductivity modifiers, pH adjusters, corrosion inhibitors, and biocides. The final press-ready inks also include a proprietary polyurethane binder (9).

Color	Pigment(s) (wt. ratio)	Ink Pigment Concentration (wt%)	D_{50} (vol.) (nm)	D_{95} (vol.) (nm)
Orange	PO34	3.3	10	27
Green	PG7/PY74* (3.74:1.0)	3.0	13	62
Blue	PV23/PG7/PB15:4** (1.07:0.50:1.88)	3.4	30	80

*PY74 = pigment yellow 74, Sunbrite Yellow, Sun Chemical.
**PB15:4 = pigment blue 15:4, Sunfast Blue, Sun Chemical.

Table 1. *Summary of the pigment dispersions used for the orange, green, and blue inks selected for the order-of-laydown and press verification studies.*

Substrates. For our initial 4+1 screening and follow-up studies investigating order-of-laydown effects, a coated paper, Sterling Ultra Gloss (SUG), manufactured by Verso Paper, was used as a proxy for a high quality clay- coated folding carton board. This paper was pre-treated with Kodak PROSPER Enhanced Optimizer Agent (EOA) at a dry coverage of ca. 0.4 g/m^2. The EOA is designed to instantly immobilize the pigments at the surface of the paper and thus minimize coalescence or loss of density due to lateral spreading or penetration of the pigments into the coating (10). This in turn maximizes the optical density and color response of the inks.

For the full-process 7-color web press printing verification studies a white, 38-µm, biaxially oriented polypropylene (BOPP) film (38LL247), manufactured by Jindal Films was first treated with a corona discharge unit, and then flood-coated at a dry coverage of 0.43 g/m^2 with an experimental pre-treatment formulation, similar to EOA, but optimized for use on flexible film substrates (11).

Post-coatings. For our initial 4+1 screening experiments on the EOA-treated SUG, the printed samples were evaluated with and without a protective post- coating. The post-coating that was used for these studies is an experimental water-based varnish provided by Actega Coatings and Sealants. This varnish was applied by hand drawdown at an aim dry coverage of 2 g/m^2.

For the full-process 7-color web press printing verification studies a solvent- based varnish (Gecko Overprint Varnish 18056 Label) was obtained from Huber Group and was flood-coated over the printed BOPP film at an aim dry coverage of ca 2.1 g/m^2 using a standard flexographic process in a roll-to-roll operation.

Printing hardware and methods. For our initial 4+1 screening studies, we were limited to using a combination of laboratory printing fixtures. For the CMYK printing, we used a 4-color print stand comprising four stationary Kodak S- Series printing modules and a translating drum upon which a letter-size sheet of the EOA-SUG substrate was mounted in landscape orientation. The drum was rotated at a linear speed of 100 m/min and was moved sequentially under the cyan, magenta, yellow, and black printing modules in that order. For these studies we printed at a resolution of 600 x 900 dpi with a drop volume of 9.6 pL (0.88 g/m^2 maximum dry ink coverage per color). This configuration is capable of depositing two swaths of ink over an area per swath of approximately 4.2 in (107 mm) by 7.5 in (190 mm) per sheet of paper. For the 4 + 1 prints, due to difficulties in registering the fifth color, we were limited to printing just a single swath per page. In order to address these limitations, we developed a modified color patch target for the 4 + 1 screening studies. The standard CMYK IT8 target has 1617 colors. Simply adding a 5th color expands the number of patches by about a factor of 4, making it very tedious to print and measure. As a compromise we designed a custom target that comprises only 1276 patches. The target used for the 4+1 studies was derived from Kodak Spotless software, which offers targets for profiling 4-, 5-, 6-, and 7-color printers. This target samples 1276 color patches using combinations of up to five inks and was formatted to fit the available print swath on the test stand (see Figure 1). Additionally, the target was limited to 250% total area coverage (TAC), as the original used up to 500% ink, which would not dry acceptably. The target was split into two separate image files for printing – a CMYK image and a single color (5th color) image. The samples were printed without active drying between each color and then allowed to air dry on the bench top before overprinting with a fifth color. These targets were then mounted on a separate single-color drum print stand, and a fifth color was overprinted on top of the 4- color targets at the same line speed, resolution, and drop volume. These samples were also air dried on the bench top before further evaluation or post-coating. In a few cases, we investigated reversing the print order, i.e., printing and drying the extra color first, then overprinting with CMYK on the 4-color stand.

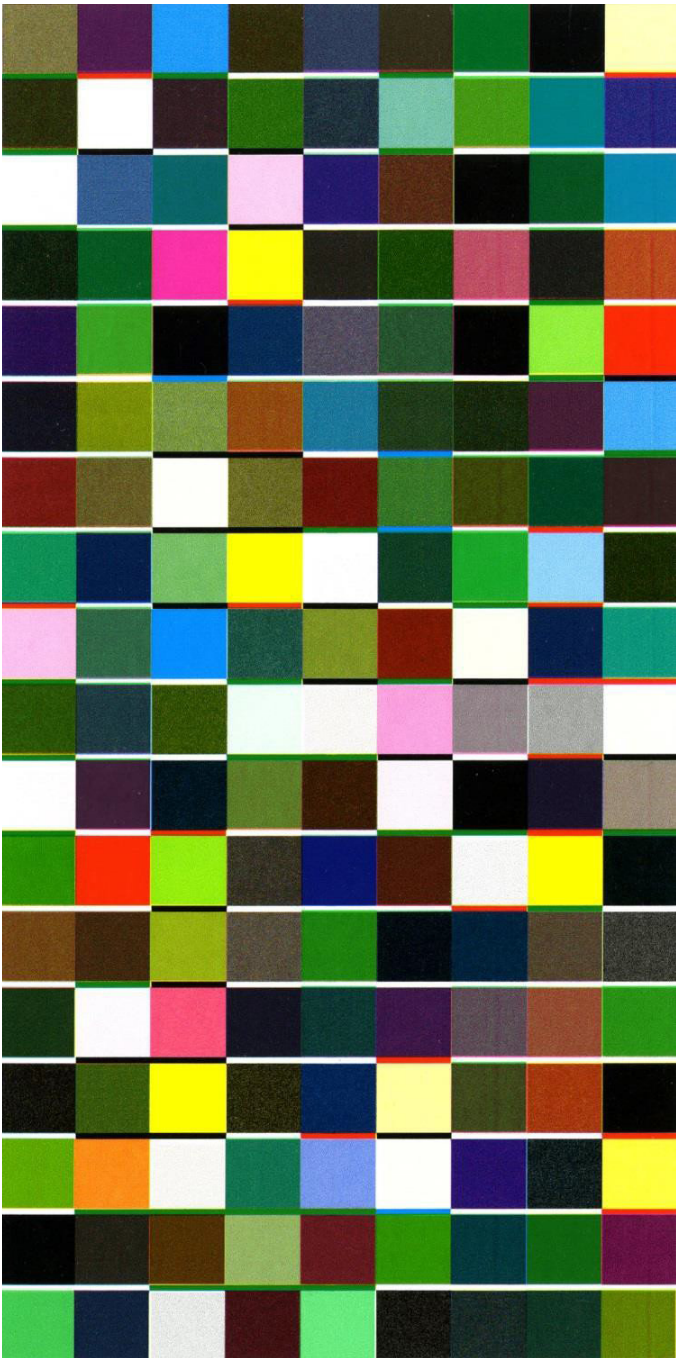


Figure 1. *An example of one page of a custom color patch target where CMYK was printed first followed by one of the green inks on the second print stand.*

For the order-of-laydown studies, we used an engineering web press which was equipped with four sets of two S-Series printing modules. Each set of S-Series modules was fed with a single color of ink, and in its base configuration it was set up to print two parallel 4.18 in (106 mm) swaths of cyan, magenta, yellow, and black ink, in that order, with a final near-IR drier (Adphos) incorporating forced air to remove the released moisture. The standard IT8 target was printed at a resolution of 600 x 600 with a drop volume of 11.4 pL (0.65 g/m^2 maximum dry ink coverage per color). An upper ink limit of 250% and a maximum print speed of 76 m/min (250 ft/min) was imposed due to drying constraints. After printing a baseline set of IT8 targets with CMYK, we replaced one of the chromatic inks with one of the expanded gamut color inks, orange, green, or blue, that was selected from the initial 4 + 1 screening studies. For example, in order to evaluate the order-of-laydown effect with the orange ink, we replaced the cyan ink with orange, then we varied the order of the orange, magenta, and yellow inks, leaving the black ink in the last position, e.g., OMYK, MOYK, and MYOK. Similarly, for the green ink, we removed the magenta and varied the order of the green, cyan, and yellow inks, again with black printed last: CYGK, CGYK, and GCYK. Then we swapped out the yellow ink with the blue ink in a similar fashion: CMBK, CBMK, and BCMK. Finally, we repeated the CMYK targets, but moved the black ink into first the first position: KCMY. The individual data sets for each of the distinct 4-color combinations, e.g., CMYK, OMYK, CYGK, and CMBK as one example, were merged to estimate the overall 7-color gamut volume. As will be discussed in more detail below, as a result of these studies we settled on the following ink order for printing verification studies on the seven-color web press that was used for the drupa demonstration: KGCBMOY.

The final verification of the performance of the expanded gamut ink set was done on a roll-fed press designed and manufactured by UTECO, using the pre- treated white BOPP substrate described above. This press was equipped with seven sets of S-Series printing modules. Each set of S-Series modules was fed with a single color of ink, and in its base configuration it was set up to print two parallel 4.18 in (106 mm) swaths of black, green, cyan, blue, magenta, orange, and yellow ink, in that order, with a final drum dryer that used a combination of hot forced air and near-IR. An IT8 target was printed at a resolution of 600 x 600 with a drop volume of 11.4 pL, an upper ink limit of 250%, and a print speed of 300 ft/min (92 m/min). The print samples were flood coated in a separate step as described above.

Color gamut and Pantone coverage calculations. The custom color patch targets used for the initial 4 + 1 studies were measured using an X-Rite i1iO Automated Scanning Table Spectrophotometer producing CIELab data (D50, 2° observer). The CIELab data was then used to create a 3D gamut volume with a surface, for each set of targets. The resulting gamut volume represented all of the possible colors achievable with that particular ink set. In order to determine if a specific Pantone color was achievable, it was necessary to determine whether or not the CIELab values for the Pantone color fell inside or outside of the desired gamut volume. Colors that fell inside of the gamut surface were considered within gamut, while colors that fell outside were considered out of gamut. For colors that were out of gamut it was desired to know how far out of gamut they actually were, since colors very close to the gamut's surface (less than 2 ΔE_{00}) could still be considered acceptable. This was accomplished by calculating the ΔE_{00} distance between the Pantone color's CIELab value and the closest point on the gamut's surface. Groups of Pantone colors were then assessed by generating a*b* plots and cumulative histograms of their ΔE_{00} values.

Results and Discussion

The original 4-color ink set that was developed for the Kodak PROSPER press was leveraged from Kodak's long history of serving the chemical, photographic, and graphic arts industries. The CMYK colorants were selected based on a combination of their ability to meet current (2008) SWOP and GRACoL standards (12,13) as well as to provide a high degree of permanence when exposed to environmental factors such as light, ozone, heat and humidity (14). To this end, the cyan ink comprises a blend of pigment blue 15:4 (PB15:4) and pigment green 7 (PG7) at a weight ratio of 3.75:1, the yellow ink comprises pigment yellow 74 (PY74), the magenta ink comprises a blend of pigment red 202 (PR 202) and pigment violet 19 (PV19) (originally available in a mixed crystal from Ciba Corporation under the designation "2BC"), and the black ink comprises pigment black 7 (PB7, carbon black).

In addition to the specific choice of the chromatic CMY pigments, another key enabler to maximizing the chroma and color gamut is Kodak's unique capability of producing nanoparticle pigment dispersions which have very narrow particle size distributions (8). Inks made from these pigment dispersions produce essentially transparent, non-scattering ink layers, which also display low metamerism when viewed under various standard illuminant conditions (15).

Another requirement for visually matching specific Pantone colors when printing at production inkjet speeds in a single pass is the ability to produce ink layers that are very uniform and are free from print artifacts, such as coalescence and mottle, that result from ink drops spreading on the surface of the substrate and merging with neighboring ink drops of the same or different color. This is especially problematic on commercial offset coated papers and impermeable flexible films. To address this issue, we have developed a sub-micron surface treatment based on the well-known ability of water soluble divalent metal salts to rapidly gel anionically charged polymers via the formation of ionic crosslinks (10,16). When water-based pigment inks that employ a polymeric dispersant which contains negatively charged acrylate or methacrylate moieties are deposited on such a surface layer, the pigments are instantly immobilized. This prevents the pigments from migrating both into and across the surface of the substrate, and the individual drops of ink that are jetted onto the substrate are preserved as discrete circles (dots) of polymer-dispersed pigment (Figure 2).

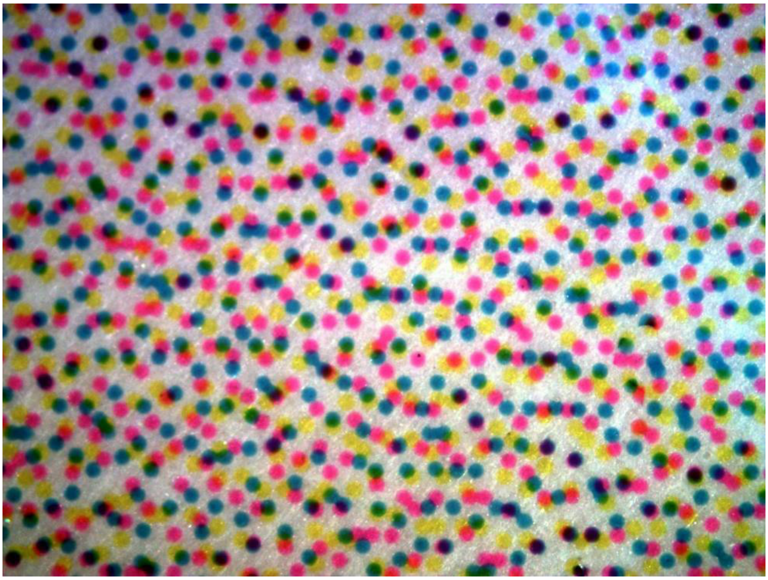


Figure 2. *Photomicrograph of a 10% patch of CMY inks printed on white BOPP that has been surface-treated with polymer-dispersed divalent metal salt.*

Initial 4+1 screening studies. Based on available product literature, we first evaluated a large number of commercially available orange, red, violet, blue, and green pigments. A fair number of these pigments were eliminated from further consideration due to either an incompatibility with the micromedia milling process and/or an inability to generate stable nanoparticle dispersions. Based on these results, dispersions based on PO34, PR254, PV23, and PG7 were selected for ink formulation and printing for the 4+1 screening study. Initial model inks were prepared from these single pigment dispersions, and each of these inks were printed as a fifth ink either before or after the CMYK were printed using the process described above. The 5-color modified IT8 targets were then flood coated with Actega water-based varnish and evaluated for potential to reproduce a subset of 100 popular Pantone colors.

Figures 3 – 5 compare the addition of either orange or red ink vs the base CMYK ink set. For these a*b* plots, the green diamonds represent Pantone colors which are within gamut, orange squares are colors that are less than 2.0 ΔE_{00} out of gamut, and red triangles are greater than 2.0 ΔE_{00} out of gamut (with Pantone color number shown). Only the yellow-red quadrant is shown in Figures 4 and 5 because the impact of orange and red outside of this region of the color space is negligible. It can be readily seen that the pure orange ink is advantaged over the pure red ink, with all but Pantone 226C pulled within 2.0 ΔE_{00}.

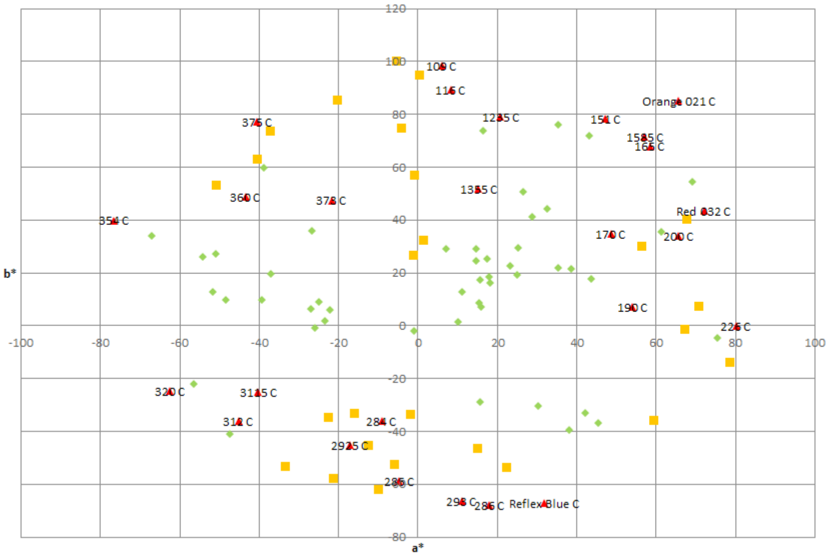


Figure 3. *Pantone coverage a*b* map for baseline CMYK + varnish.*

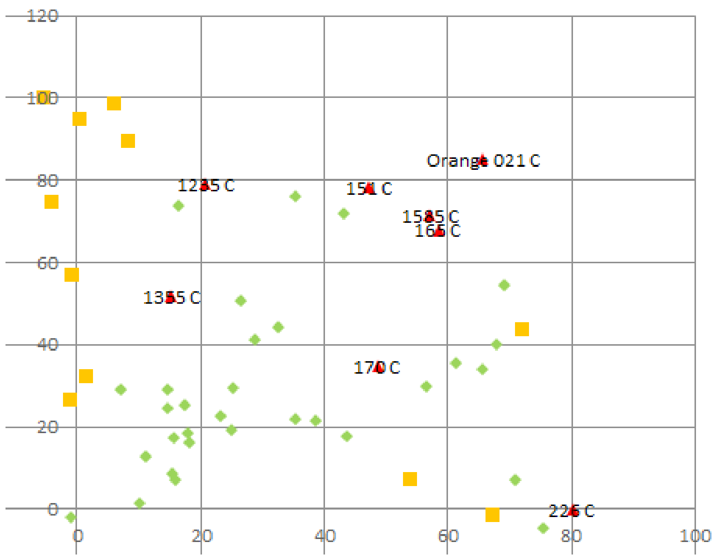


Figure 4. *Pantone coverage a*b* map for R + CMYK + varnish.*

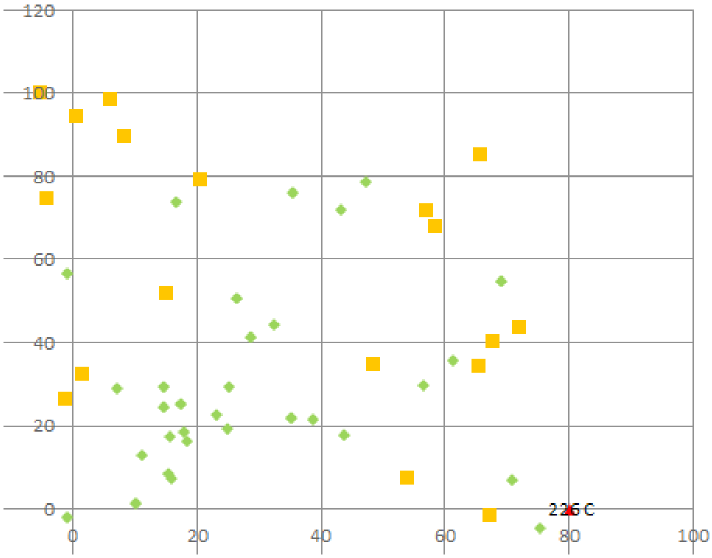


Figure 5. *Pantone coverage a*b* map for CMYK + O + varnish.*

In a similar fashion, the modified IT8 target was printed with a pure violet ink based on PV23 printed in addition to the base CMYK ink set. The a*b* plot for the violet-blue quadrant is shown in Figure 6. Although several of the Pantone colors represented by red triangles in the CMYK only prints shown in Figure 4 have now moved to either orange squares or green diamonds, we were not satisfied with this result. In an effort to further improve the Pantone coverage in this sector, we formulated a blue ink by combining the PV23 dispersion with our existing cyan dispersion (see Table 1). Figure 7 shows the a*b* plot for this ink. As can be seen, only Pantone 285C is greater than 2.0 ΔE_{00} out of gamut, and many more colors in this sector now fall within gamut (green diamonds). Based on these results, we decided to move forward with the blue ink using the blend of PV23, PB15:4, and PG7 in the weight ratios shown in Table 1.

Next we turned to the green sector, and we looked at two different green inks. The first was based on pure PG7 ink (G1), and a second ink comprised a blend PG7 and PY74 inks (G2) to produce a warmer shade of green, closer to Hexachrome green. Figures 8 and 9 compare the results for these two inks, focusing on the green quadrant. At first glance, it appears that G1 picks up more of the green-cyan out-of-gamut inks compared to Figure 4, for example Pantones 320C and 3115C, while G2 does a better job with the green-yellow colors. Either ink addresses the more saturated out-of-gamut green inks such as Pantones 354C and 375C. Given the closeness of these results, we looked at $\sum[\Delta E00]$ over all 100 colors for each ink + CMYK, and found that G2 was slightly advantaged over G1: 83.6 vs 87.9. A further consideration favoring G2 was the observation that dispersions and inks made with a proprietary method of blending PG7 and PY74 exhibited better milling behavior and gave more stable dispersions and inks compared to pure PG7 (17).

Based on further ink formulation optimization, we settled on the ratio of PG7:PY74 shown in Table 1 for the subsequent order-of-laydown studies and 7-color press demonstrations.

Additional high level observations were made based on these initial studies. Printing the fifth color first vs last has a small but measureable effect on the calculated Pantone coverage, but depending upon the color, the preferred order is not always the same. The data shown in Figures 4 – 9 represent the better of the two print orders for each ink. Given the time delays between printing the fifth color and the CMYK ink set, as well as preliminary nature of this phase of the study, we decided to further investigate order of laydown effects in more detail in the next phase of our study. Flood coating with varnish generally expands the color gamut and increased the chroma, especially in the darker regions. Because most packaging and label applications will use some form of protective post-coating, we based most of our analyses and decisions with a flood coat of varnish over the print samples. We also briefly evaluated the effect of pigment concentration for several of the expanded gamut inks. Although small differences were noticed, we decided to delay final pigment concentration optimization until after we investigated order-of-laydown effects.

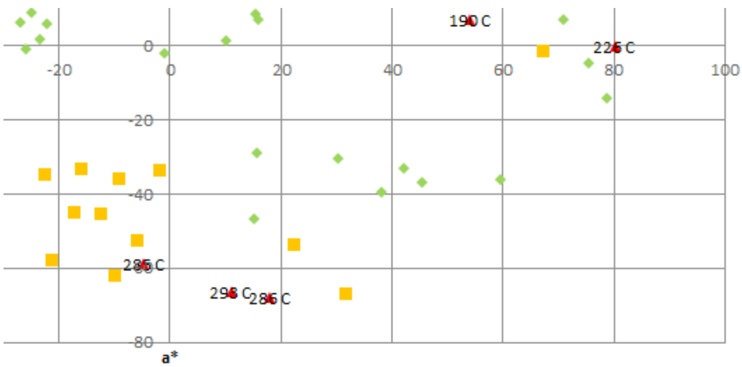


*__Figure 6.__ Pantone coverage a*b* map for CMYK + V + varnish.*

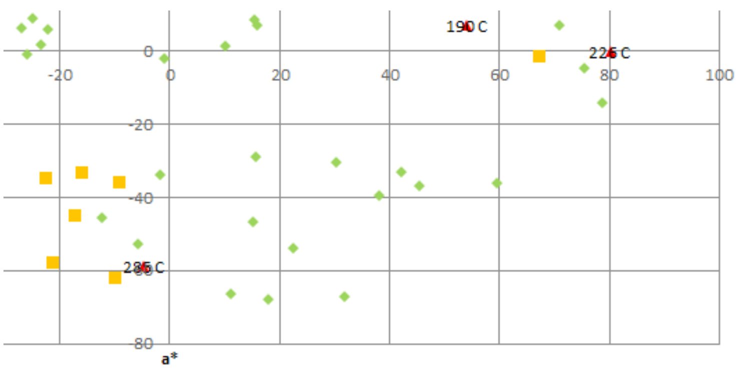


*__Figure 7.__ Pantone coverage a*b* map for CMYK + B + varnish.*

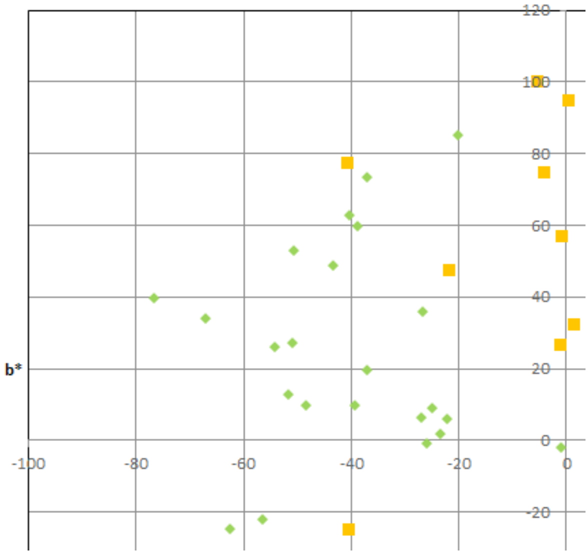


*Figure 8. Pantone coverage a*b* map for G1 + CMYK + varnish.*

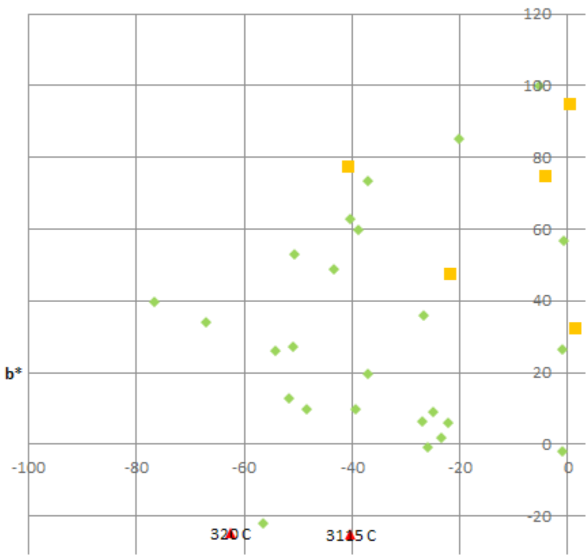


*Figure 9. Pantone coverage a*b* map for G2 + CMYK + varnish.*

<u>*Order-of-laydown studies*</u>. From the initial 4 + 1 phase of this study, it became obvious that the order in which the colors were laid down could have a measureable impact on overall color gamut and our ability to match the Pantone color library. But before discussing the order-of-laydown phase of this project, a bit of background is in order. The existing order of ink laydown (CMYK) for the Kodak PROPSER press was influenced by a combination of system level considerations, such as the drying strategy and color-to-color registration, and, to a lesser extent, overall print

quality and color gamut potential. For example, as a result of the decision to use near-IR inter-color dryers, the black ink was necessarily moved to the last position. If black were printed first, then the subsequent near-IR drying modules used for the chromatic inks would tend to over dry the black ink, possible leading to paper scorching. The decision to print cyan first, followed by magenta and then yellow allowed for improved color-to-color registration.

On the other hand, the initial target market application for the expanded gamut press was for roll-to-roll printing on flexible films. Given the greater sensitivity of film-based substrates to stretching and/or distortion as a result of excess heating, it was decided to avoid interstation drying in favor of a final drum- based drying subsystem. Ideally, we would have liked to conduct full factorial experimental design around the color order to fully optimize the system for both color response as well as drying efficiency, image quality, print durability, and so on. However, due to schedule constraints, we were limited to investigating order-of-laydown effects by using an engineering press which was only capable of printing with four colors on paper-based substrates, and which had a final near-IR web dryer augmented with forced air described above.

To accommodate these constraints, we decided to break up the test plans as follows. Print targets were first printed and characterized in the base CMYK configuration. Then the chromatic ink laydown order was systematically varied as described above. We first replaced C with O, and printed the same targets in the following order: OMYK, MOYK, and MYOK. Next we replaced M with G: CYGK, CGYK, and GCYK. Then we swapped out Y for B in a similar fashion: CMBK, CBMK, and BCMK. Finally, we repeated the CMYK targets, but moved the black ink into first the first position: KCMY. For these studies we printed on IOS-SUG as a proxy for pre-treated white BOPP. To save time, we also decided not to post-coat these print samples under the assumption that any observed trends in the color gamut, image quality, and color-to-color registration responses would be independent of the varnish.

Figure 10 shows a*b* responses at four different levels L* for the base CMYK compared to OMYK, MYOK, and MOYK. Although all of the orange- containing slices clearly show the expected gamut expansion compared to the base CMYK, there was very little difference in gamut shape due to the color
order. Similar results were observed for the blue and green a*b* vs L* response (Figures 11 and 12).

Using a separate test target we briefly investigated the visual appearance of selected bi-chrome and tri-chrome patches at two different print speeds, 30 and 76 m/min (100 and 250 ft/min). These results are shown in Figures 13 – 15. At a given print speed, the differences in hue, print uniformity (grain and mottle), and intercolor bleed are negligible for the bi-chrome patches that did not contain K. In some cases, there is a slight observable hue shift between the two different print speeds. The most noticeable effect of print speed was the degree of the under color show-though for the K-containing bi- and tri-chrome patches.

Figure 16 directly compares Y-K bi-chromes for CMYK vs KCMY print order printed at 30 m/min. Focusing on the 80% to 100% sectors of these targets, it can be seen that there is less yellow hue apparent when K is printed first. Although not as evident for the C-K and M-K bi-chromes at 30 m/min (not shown), the degree of under color show-through as noted in Figure 10 – 12, when K is printed last, becomes more noticeable, even objectionable, at higher print speeds in general. In a separate investigation comparing CMYK vs KCMY on an IOS-treated carton board substrate, it was found that the dry rub performance was noticeably improved when K is printed first.

Based on the combination of these observations, and given that intercolor near-IR drying was not part of the system design for the expanded gamut press, it was decided that K should be printed first. With regards to the remaining six chromatic process color inks, there were no clear signals from this phase of the study based on either a color gamut or print quality perspective to favor one particular color order over another. Because previous experience on the Kodak PROSPER press favored the order CMY from a color-to-color registration, it was decided to preserve this general order.

With respect to where to position the OGB inks, a number of options were considered. One thought was to either place them either before or after a base KCMY configuration. Placing the OGB after KCMY would allow for a modular option wherein either a 5th, 6th, and/or 7th color could be added to a standard 4- color printing system. On the other hand, from a color management and color- to-color registration perspective for a dedicated 7-color press, interspersing the OGB inks in some fashion within a KCMY framework may be advantageous. At the end of the day, with limited time to further investigate the pros and cons of these options on the 7-color demonstration press targeted for drupa, it was somewhat arbitrarily decided to simply arrange the chromatic colors in the order that they naturally occur around an a*b* plane: KGCBMOY. Pending verification studies on the 7-color press which might uncover reasons for modifying this color order, this is the color order that was defined and ultimately used for the drupa demonstration press.

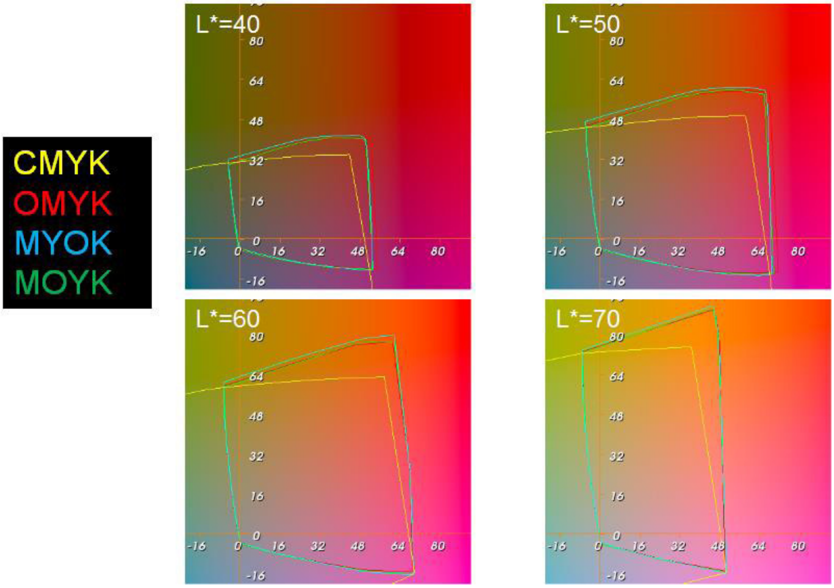


Figure 10. *Color gamut slices for OMYK, MYOK, and MOYK compared to the reference CMYK ink set.*

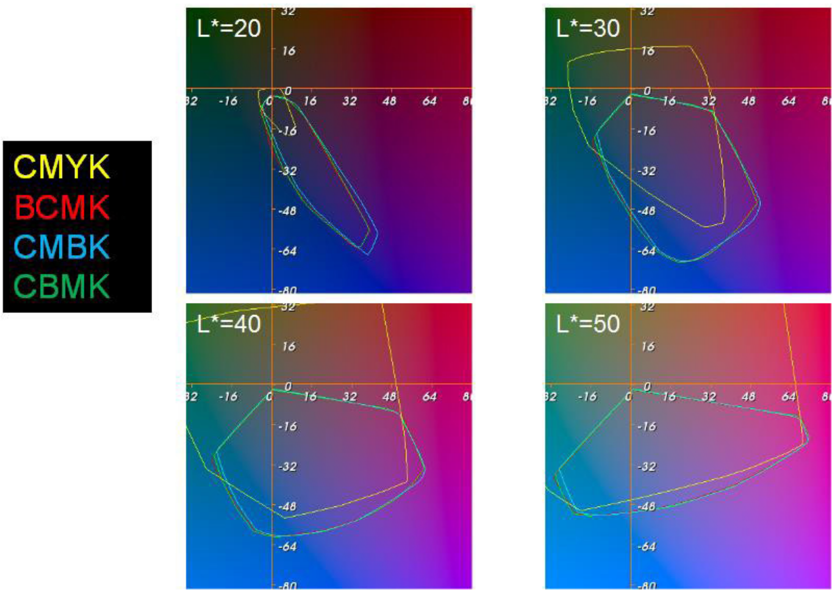


Figure 11. *Color gamut slices for BCMK, CMBK, and CBMK compared to the reference CMYK ink set.*

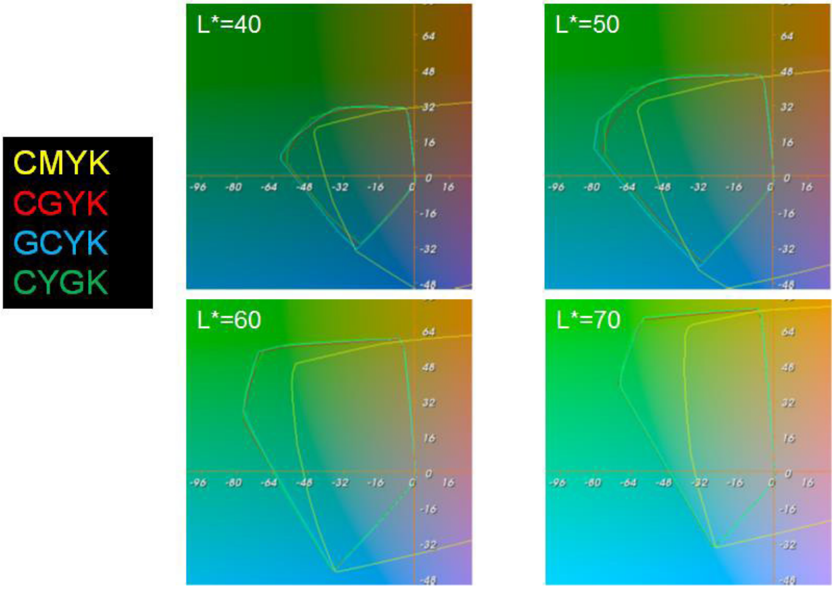


Figure 12. Color gamut slices for CGYK, GCYK, and CYGK compared to the reference CMYK ink set.

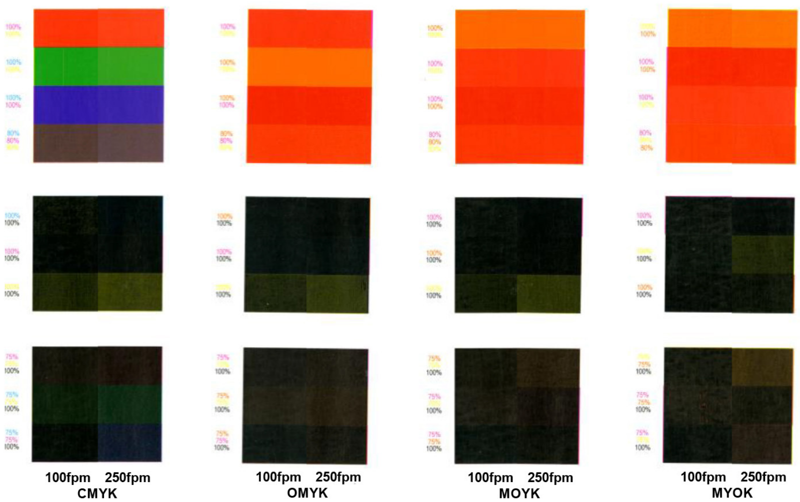


Figure 13. Visual appearance targets as a function of laydown order and print speed for OMYK, MOYK, and MYOK compared to CMYK.

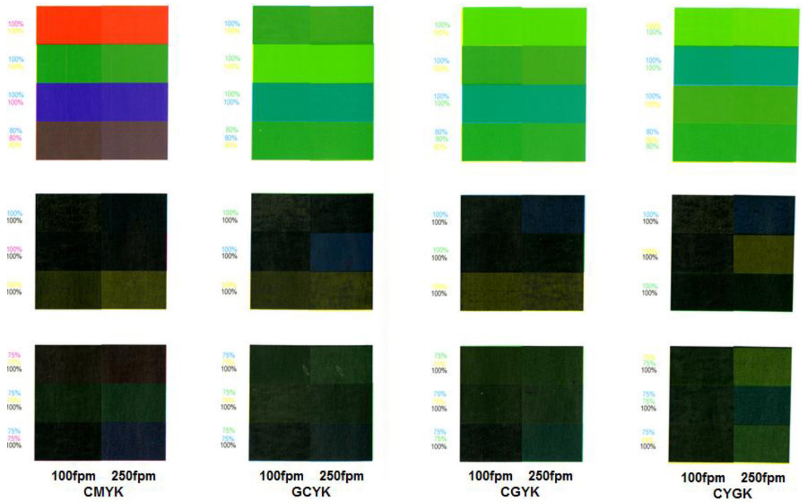


Figure 14. *Visual appearance targets as a function of laydown order and print speed for GCYK, CGYK, and CYGK compared to CMYK.*

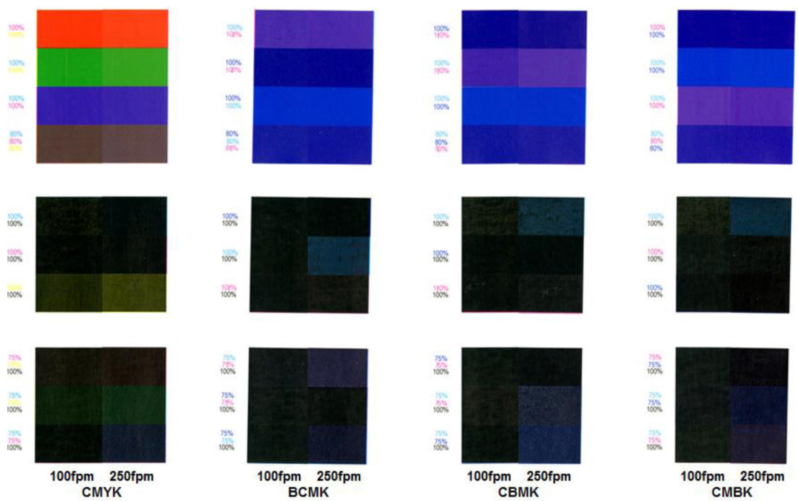
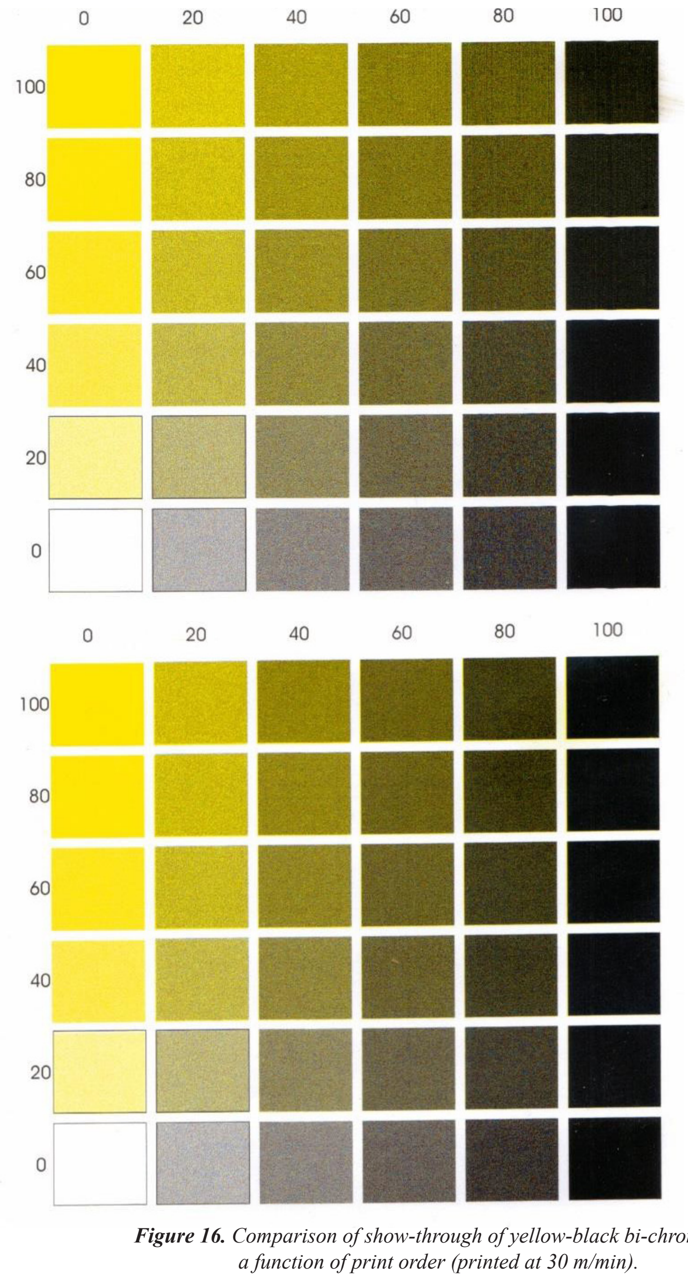


Figure 15. *Visual appearance targets as a function of laydown order and print speed for BCMK, CBMK, and CMBK compared to CMYK.*



K over Y

Y over K

Figure 16. *Comparison of show-through of yellow-black bi-chromes as a function of print order (printed at 30 m/min).*

7-Color press verification. The final quantification of color gamut volume and Pantone coverage was performed on the 7-color roll-to-roll demonstration press, first just KCMY as a reference, then using the KGCBMOY color order just defined. Step wedges of the individual colors in the 7-color ink set as printed on the demonstration press are shown in Figure 17. IT8 targets were printed onto a pre-treated white BOPP label film as described above at a resolution of 600 x 600 dpi with a drop volume of 11.4 pL. Prior to analysis, the printed web was off-line flood coated with a commercially available solvent-based varnish. Using the methodology described above, we calculated 4-color gamut volume of 563,000. For the 7-color configuration, the gamut volume increased by 44% to 813,000. Figures 18 – 20 show a*b* slices at various L* values.

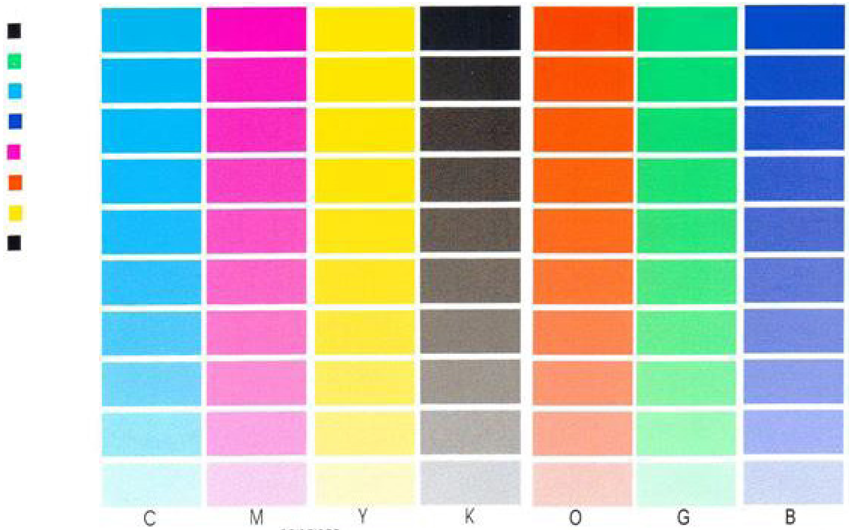


Figure 17. *Step wedges of the individual colors in the 7-color ink set printed on the drupa demonstration press.*

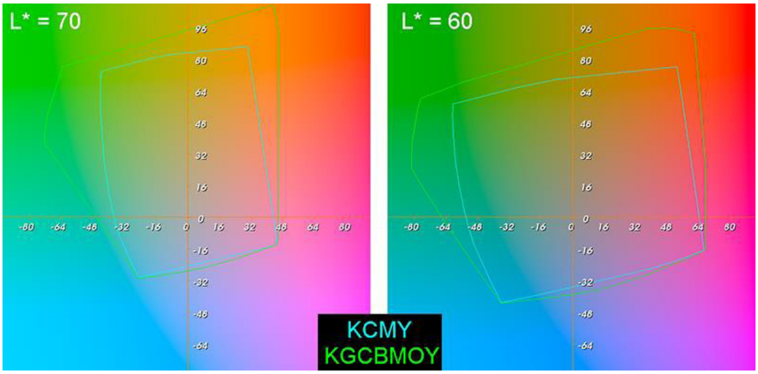


Figure 18. *Color gamut slices for KCMY and KGCBMOY at L* = 70 and 60.*

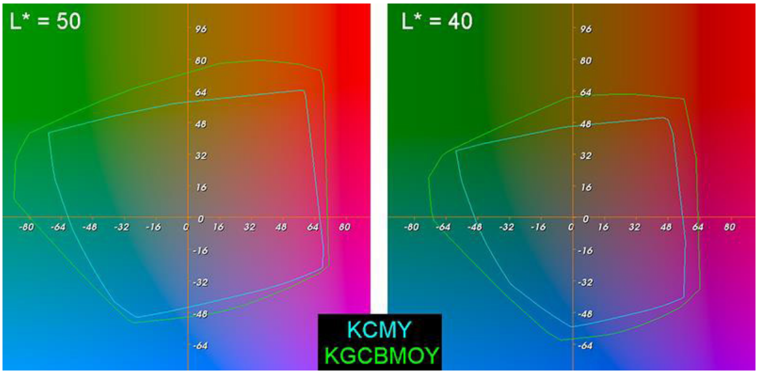


Figure 19. Color gamut slices for KCMY and KGCBMOY at L* = 50 and 40.

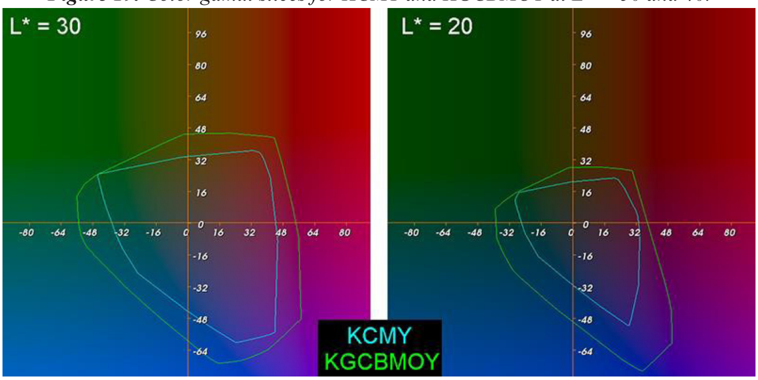


Figure 20. Color gamut slices for KCMY and KGCBMOY at L* = 30 and 20.

Figures 21 and 22 show a histogram and cumulative curve of Pantone color matching for the 4-color and 7-color configurations. Going for 4 to 7 colors dramatically increases the Pantone coverage, resulting is 90% of the Pantone coated library falling within ΔE_{00} 2.0 and 98% falling within ΔE_{00} 3.5 of aim.

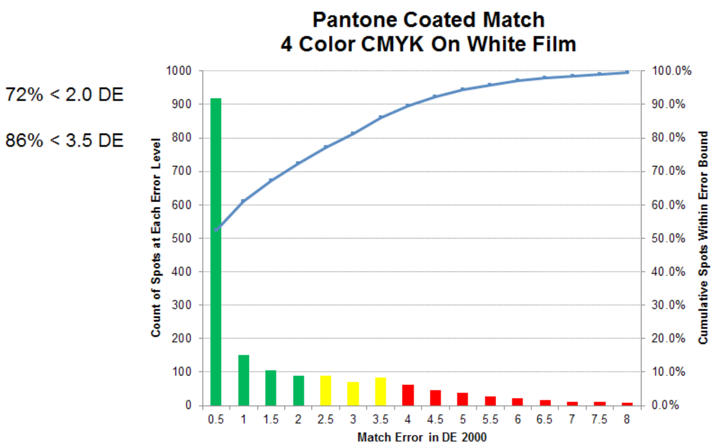


Figure 21. Pantone color matching results for the KCMY configuration.

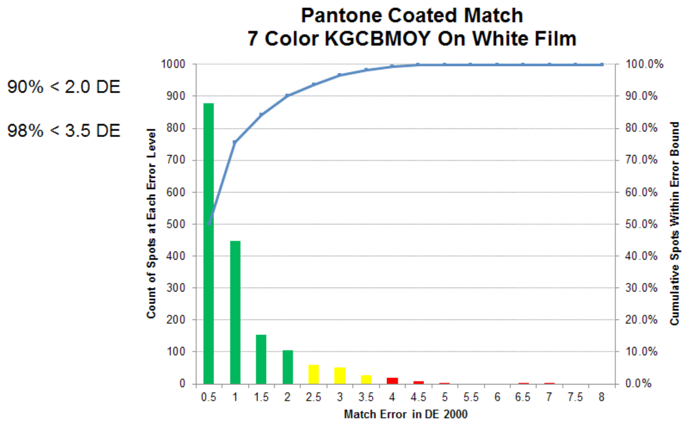


Figure 22. *Pantone color matching results for the KGCBMOY configuration.*

Summary and Conclusions

In this paper, we describe the methodology that was used to achieve an expanded gamut water-based ink set capable of being inkjet-printed at high speed in a single pass directly onto either folding carton or flexible film substrates for packaging and label applications. Key enabling technologies include: (a) submicron pre-treatment layers, which instantly immobilize the ink drops and prevent print quality artifacts such as coalescence and intercolor bleed, (b) nanoparticulate pigmented inks, which dry down to very thin, non- tacky, essentially transparent ink layers, and (c) compatible post-coatings, which further enhance the chroma and durability of the printed inks. Even before adding additional chromatic inks, the combination of the above materials on a white BOPP film can reproduce 86% of the Pantone library of colors to within 3.5 ΔE_{00} of aim.

Without a 7-color printing fixture or press available at the outset of this project, we were limited to printing and evaluating one additional color ink, either before or after printing a custom color patch target with the base CMYK ink set. We did this for each of the prototype expanded gamut inks by focusing on the improvement in Pantone coverage for the relevant sector of the a*b* compared to the CMYK reference. For example, in order to assess the merits of adding an orange vs a red ink, we looked a subset of 100 popular Pantone colors that fall roughly within the upper right a*b* quadrant (yellow-magenta sector), and compared the number of colors that were greater than 3.5 ΔE_{00} out of gamut when printed with just CMYK to the number of colors that could be pulled within 3.5 ΔE_{00} of aim with either of the prototype inks. Based on this analysis, it was clear that the orange ink was a better choice than red to reach the out-of- gamut colors. Likewise, we compared prototype violet and blue inks by looking at the cyan-magenta sector, and found that the blue ink gave the best results. Finally, we looked at two different green inks and a subset of the Pantone colors falling within the yellow-cyan sector, and selected the yellow-ish green ink for further evaluation.

Although we were able to use this multistep 4 + 1 approach to select the prototype O, G, and B inks, we were unable to evaluate wet-on-wet printing, and we were also unable to print the 5th ink in various positions within the baseline CMYK print order. To explore these second order effects on both color gamut expansion as well as overall print quality and color-to-color registration, we turned to a 4-color engineering press capable of printing four colors wet-on-wet at up to 76 m/min. We sequentially replaced one of the C, M, or Y inks with the complementary expanded gamut ink, and then we systematically varied the color order. For example, we first replaced the cyan ink with orange, and then varied the yellow, orange, magenta print order, in each case printing black last. We repeated this process for the blue ink (replacing it with yellow) and green ink (replacing it with magenta). Although differences among the different color orders were subtle, the result of this phase was to use the following color order as our starting point for the 7-color demonstration press: KGCBMOY.

Full process 7-color prints were produced on a pre-treated white BOPP film at a resolution of 600 x 600 with a drop volume of 11.4 pL, an upper ink limit of 250%, and a print speed of 300 ft/min (92 m/min). These print samples were flood coated with a solvent-based varnish is a subsequent operation. Characterization of these 7-color print samples compared to 4-color CMYK reference print samples made under the conditions indicated a gamut volume increase of 44%, and an increase of coverage of the Pantone library from 86% to 98% of colors within ΔE_{00} 3.5 of aim. Further improvements to color gamut volume and Pantone coverage are possible with continued optimization of pigment concentrations in the full ink set, ratios of the pigments used in the green and blue inks, in combination with fine tuning the order of laydown in the full process press configuration.

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References

1. Küppers, H., "Printing process where each incremental area is divided into a chromatic area and an achromatic area and wherein the achromatic areas are printed in black and white and the chromatic areas are printed in color sub-sections," U.S. Patent 4,812,899 (1986).

2. Herbert, R., and DiBernardo, A., "Six-color process system," U.S. Patent 5,734,800 (1998).

3. Reid, D., “Hexachrome Print Process,” Digital Output, XI (8), pp 2 – 4, (2005).

4. Baldwin, C., “Expanded gamut printing 101,” Labels & Labeling, pp 51 – 55 (2016).

5. Spencer, D., “Stream Concept Press for Kodak – On the Way to Offset-Class Print Quality,” SpencerLab Digital Color Laboratory White Paper, March, 2008; www.spencerlab.com/Reports/SpencerLab-Kodak%20Stream_WhitePaper.pdf.

6. Lindstrom, B. L., Bermel, A. D., Nelson, D. J., Sowinski, A. F., Jeanmaire, D. L., and Griffin, T. R., “Ink composition for continuous inkjet printing,” U. S. Patent 8,455,570 (2013).

7. Bishop, J. F. and Czekai, D. A., “Ink jet inks containing nanoparticles of organic pigments,” U. S. Patent 5,679,138 (1997)

8. House, G. L., Wang, X., and Sowinski, A. F., “Pigment ink jet ink composition,” U.S. Patent Application Publication 2007/0043144 (2007).

9. Falkner, C. A., Wang, Y., Yau, H.-L., Robello, D. R., and Mis, M. R., “Recirculating fluid printing system and method,” U.S. Patent 8,434,857 (2013).

10. Dannhauser, T. J. and Campbell, G. A., “Inkjet recording medium and methods therefor,” U. S. Patent 9,434,201 (2016).

11. Dannhauser, T. J., Bugner, D. E., Putnam, D. D., and Lindstrom, B. L., “Printing on water-impermeable substrates with water-based inks,” U.S. Patent 9,376,582 (2016).

12. “Guidelines and specifications, SWOP 2007 specs”, IDEAlliance SWOP Committee, supplement to Graphic Arts Monthly, pp 11 – 24, May 2007.

13. General Requirements for Applications in Commercial Offset Lithography (GRACoL) G7 Specification 2008; see also: ISO 2846-1:2006, “Graphic technology — Colour and transparency of printing ink sets for four-colour printing — Part 1: Sheet-fed and heat-set web offset lithographic printing,” and ISO 12647-2:2013, “Graphic technology — Process control for the production of half-tone colour separations, proof and production prints — Part 2: Offset lithographic processes.”

14. Lindstrom, B. L. and Bugner, D. E., "A comparison of image permanence and print durability attributes for commercial digital print materials with traditional offset," Proceedings of NIP26: International Conference on Digital Printing Technologies, pp 400 – 403 (2010).

15. Bermel, A. D. and Bugner, D. E., "Particle size effects in pigmented inkjet inks," J. Imaging Sci. Tech., 43(4), pp 320 – 324 (1999).

16. Wall, F. T. and Drenan, J. W., "Gelation of polyacrylic acid by divalent cations," J. Poly. Sci., 7 (1), pp 83 – 88 (1951).

17. Lussier, B. B. and Linehan, D. T., U.S. Patents pending.