Chapter 4: Performance

CHAPTER CONTENTS

CHAPTER OVERVIEW

This chapter describes the data collection that was done to evaluate performance of the different ink systems, and presents highlights of the results.

METHODOLOGY: The methodology of the data collection and tests for this CTSA is summarized in Section 4.1. The methodology section describes the performance demonstrations, the laboratory tests that were performed on all the ink/substrate combinations, and the specific sites at which the demonstrations were run. (The complete performance demonstration methodology can be found in Appendix 4-A, and other information relevant to the methodology is in Appendix 4-B through 4-D.) Western Michigan University conducted separate laboratory runs on all substrates using water-based and solvent-based inks. The use of a single press under controlled conditions was intended to provide some consistency and a basis of comparison for the results of the performance demonstrations. Highlights of the tests that were performed for the laboratory runs are discussed in Section 4.2, and more detailed information is provided in many of the appendices to Chapter 4, particularly Appendices 4-A through 4-E.

PERFORMANCE DEMONSTRATION TEST RESULTS: The printed substrates completed at the performance demonstrations were sent to Western Michigan University, which tested each ink/substrate combination. A total of 18 tests were performed to measure a wide range of capabilities for solvent-based, water-based, and UV-cured ink systems. The performance demonstration test results for solvent-based and water-based inks are summarized in Section 4.2 . Because the technology for UV-cured inks was still in a developmental phase at the time of the performance demonstrations (November 1996 — March 1997), the results for UV-cured inks are presented separately in Section 4.3. To provide a more current picture of UV-cured inks, The section also discusses some of the relevant advances that have been made in UV technology since the performance demonstrations were completed.

PERFORMANCE DEMONSTRATION SITE PROFILES: Demonstration runs were done at 11 sites, which are numbered to protect confidentiality. Section 4.4 provides detailed data about each of the volunteer printing facilities. For each facility, the type of ink used, control equipment, annual production, operating hours, and average production run are provided. Details are also provided about the presses on which the demonstrations were run.

HIGHLIGHTS OF RESULTS: At the end of Sections 4.3 and 4.4, readers will find brief summaries of the overall test results. This study was set up to explore a wide range of characteristics and interactions between inks and substrates that can be important in flexographic printing. The demonstrations were all performed by different press operators at different flexographic facilities under widely varying circumstances, and consequently the test scores show considerable variation over both ink systems and substrates, and often between individual ink product lines as well. That is, they show the kinds of differences that are typically encountered in the real world of flexographic printing. Such variances indicate that printers need to give careful consideration to a variety of different factors in determining acceptable quality for their facility. These factors—among them cost, health and environmental risks, energy use, and pollution prevention opportunities—are discussed in other chapters of this CTSA.

CAVEATS

The use of the terms *quality* and *acceptable print* are highly subjective. What one printer finds acceptable and salable in a printed product may be considered scrap by another printer. Thus, caution must always be used when making statements about what constitutes acceptable printing and high quality.

4.1 METHODOLOGY

The Flexography Project Technical Committee (whose members are listed at the front of this CTSA) developed this methodology to investigate the performance of solvent-based, water-based, and UV-cured ink systems on three film substrates. The substrates that were used are low-density polyethylene (LDPE), co-extruded polyethylene/ethyl vinyl acetate (PE/EVA), and oriented polypropylene (OPP). The methodology involved two types of data collection: performance demonstrations at 11 volunteer printing facilities, and laboratory runs conducted at the printing facility of Western Michigan University.

Facility Selection Process

Ten commercial printing facilities in the United States, and a press manufacturer's pilot line in Germany, volunteered to participate in this study. To participate in the project, facilities needed to be proficient with the ink system and the product-substrate combination that they would test. In some cases, this use of "real world" facilities and conditions required modifying the specifications, because all printers do not necessarily have the precise mixture of requirements desired. All facilities that participated donated press time to print the appropriate ink/substrate combinations on wide-web presses.[a]

Each facility that volunteered to participate in the project also contributed a significant amount of technical information via a detailed Facility Background Questionnaire (Appendix 4-B). The Site Profiles in Section 4.4 present much of this information.

Methodology for On-site Performance Demonstrations

Each ink/substrate combination was run on a standardized image in at least two of the facilities. Table 4.1 lists the ink-substrate combinations run at each of the facilities. Four of the 12 sites used a solvent-based ink system, five used water-based, and three used UV-cured. Seven sites ran LDPE, six sites ran PE/EVA, and seven sites ran OPP. Appendix 4-A details the specifications of the printing presses, plates, substrates, and demonstration runs.

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[a] One facility, Site 9, ran two different inks at the same location and was separated into two performance demonstrations (Sites 9A and 9B). This made a total of 12 "sites."

Table 4.1 Ink System and Substrates Tested at Each Site

Ink System	Substrate(s)	Site
Solvent-based	LDPE, PE/EVA	Site 5
	LDPE, PE/EVA	Site 7
	OPP	Site 9B
	OPP	Site 10
Water-based	LDPE, PE/EVA	Site 2
	LDPE, PE/EVA	Site 3
	OPP	Site 4
	OPP	Site 1
	OPP	Site 9A
UV-cured	LDPE, PE/EVA, OPP	Site 6
	LDPE, PE/EVA, OPP	Site 8
	LDPE	Site 11

During each demonstration, the press was run at production speeds (approximately 300 to 500 feet/min) for about two hours to produce up to 60,000 feet of printed product. Flexographic printing experts from Western Michigan University's (WMU) Department of Paper and Printing Science and Engineering were present at all demonstration runs to ensure consistent adherence to the methodology. At the completion of each demonstration, the printed substrate was sent to Western Michigan University for analysis.

These press runs were intended to provide a "snapshot" of performance under actual production conditions, rather than a tightly controlled experiment. The performance demonstrations collected information about the real-world print quality issues associated with different ink systems using different film substrates and printed on wide-web presses. Additionally, information was collected for the cost, environmental and health risk, and energy and natural resources analyses. (These issues are the focus of other chapters of this CTSA.)

The complete performance demonstration methodology and data collection sheets can be found in Appendices 4-A and Appendix 4-C.

Tests Performed on Samples from Performance Demonstrations and Laboratory Runs

All the samples collected in both the performance demonstrations and the laboratory runs were subjected to an extensive series of tests. A total of 18 different tests were conducted to analyze a wide range of ink properties and inks' effects on substrates, focusing on aspects that would be important to many flexographic printers. The purpose, procedure, and interpretive information for each test are provided in Table 4.2. The inclusion of laboratory runs allows comparative analysis about field performance. The results of these tests are described in Sections 4.2 and 4.3, and the details of the laboratory test procedures and performance data can be found in Appendix 4-E.

Table 4.2 Purpose, Procedure, and Interpretation of Tests

Test Name	Purpose	Procedure (detailed demonstration and laboratory procedures described in Appendix 4-E)[a]	Interpretation
Adhesive lamination	Measures bond strength between the adhesive layer of the lamination and the ink. In laminations, the ink needs to bond well to both top and bottom lamination structures.	A laminated sample was attached to a force measurement instrument (an Instron tensile tester). The instrument separated the lamination layer from the substrate. The amount of force in kilograms (kg) necessary to cause the separation was measured and recorded as the delamination force.	Adhesion is influenced by volume of ink applied, chemical composition, and ink-substrate interaction. Each measurement listed is an average of five measurements. Readings above 0.350 kg are considered acceptable.
Block resistance	Measures the bond between ink and substrate when heat and pressure are applied. Ink transfer from a printed substrate to a surface in contact with the print indicates that blocking has occurred.	Folded samples of the printed substrate were layered between sheets of aluminum foil. Pressure was applied to the foil/substrate/foil sandwich using a clamping device. Blocking was measured in the laboratory with samples collected from each site.	There is no industry standard for blocking. The integrity of the ink bond to the substrate is an important performance characteristic of the ink; no blocking (0) reflects good print quality. The results of the test were recorded on a scale from 0 (no blocking) to 5 (complete blocking).
CIE L*a*b*	Measures the reflected light of a printed color and calculates a unique numerical value. The ability to match L*a*b* values is crucial in producing high-quality graphics and meeting customer specifications.	Using a Datacolor Spectraflash 600, measurements were taken for four colors at four locations during each performance demonstration. For laboratory runs, measurements were taken for only one color measured at three locations.	CIE L*a*b* values have no units and are used only for relative consideration and reference. No conclusions can be drawn from the data because the ink systems use different pigments. Only the L* component of the L*a*b* values provides direct information about changes in density. A higher L* value=a lighter color; a lower L* value=a darker color; a higher a* value=a redder (less green) color; a lower a* value=a greener (less red) color; a higher b* value=a more yellow (less blue) color; lower b* value=a bluer (less yellow) color; The a* and b* components are a function of ink pigment, which differs by ink systems.
Coating weight	Measures the weight of the ink film layer on a substrate after drying; affects all final printed properties, both optical and physical.	This test was performed by drying printed samples in a 150°F oven for 1 hour to remove any remaining solvents. The samples were weighed, along with an equal number of unprinted samples of the same film type. The weight of the unprinted samples was subtracted from the weight of the printed samples. The difference was then divided by the total linear footage of the printed samples.	Coating weight is the weight of the ink film layer and is expressed in grams per square centimeter (g/cm^2). There is no industry standard for coating weight; it is only a relative value. Coating weight is a function of anilox roll volume, wettability of the substrate, ink viscosity, and weight of the solids content of the applied ink.

Table 4.2 Purpose, Procedure, and Interpretation of Tests (continued)

Test Name	Purpose	Procedure (detailed demonstration and laboratory procedures described in Appendix 4-E)[a]	Interpretation
Coefficient of friction (COF)	Determines the resistance of a printed object to sliding. High COF is important is some situations, low COF in others.	COF was measured in the laboratory using an Instron tensile tester equipped with a friction sled. The COF values were then converted to angle of inclination.	Results are expressed as the angle of inclination, where high angle values indicate high resistance, or friction, between the ink and film substrate. COF values are relative and are used only as a reference based on the needs of the final product.
Density	Measures the degree of darkness (light-absorption) of a printed solid.	An X-Rite 418 densitometer measured the amount of reflected light from the surface of a printed sample.	Density is primarily a function of anilox roll volume and the resulting thickness of the applied ink film. Density fluctuations may be the result of changes in ink viscosity and impression pressure.
Dimensional stability	Measures how printing conditions distort the linear dimensions of the substrate. Various factors, such as heat from the dryers, can affect stability by changing the physical dimensions of the substrate — in either the cross-web direction (perpendicular to the movement of the web) or the machine direction (the direction in which the web moves).	Measured the length and width of the printed solid blocks, and compared those measurements to the size of the original images on the printing plate.	Any change in the dimensions of the printed areas indicates instability of the substrate due to printing conditions. The average percent change in the width of the sample represents the distortion in the cross-web direction compared with the original plate, and the average percent change in the length represents the distortion in the machine direction. The smallest percent change indicates the least amount of distortion.
Gloss	Measures the reflection from a light source directed at the surface from an angle.	A Gardner Microgloss glossmeter shone a beam of light at a 60° angle onto the sample; the light was reflected back onto a photoelectric cell. On LDPE, gloss was measured for magenta, cyan, blue, and green over a white ink background, and also for white, green, and blue on clear film. On PE/EVA, gloss was measured for magenta, cyan, blue, and green on white film.	The measurements are reported on a scale from 0 to 100 (higher numbers indicating higher reflectivity). These values have no units and are used only for comparison purposes. Gloss is a function of ink composition, ink film thickness, substrate, and, to a lesser extent, how well the ink dries on the substrate. The visual assessment of gloss is subjective.

Table 4.2 Purpose, Procedure, and Interpretation of Tests (continued)

Test Name	Purpose	Procedure (detailed demonstration and laboratory procedures described in Appendix 4-E)[a]	Interpretation
Heat resistance/ heat seal	Measures the degree to which a printed substrate will resist transfer when heated. Many printed products are subjected to extreme heat during handling and storage.	A printed sample was folded on itself and sandwiched between two pieces of aluminum foil. This sandwich was heated to 400°F. After the sample cooled back down, it was peeled apart and checked for ink transfer.	The test results are recorded as “pass” (no ink transfer), or “fail” (transfer of ink). In the case of a failure, the percent of ink transferred is evaluated and recorded.
Ice water crinkle adhesion	Measures the integrity and flexibility of the ink on the substrate when exposed to refrigerator and freezer conditions. Many flexographically printed products, such as those used for frozen foods, are subjected to very cold conditions. The inks must stay flexible and maintain the integrity of their adhesion to the substrate under these conditions so that they don’t rub off or flake off.	A printed strip was submerged in a container of ice water for 30 min. Then it was removed and twisted rapidly 10 times. This was done by grasping the print firmly between the thumb and forefinger of each hand with about one inch of print between the thumbs, bringing the hands almost together, and then rotating the wrists in opposite directions fairly rapidly.	The adhesion results of this test are expressed as a “no” (no ink was removed) or a “yes” (some of the ink was removed). If a “yes” is reported, the approximate amount of ink removed is given as a percentage; the higher the percentage, the lower the print quality. A “no” indicates that the ink maintained the integrity of its adhesion and flexibility when exposed to cold conditions.
Image analysis	Measures how well the image is formed. Good image detail is important for printing, particularly for small type, reverse type, and halftones (single or process color).	The test was performed using high-resolution optics, an RGB digital frame grabber, and a computer with Image ProPlus Analysis software. The average dot area and the average perimeter of the printed dots were measured and analyzed.	There is currently no industry standard for image detail. The data are only relative and can be used for comparing the formation of the tones among ink samples. The dot area and perimeter correspond to the spread of the ink and may indicate dot distortion. The test evaluates screened dot detail as used in process color reproduction. Dot detail information is dependent on the wettability of the substrate, impression pressure, viscosity, and cell volume of the anilox roll.
Jar odor	Measures the type and strength of odor produced by ink film on the substrate. Many flexographically printed products are used for food packaging, so it is important that ink odor does not affect the packaged product.	A printed sample was placed in a glass jar and sealed. The jar was put into a 100°F oven for 2 hours. It was removed, opened, and sniffed immediately. The same procedure was repeated with an unprinted sample of the substrate as a control.	The results of this test are expressed both quantitatively (on a scale from 0 to 5, with 0 signifying no odor and 5 signifying an unpleasant, offensive odor) and qualitatively (a comparative description of the odor).

Table 4.2 Purpose, Procedure, and Interpretation of Tests (continued)

Test Name	Purpose	Procedure (detailed demonstration and laboratory procedures described in Appendix 4-E)[a]	Interpretation
Mottle/lay	Measures spottiness or non-uniformity of an ink film layer. Minimizing mottle is important for high-quality printing.	Multiple density measurement points (250-500) were collected with a Mottle Tester during 20 linear scans over the sample area.	Minimizing mottle is a particular challenge when printing large solid areas, which are typical in line printing. There are no industry standards for “good” or “bad” mottle. The values should be used only for comparative analysis. The higher the Mottle Index, the lower the print quality. Also, the higher the standard deviation, the more variable the print quality.
Opacity	Measures the percentage of light blocked from being transmitted through the ink film and substrate. The opacity values indicate the uniformity of ink coverage of the substrate. Opacity is critical on clear substrates, where an opaque background is needed to provide a backdrop for other color graphics.	Samples were taken using a Datacolor Spectraflash 600 and a Diano-BLN opacity meter. The measurements were averaged to obtain one reading for each location.	Opacity is expressed as the percentage of light blocked. Average values greater than 48% are generally considered desirable. Factors such as anilox roll volume play a greater role in opacity than does ink type. High opacity is best achieved by using inks with high solids content and high application weights as governed by the anilox roll. Opacity is also a function of substrate and plate wettability. When interpreting opacity data, the anilox roll volumes, printing viscosity, and substrates must be evaluated as a complete system.
Rub resistance	Indicates the ink’s ability to resist being rubbed off substrate. Dry rub resistance is critical on products such as retail bags and bread bags, as the exposed ink film is abraded and scuffed during end use. Wet rub resistance is very important on frozen food bags, which can be subjected to abrasion during handling.	The initial density of the ink on the printed sample was measured using a Sutherland Rub Tester. For the dry rub test, a printed sample was mounted on the base of the rub tester, and an unprinted sample of substrate was mounted on a rubbing block. The rubbing block oscillated against the printed sample. Results were expressed as the percent of retained density. For the wet rub resistance test, distilled water was first placed on the printed surface at the start of the test; and a maximum of ten strokes was specified but no number of strokes per cycle was specified.	Both wet and dry rub are a function of ink film integrity and bonding to the substrate. Rub is influenced by volume of ink applied, chemical composition, and ink-substrate interaction. Rub is not considered as critical a factor on laminated OPP products, since the ink will be layered between two polymer substrates. The dry rub test results are reported as percent retained density after 50 strokes. For perfect print quality, the ink retains 100% density. Failure is determined by color transferred from the printed substrate to the unprinted substrate. The higher the number of strokes at which the sample fails, the better the rub resistance.

Table 4.2 Purpose, Procedure, and Interpretation of Tests (continued)

Test Name	Purpose	Procedure (detailed demonstration and laboratory procedures described in Appendix 4-E)[a]	Interpretation
Tape adhesiveness	Measures the bond of the dry ink to the substrate. Adequate ink adhesion is critical; if the ink doesn't adhere well enough, it will not be able to stand up to the normal demands placed on the finished product.	A length of adhesive tape was smoothed over a printed area of the sample, and the tape was pulled off with a smooth, quick movement at a little less than a 180° angle to the surface. The tape was pulled off with one hand while the substrate was held down on a flat surface with the other. This test was conducted on single and multiple layers of ink.	The results of this test are expressed as either "pass" (no ink was removed) or "fail" (some or all of the ink was removed). A "pass" indicates good ink adhesion.
Trap	Measures how well one ink prints on top of another. Good trapping is necessary to ensure adequate overprinting and to produce the desired color hue.	An X-Rite 418 densitometer measured the trap of magenta and cyan. Average trap, given as a percent, was calculated from densitometer readings.	Trap measurement of 100% is considered ideal.
Uncured residue (UV-cured inks only)	Measures whether uncured residue from UV-cured ink remains on the printed substrate after the final UV curing station. Uncured ink may have possible negative results, such as odor, ink transfer to the rollers, and ink contact with food after packaging.	Three jars were filled with enough alcohol to fully immerse one printed sample in each jar. After 24 hours, the first jar was checked for evidence of discoloration of the alcohol, indicating the presence of uncured residue on the sample. After 48 hours, the second jar was evaluated, and after 72 hours, the third jar was evaluated.	The degree of uncured residue is measured by the percent (by weight) of uncured ink removed. This number reflects the amount of uncured ink; the lower the percent, the better the UV cure.

[a] During performance demonstrations, up to four "locations" were marked on the printed test roll, determined by time into the test: w=start of run, x=30 minutes into run, y=60 minutes into run, and z=end of test or 120 minutes into run (whichever came first). These locations were analyzed during the laboratory tests.

Inks Used for the Study

Participation in the study was open to all ink formulators. The ink companies that participated in this study donated all the inks and submitted their formulations to EPA. Two different product lines were used for solvent-based inks, four product lines for water-based inks, and three product lines for UV-cured inks. Both line colors and process colors were printed, to cover the range of flexographic applications. Colors were printed to match colors identified in the Pantone Color Selector/Film Guide. The colors used in the demonstration are listed in Table 4.3.

Table 4.3 Colors Used for the Tests

	Color (as listed in the text)	Specific Color
Line colors	Blue	Reflex Blue
	Green	354 Green
	White (opacity target 48%)	
Process colors	Cyan	Phthalocyanine Blue
	Magenta	Rubine Red

Substrates Used for the Tests

Flexographic printers produce many different products on a variety of substrates. This project selected film substrates so that data could be collected on technical issues related to printing inks on film (e.g., drying times for non-solvent-based inks) and environmental issues (e.g., VOC emissions from solvent-based inks). The DfE team, along with the Technical Committee, chose three commonly used substrates that correspond to particular product segments. The substrates selected were (1) clear low-density polyethylene (LDPE), (2) white polyethylene/ethyl vinyl acetate (PE/EVA), and (3) clear oriented polypropylene (OPP). These three substrates represent a common selection of films to allow a wide range of flexographic printers to benefit from the data analysis. Table 4.4 describes the substrates.

Table 4.4 Substrates Used for the Tests

Substrate	Characteristics	Printing Type	Typical Products
Low-density polyethylene (LDPE)	1.25 mil, medium slip, clear	Surface	Shopping bags and bread bags
Polyethylene / ethyl vinyl acetate (PE/EVA) co-extruded film	2.5 mil, high slip, white, prints on polyethylene side	Surface	Frozen food bags
Oriented polypropylene (OPP)	0.75 mil, slip modified	Reverse	Snack food bags and candy bar wrappers

Film manufacturers donated the substrates used in the study. With two exceptions, all the LDPE was supplied by one manufacturer, all the OPP was supplied by another manufacturer, and all the PE/EVA was supplied by another. One exception was Site 11, where UV-cured ink was printed on an LDPE film that was extruded with no slip additives. The other exception was Site 7, which received a different PE/EVA substrate.

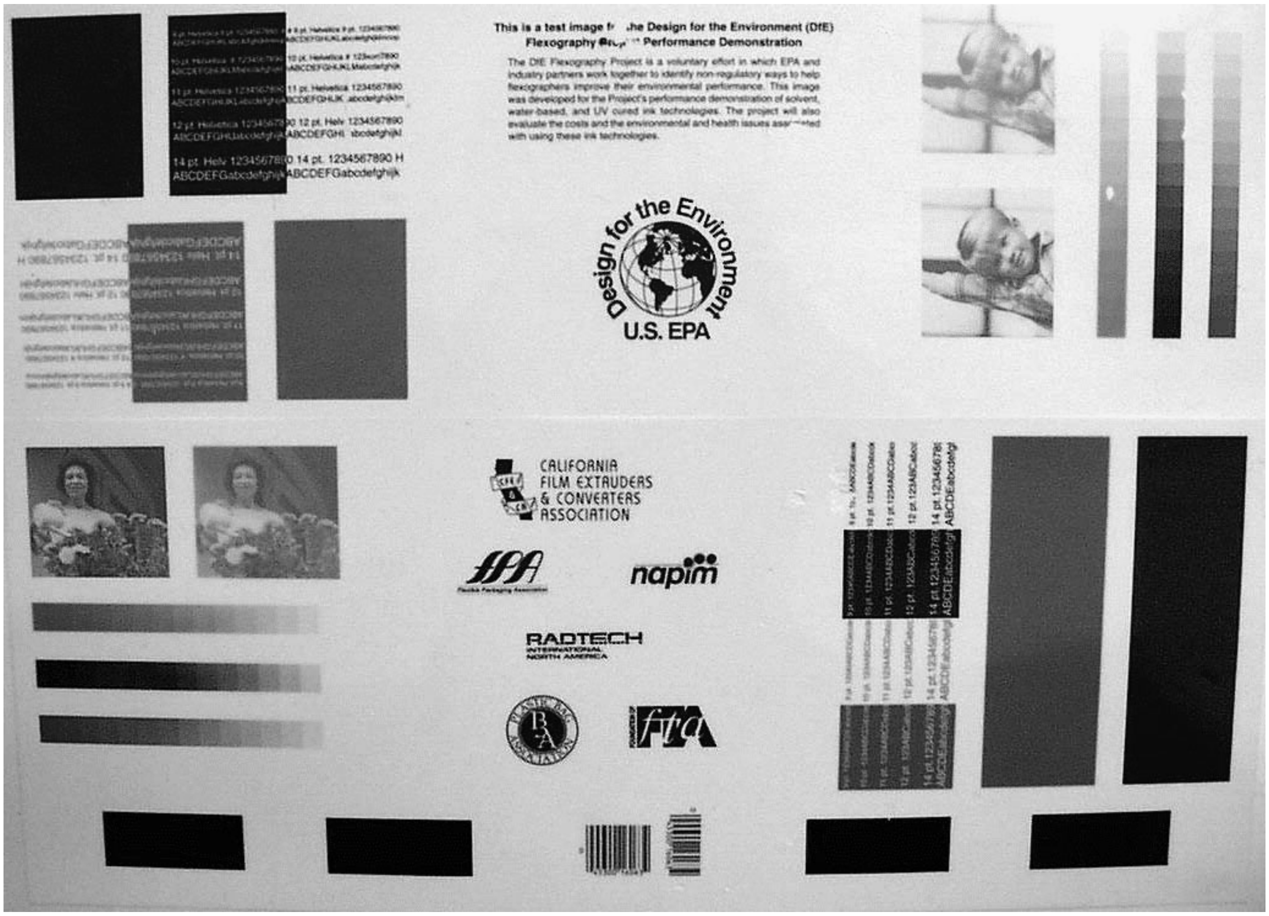
All films used with water-based and UV-cured inks were treated on press with a corona treater to achieve a dyne level specified by each ink manufacturer. The dyne levels of the films treated in the demonstration runs ranged between 40 and 44 dynes. The one exception was Site 4, for which the surface tension was known to be greater than 44 dynes but could not be measured with the available equipment.

Image and Plates Used for the Tests

The methodology specified photopolymer printing plates for the performance demonstration. The volunteer facilities were given the option of using donated plates or plates supplied by their own vendors. The caliper (thickness) of the plates was optimized for each press.

The test image was developed with the intent of covering the technical spectrum of printing on film at the time the project was designed, using recommendations made by the Technical Committee. The image was 20 inches wide and 16 inches long. The image included both process tone printing in various gradations and two-color line printing. A reduced-size copy of the image below and in Appendix 4-D.

Test Image Used in CTSA



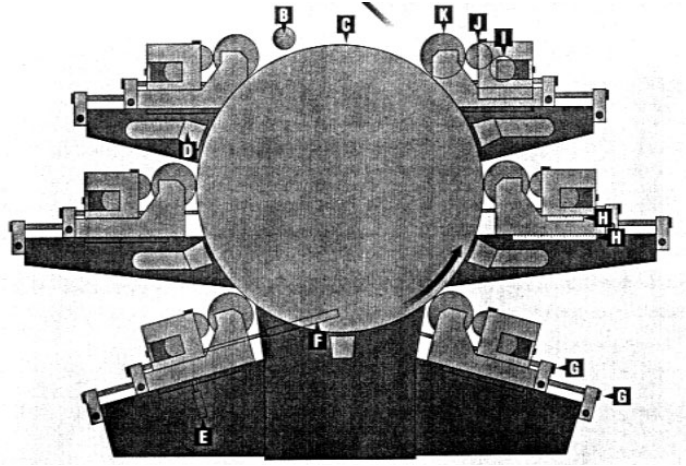
This is a test image for the Design for the Environment (DfE) Flexography Project Performance Demonstration

The DfE Flexography Project is a voluntary effort in which EPA and industry partners work together to identify non-regulatory ways to help flexographers improve their environmental performance. This image was developed for the Project's performance demonstration of solvent, water-based, and UV cured ink technologies. The project will also evaluate the costs and the environmental and health issues associated with using these ink technologies.

Printing Presses Used

There are three major types of flexographic printing presses: in-line, stack, and central impression (CI). The CI press was selected for use in the CTSA performance demonstrations. In many ways the CI press represents the standard for quality in the flexographic printing industry, especially in converting. This type of press has a particular advantage in holding tight register, which allows it to be used for technically demanding multiple-color jobs on many different substrates. The CI press is distinguished and named for its structural configuration, in which different color stations are arranged around a single large (central impression) drum. The number of stations can vary. Most CI presses have six color stations, but presses are now being built with eight and ten stations.

Diagram of Central Impression Press
(from *Flexography: Principles and Practices,* 5th edition, volume 6, page 6)



The performance demonstrations required wide-web CI presses, with a target width of 24 inches, six color stations, and capability of running the film substrates selected for the project. Suggested specifications of the presses chosen for the performance demonstrations are listed in Appendix 4-A. The point of choosing this type of press was to gather data about the three primary ink systems on commonly used presses running film substrates. At the time the project was designed this combination represented some of the most complex printing situations, as well as the anticipated future direction of flexographic printing. Wide-web printing in particular can pose many challenges. As a case in point, at the time this project was being developed, UV-cured inks were making inroads in narrow-web printing but not yet in wide-web printing.

Types of Printing Performed

The test image included process and line printing, to represent a wide range of types of flexographic printing. The performance demonstration runs also included both surface and reverse printing. In surface printing, the dried ink film sits on the surface of the product, so the physical properties of the ink can be extremely important. For example, the printing on food packages must be able to withstand extremes of temperature, wetness, and handling. In reverse printing, the ink is trapped between two layers of film, protecting it from outside physical contact. The chemical properties of the ink film are essential for keeping the substrate layers bound together and ensuring that the ink adheres well to the substrate.

Limitations of the Performance Demonstrations

Close adherence to the performance methodology was attempted throughout the study. Because of the voluntary nature of this project and the manufacturing diversity of the flexographic industry, however, occasional adjustments to the methodology were required. Overall changes, such as ink or substrate substitutions, were evaluated and approved by the Steering Committee, the DfE staff, or the field testing teams as they arose. Specific changes to the methodology made at the individual performance demonstration sites are described in the site profiles. Significant deviations from the methodology included the following:

- Adhering to the full two-hour run time of each ink-substrate combination would have placed an unacceptable burden on the production schedules of the volunteer facilities in six cases (Sites 2, 5, 6, 8, 9, and 10). At these sites, the press crew and DfE team continued the runs only as long as was deemed necessary to get accurate results.

- Some sites experienced shortages of materials, such as substrate, which decreased the run lengths. In addition, the overheating of the chill roller at Site 6 caused the run to be aborted.

- Although target ranges for the anilox roll volumes were specified in the methodology, the volunteer facilities did not all have rolls with these specifications available at the time of the performance demonstration. Again, because of the production needs of the volunteer facilities, changing or acquiring anilox rolls to meet the specified targets was impractical. A summary of the actual anilox roll specifications for all of the demonstration sites, along with the target specifications, can be found in Appendix 4-F.

- Ink type, although the focus of this project, is only one aspect of the very complex printing process. The project was not designed to control for other variables, so caution should be used when reviewing the test results.

- Although every effort was made to match the volunteer facility with the type of ink and type of printing that the facility normally runs, this was not possible at Site 9B, which normally runs water-based inks but ran solvent-based inks for the performance demonstration. This may have had an impact on the performance demonstration results.

In addition, the interpretation of the data is limited by the following caveats:

- Although the performance methodology set forth guidelines and parameters for the on-site printing runs, variable conditions between and within printing facilities, the limited number of facilities, and the relatively short duration of the performance demonstrations do not allow the results to be interpreted as definitive performance testing of the ink systems.

- Press operators' experience with ink systems differs substantially and can affect ink performance. Some of the information recorded was subjective and depended on the perception and previous experiences of the operators and the DfE team.

- Standardization of test protocols within the flexible packaging industries is limited. Some of the tests used in this project were developed at WMU. Other procedures were obtained from ink manufacturers and trade organizations. In addition, during the testing of the printing products, some methods were modified to improve accuracy and efficiency. The test procedures can be found in Appendix 4-E.

- Demonstration facilities were chosen based on their ink technology and relative experience with the system, rather than on their ability to attain a close match to all aspects of the performance test design.

Methodology for Laboratory Runs

Industry representatives decided that collecting data under both production and laboratory conditions would give printers a better sense of the actual capabilities of the ink/substrate combinations under a variety of conditions. Thus, laboratory runs were conducted at Western Michigan University's printing laboratory to collect baseline data. These runs used the same ink/substrate combinations and the same test image.

For all solvent-based and water-based ink formulations, laboratory runs were performed on a flexographic press at Western Michigan University (WMU). This was done to provide consistency of results and a context in which to interpret the performance test data. Due to equipment difficulties, the UV-cured ink combinations were not printed at WMU.

This section presents technical information about the laboratory facility and the press. Section 4.2 includes relevant data from the laboratory runs as well as the performance demonstration sites. (Laboratory site codes begin with an "L".) Appendices 4-E and 4-L provide a narrative description of the laboratory procedures and runs. All the results of the laboratory runs are included in the tables in Appendix 4-E.

Some general information about the facility at Western Michigan University is provided in Table 4.5.

Table 4.5 Summary Facility Background Information for Laboratory Runs

Item	Description
Ink type used	Solvent-based and water-based for education and test runs only
Emission control equipment	None
Annual production	This facility is an educational institution, not a commercial printing facility.
Operating hours	n/a
Avg. production run	n/a

The solvent-based and water-based inks used were provided by the same suppliers and formulators that supplied inks for the performance demonstrations. Table 4.6 lists the ink system, substrate, and product line that correspond to each laboratory run.

Table 4.6 Ink-Substrate Combinations for Laboratory Runs

Site[a]	Ink System	Substrate	Product Line
L1	Water-based	LDPE	W3
L2	Water-based	OPP	W4
L3	Water-based	OPP	W2
L4	Solvent-based	OPP	S2
L5	Solvent-based	LDPE	S2
L6	Water-based	PE/EVA	W3
L7	Solvent-based	PE/EVA	S2

[a] "L" indicates that this was a laboratory run.

The laboratory runs were conducted on a pilot press. The press used in the laboratory runs has an in-line design. Information about the press and configuration is shown in Tables 4.7 and 4.8. All laboratory runs were completed as designed, with no significant deviations from the methodology. A summary of information about the laboratory runs is provided in Table 4.9.

Table 4.7 Press Information for Laboratory Runs

Item	Description
Press	Zerand
Size of press	24 inches wide, two-color
Printing type	Surface
Typical production speed	500 feet/minute
Plates	0.107" Dupont EXL photopolymer: 1) Two process plates (magenta and cyan) mounted using compressible stick back 2) Three line plates (green, blue, and white) mounted using hard stick back
Corona treater	Enercon
Ink metering system	Two-roll with doctor blade
Type of doctor blade	Stainless steel
Ink pumping and mixing system	Electric

Table 4.8 Color Sequence and Anilox Configurations for Laboratory Runs [a]

Sequence	Color	Anilox lpi[b]	Anilox BCM[c]
Deck 1	White	220	6.4
Deck 2	Green	440	2.8

[a] Deck 1 (white ink) was changed to cyan ink for the PE/EVA substrate.
[b] lines per inch
[c] billion cubic microns per square inch

Table 4.9 Summary Information from Laboratory Runs

	Lab Run #1	Lab Run #2	Lab Run #3	Lab Run #4	Lab Run #5	Lab Run #6	Lab Run #7
Substrate	LDPE	OPP	OPP	OPP	LDPE	PE/ EVA	PE/ EVA
Ink	#W3	#W4	#W2	#S2	#S2	#W3	#S2
Press Speed	343	231	292	324	311	274	305
Total Footage Consumed	41,143	27,732	35,097	38,851	37,263	32,930	36,875

The laboratory runs were optimized for speed, to maximize quality and drying efficiency. Because these tests lasted only a few hours, the press speeds listed in Table 4.9 do not necessarily reflect running speeds that may be more commonly seen in flexographic printing facilities.

The complete results for each test, including the laboratory runs, are provided in the tables in Appendix 4-E, Laboratory Test Procedures and Performance Data.

Impression on an in-line press is not as accurate as a central impression (CI) flexographic press. As a result, more mottle occurred during printing on all laboratory runs. In general, the water-based ink did not wet as well as the solvent-based ink, and more mottle was evident. Excessive foaming of the ink was evident for L3 (Water #2). L1, L2, and L6 (Water #3, #4) also showed some foaming after 15 minutes. Drying on the plates and poor re-wettability was noted in L7 (Solvent #2) after 20 minutes. In all runs, it was necessary to wash the plates during roll changes.

Block resistance scores were fairly consistent between the laboratory runs and the performance demonstrations (slight cling to slight blocking). No test received a score higher than 3, indicating that blocking was not a serious problem in this setting.

For the gloss test, the laboratory readings tended to be quite a bit lower than the site readings, indicating less gloss. This was especially evident with green water-based ink on LDPE, which had gloss readings below 25%.

For the opacity test, the average percent opacity was very high for site L5 (solvent-based ink on LDPE), but fairly low for the other scenarios. A high score indicates better opacity and higher quality of this aspect of the printing.

4.2 RESULTS OF PERFORMANCE DEMONSTRATION AND LABORATORY RUN TESTS — SOLVENT-BASED AND WATER-BASED INKS

This section discusses the results of the performance demonstration tests on solvent-based and water-based inks using all three film substrates. These two ink systems are discussed together to allow printers to compare how the systems perform with different substrates and in different tests.

The 18 tests (listed in alphabetical order) measure many aspects of appearance, odor, and durability of the inks, as well as evidence of interactions between the inks and film substrates. Some of these tests have established quality standards, whereas many do not. For example, the adhesive lamination and opacity tests each have a standard below which results are considered unacceptable by the industry. For CIE L*a*b* and coefficient of fiction tests, on the other hand, acceptability is a relative concept and depends entirely upon the needs of the printing situation. Also, some tests, such as jar odor, which measures the amount and type of odor from the different printed ink samples, are clearly subjective. Tests such as dimensional stability measure how the ink (and the process that applies it) affect the structure of the substrate on which the ink is printed. Table 4.2 describes the purpose, procedure, and interpretation for each test that was performed during the performance demonstrations and laboratory runs.

Data for the laboratory tests were obtained by examining up to four different locations on the printed rolls. The locations from which samples were collected are described in Appendix 4-A. A detailed description of each laboratory test procedure and results for the performance demonstrations can be found in Appendix 4-E. The tests and results for the laboratory runs are included in Appendix 4-I, and particularly interesting results are highlighted in the text.

Adhesive Lamination — Solvent-based and Water-based Inks

OPP was the only substrate that had a lamination layer to be tested. A clear propylene substrate was laminated to the printed sample at Sites 1 and 4, while a metallized propylene substrate was laminated to the printed sample at Site 9. Site 10 did not test for adhesive lamination; although the test substrate was intended to be laminated, the site did not have lamination capabilities.

Table 4.10 presents the adhesive lamination data. All four product lines tested had less than the minimum 0.350 kg that is considered acceptable. However, the solvent-based ink product line displayed a delamination force 16% greater than the average of the three water-based ink product lines.

Table 4.10 Adhesive Lamination Results — Solvent-based and Water-based Inks

Ink	Film	Product Line	Site	Average Delamination Force (kg)	Standard Deviation (kg)
Solvent-based	OPP	#S1	9B	0.3040	0.0132
Water-based	OPP	#W1	4	0.2649	0.0012
		#W2	1	0.2631	0.0000
		#W4	9A	0.2575	0.0158

Block Resistance — Solvent-based and Water-based Inks

Table 4.11 summarizes the block resistance test data. The averages are based on four measurements taken from each site sample. The two variables were the location of the sample (e.g., beginning or end of the run) and whether ink transferred to a printed or unprinted substrate. The most successful combinations of ink and substrate were water-based inks on LDPE and PE/EVA. The least successful combinations were water-based inks on OPP, followed by solvent-based inks on LDPE and PE/EVA.

Table 4.11 Block Resistance Results — Solvent-based and Water-based Inks

Ink	Film	Average Rating of Blocking Resistance[a]
Solvent-based	LDPE	2.9
	PE/EVA	2.9
	OPP	1.9
Water-based	LDPE	1.2
	PE/EVA	1.2
	OPP	3.2

[a] The following scale was used to assign a numerical score to the test results: 0 = no blocking. 1 = slight cling. 2 = cling. 3 = slight blocking. 4 = considerable blocking. 5 = complete blocking. Table 4-E.1 in Appendix 4-E provides a detailed description of this scale.

CIE L*a*b* — Solvent-based and Water-based Inks

For most sites, samples were taken at four locations on the substrate during the test run. Due to the aborted run using the PE/EVA substrate at Site 7, however, samples were taken only from the beginning and the end of the run. Sites 8 and 9 also had shorter runs, with samples taken only from the beginning, 30 minutes into run, and the end of the run.

Table 4.12 presents the results of the CIE L*a*b* test. Because this test does not have units and should be used for relative comparisons only, no overall statements can be made about the results of this test.

Table 4.12 CIE L*a*b* Results — Solvent-based and Water-based Inks

Ink	Film	Product Line	Site	Color	Average L*	Average a*	Average b*
Solvent-based	LDPE	#S2	5	magenta	47.07	58.41	-4.83
				cyan	59.82	-40.31	-13.65
				green	53.42	-48.59	29.56
				blue	38.07	5.25	-50.33
			7	magenta	50.03	54.48	-6.93
				cyan	61.75	-38.85	-23.90
				green	63.67	-39.34	31.42
				blue	42.43	0.03	-46.95
			L5	green	61.73	-40.73	30.10
	PE/EVA	#S2	5	magenta	54.11	47.73	-0.38
				cyan	62.17	-27.49	-37.61
				green	56.78	-55.08	32.32
				blue	36.84	16.46	-57.24
			L7	green	65.25	-37.46	31.32
				cyan	63.30	-28.79	-37.44
Solvent-based	PE/EVA	#S2	7	magenta	50.98	54.00	-3.89
				cyan	61.22	-31.68	-37.12
				green	67.69	-46.98	32.09
				blue	38.77	13.11	-53.87
	OPP	#S1	9B	magenta	51.98	52.20	-3.96
				cyan	59.97	-37.48	-27.02
				green	64.76	-35.20	30.42
				blue	47.64	-5.21	-39.55
		#S2	10	magenta	67.01	29.98	-5.73
				cyan	70.86	-27.42	-12.67
				green	56.29	-47.18	29.39
				blue	40.01	2.51	-46.11
			L4	green	69.86	-35.62	32.38
Water-based	LDPE	#W3	2	magenta	51.43	50.55	-1.75
				cyan	56.38	-27.94	-35.69
				green	62.31	-51.15	34.34
				blue	34.11	16.01	-49.82
			3	magenta	52.46	51.31	-7.16
				cyan	64.10	-32.03	-21.71
				green	61.77	-54.49	37.65
				blue	33.43	17.90	-50.75
			L1	green	68.39	-44.29	32.33

Table 4.12 CIE L*a*b* Results — Solvent-based and Water-based Inks (continued)

Ink	Film	Product Line	Site	Color	Average L*	Average a*	Average b*
Water-based, cont.	PE/EVA	#W3	2	magenta	55.22	48.52	-1.05
				cyan	58.57	-22.09	-40.29
				green	62.32	-58.16	34.05
				blue	33.87	19.50	-49.27
			3	magenta	54.03	55.08	-2.54
				cyan	62.00	-28.11	-39.06
				green	62.27	-59.70	34.92
				blue	35.01	18.94	-50.39
			L6	green	70.40	-51.59	29.28
				cyan	64.77	-28.94	-37.15
	OPP	#W1	4	magenta	49.22	51.22	-4.05
				cyan	59.46	-32.96	-25.57
				green	53.32	-54.58	31.23
				blue	39.75	1.28	-45.48
		#W2	1	magenta	50.17	47.82	2.44
				cyan	57.40	-30.72	-27.87
				green	64.19	-57.66	44.41
				blue	30.19	15.65	-37.30
			L3	green	72.58	-32.68	25.21
		#W4	9A	magenta	48.53	52.36	4.16
				cyan	57.80	-35.74	-29.96
				green	61.39	-53.33	32.10
				blue	42.17	-1.38	-44.90
			L2	green	66.32	-44.36	28.26

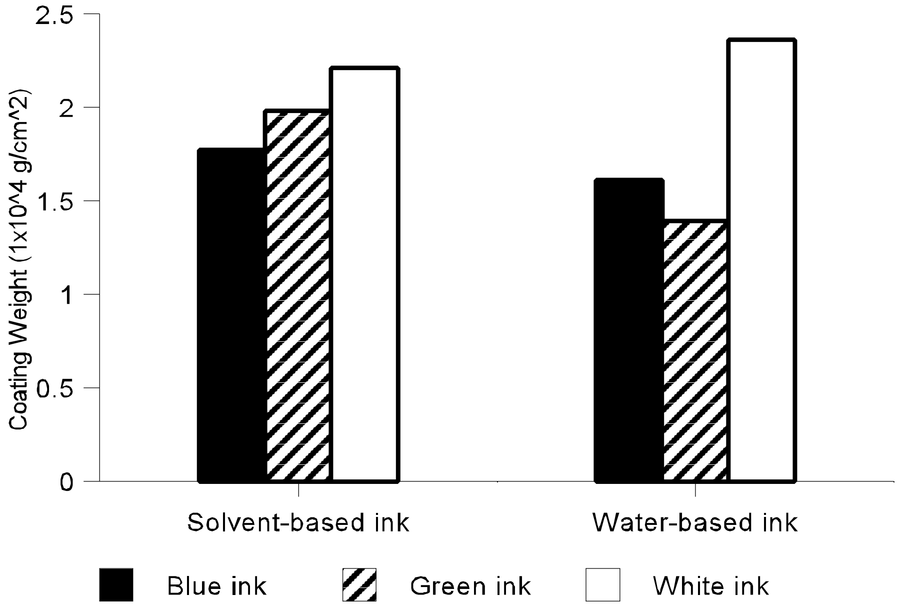
"L" in a site number indicates that the data were taken from a run conducted at Western Michigan University, not from a volunteer printing facility.

Coating Weight — Solvent-based and Water-based Inks

Coating weight was measured for green, blue, and white printed areas on OPP and LDPE. Only the green and blue inks were tested on PE/EVA because it is a white substrate.

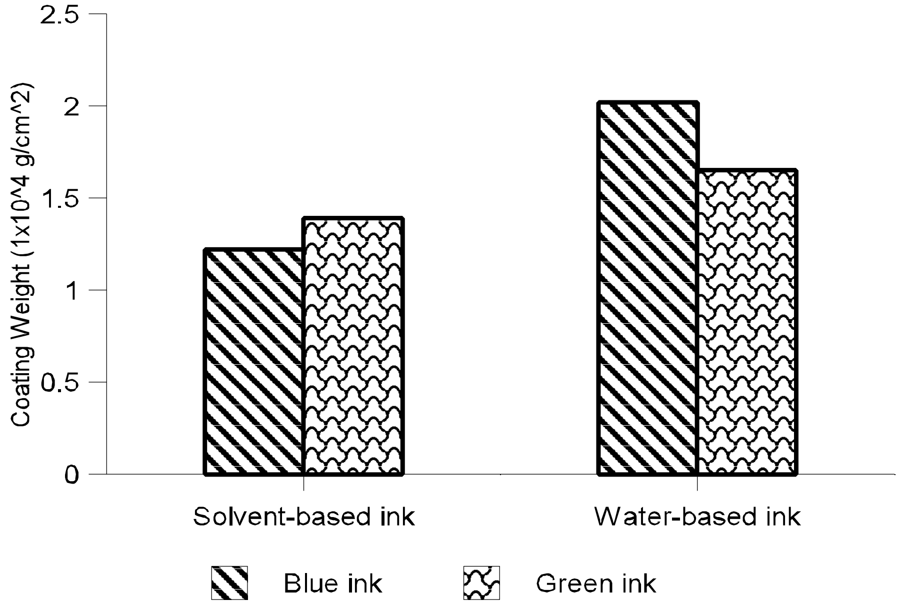
Figures 4.1-4.3 show the average coating weight data. The water-based inks in this study had higher solids content than the solvent-based inks, a typical scenario for these ink types. Therefore, on average, the water-based inks exhibited higher coating weights than the solvent-based inks on PE/EVA and OPP. This difference was most marked in the case of white ink on OPP and for blue and green inks on PE/EVA. For LDPE, on the other hand, the coating weight for water-based green ink was substantially lower than that for solvent-based green ink.

Figure 4.1 Average Coating Weight for LDPE — Solvent-based and Water-based Inks



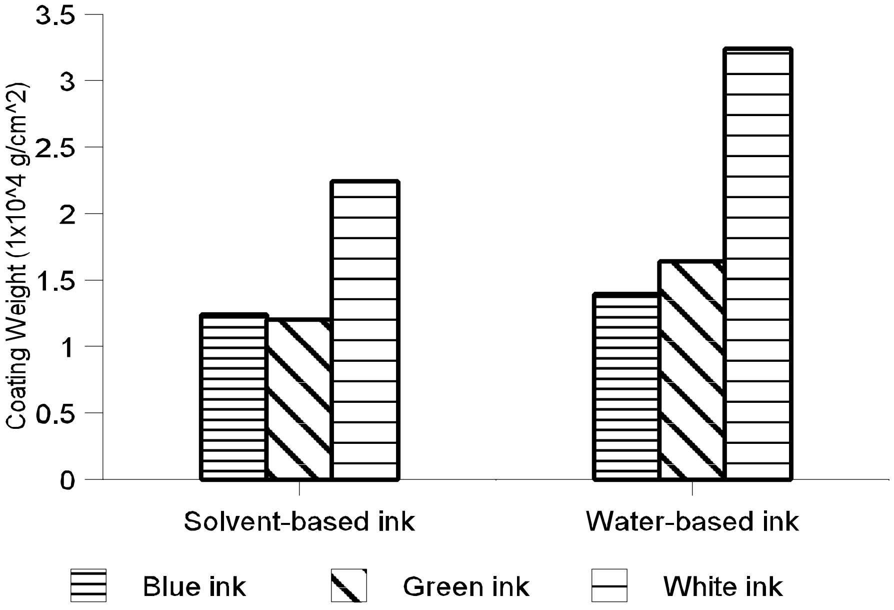
	Solvent-based ink	Water-based ink
Blue ink	1.77	1.61
Green ink	1.98	1.39
White ink	2.21	2.36

Figure 4.2 Average Coating Weight for PE/EVA — Solvent-based and Water-based Inks



	Solvent-based ink	Water-based ink
Blue ink	1.22	2.02
Green ink	1.39	1.65

Figure 4.3 Average Coating Weight for OPP — Solvent-based and Water-based Inks



	Solvent-based ink	Water-based ink
Blue ink	1.24	1.39
Green ink	1.2	1.64
White ink	2.24	3.24

Coefficient of Friction — Solvent-based and Water-based Inks

The coefficient of friction (COF) between two layers of unprinted substrate was measured to provide a control. The COF was then measured between printed substrate and unprinted substrate, as well as between printed substrate and printed substrate. Printed samples from Sites 1, 4, 9, and 10 were not tested in the laboratory because the OPP substrate printed at these sites was laminated to another substrate. The lamination traps the ink between the two substrate layers, making it unnecessary to test for COF.

Table 4.13 summarizes the COF test results. This test does not have a standard, because high COF may be desirable in some printing situations (for instance, if products are stacked on top of one another), whereas a low COF may be equally important in other cases. As would be expected, the unprinted controls had the lowest average COF, the products with only one surface printed (Ink-Un) had a higher average COF, and the products with both surfaces printed (Ink-Ink) had the highest average COF. Beyond this, however, no clear differences emerged between the two ink systems or among the different substrates.

Table 4.13 Coefficient of Friction Results — Solvent-based and Water-based Inks

Ink	Film	Product Line	Site	Average Angle of Inclination (degrees)		
				Ink-Un[a]	Ink-Ink[b]	Control[c]
Solvent-based	LDPE	#S2	5	28.4	36.5	22.3
			7	25.2	35.4	23.3
			L5	20.8	30.6	23.3
	PE/EVA	#S2	5	25.6	38.2	16.7
			7	23.5	22.2	16.7
			L7			
Water-based	LDPE	#W3	2	27.6	33.0	23.2
			3	27.8	29.4	23.3
			L1	34.2	34.2	23.3
	PE/EVA	#W3	2	24.8	32.6	16.7
			3	21.6	32.8	17.2
			L6	26.6	40.0	16.7

“L” in a site number indicates that the data were taken from a run conducted at Western Michigan University, not from a volunteer printing facility.

[a] “Ink-Un” represents the coefficient of friction for printed substrate on unprinted substrate.

[b] “Ink-Ink” represents the coefficient of friction for printed substrate on printed substrate.

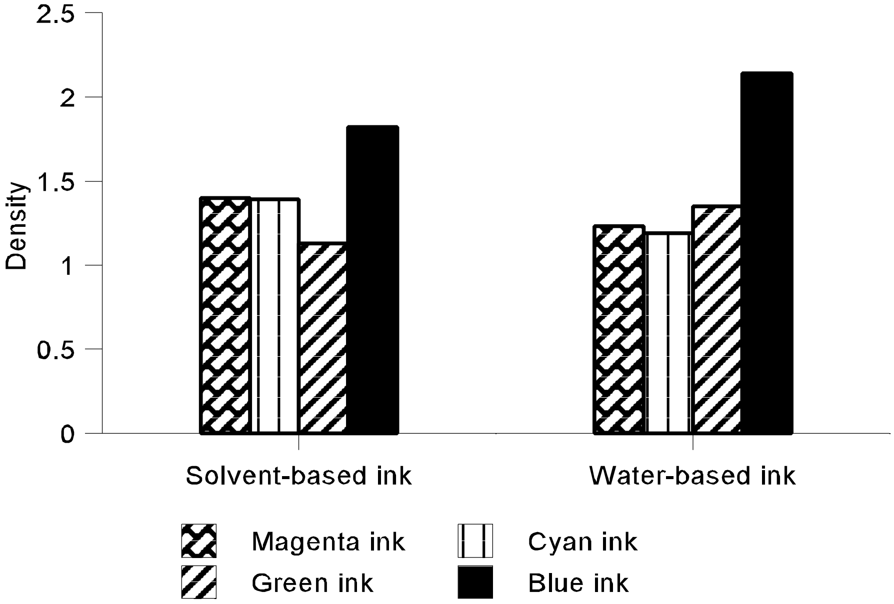
[c] “Control” represents the coefficient of friction for unprinted substrate on unprinted substrate.

Density — Solvent-based and Water-based Inks

Density was measured on areas printed with magenta, cyan, green, and blue inks. Due to shortened runs at Sites 7 and 9, samples were taken only at three of the four planned locations on the runs. Fewer samples than usual were taken for testing from the laboratory runs because they were shorter in duration than the performance demonstration runs.

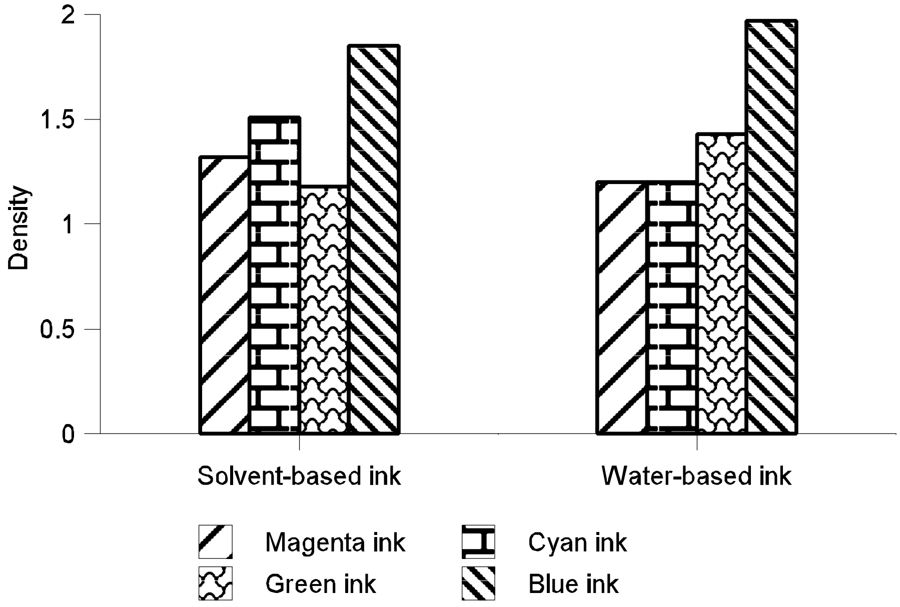
Figures 4.4-4.6 show the average density for these four ink colors on each substrate. Scores were highest for blue ink in all scenarios, and blue ink scores were higher for water-based inks than for solvent-based inks. Scores for the other colors tended to be fairly consistent with each other. On OPP, density was considerably higher on all water-based inks.

Figure 4.4 Average Density for LDPE — Solvent-based and Water-based Inks



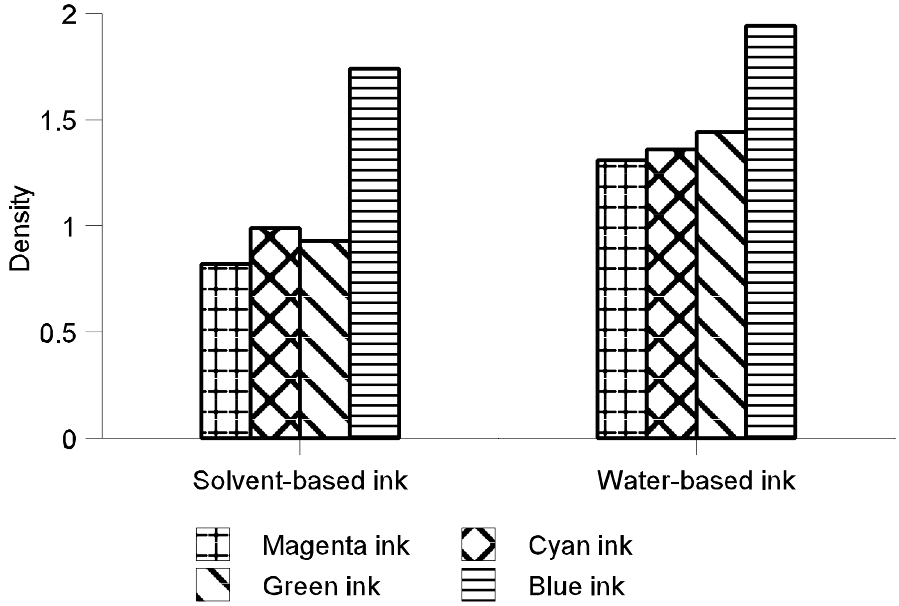
	Solvent-based ink	Water-based ink
Magenta ink	1.4	1.23
Cyan ink	1.39	1.19
Green ink	1.13	1.35
Blue ink	1.82	2.14

Figure 4.5 Average Density for PE/EVA — Solvent-based and Water-based Inks



	Solvent-based ink	Water-based ink
Magenta ink	1.32	1.2
Cyan ink	1.51	1.2
Green ink	1.18	1.43
Blue ink	1.85	1.97

Figure 4.6 Average Density for OPP — Solvent-based and Water-based Inks



	Solvent-based ink	Water-based ink
Magenta ink	0.82	1.31
Cyan ink	0.99	1.36
Green ink	0.93	1.44
Blue ink	1.74	1.94

Dimensional Stability — Solvent-based and Water-based Inks

Due to shortened runs at Sites 7 and 9, samples were taken only from some of the four scheduled locations on the run. Table 4.14 presents the results of the dimensional stability test. No statistically significant differences were evident between solvent-based and water-based ink systems.

Table 4.14 Dimensional Stability Results — Solvent-based and Water-based Inks

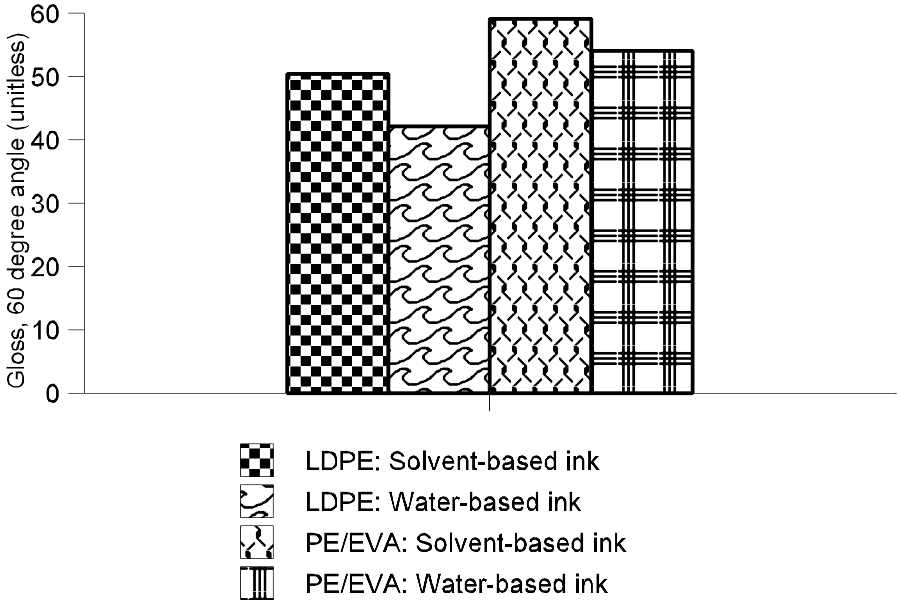
Ink	Film	Product Line	Site	Average Percent Change (Width)	Average Percent Change (Length)
Solvent-based	LDPE	#S2	5	0.5%	2.0%
			7	0.6%	0.4%
	PE/EVA	#S2	5	0.6%	2.4%
			7	0.5%	1.6%
	OPP	#S1	9B	0.7%	1.1%
		#S2	10	0.6%	2.5%
Water-based	LDPE	#W3	2	0.5%	1.0%
			3	0.4%	0.9%
	PE/EVA	#W3	2	0.5%	2.3%
			3	0.5%	1.5%
	OPP	#W1	4	0.5%	1.5%
		#W2	1	0.7%	1.6%
		#W4	9A	0.7%	1.5%

Gloss — Solvent-based and Water-based Inks

Samples from sites 1, 4, 9, and 10 were not subjected to this test because the OPP substrate printed at these sites was laminated. The ink was trapped between the two substrate layers, making it unnecessary to test for gloss. Limited data were available from Site 7 due to the shortened run on PE/EVA. Because the laboratory runs were shorter in duration than the performance demonstration runs, samples for testing were only cut from three locations.

Figure 4.7 shows the average gloss for samples on LDPE and PE/EVA. Overall, inks showed higher gloss on PE/EVA than on LDPE, and solvent-based inks on PE/EVA had the highest gloss.

Figure 4.7 Average Gloss for LDPE and PE/EVA — Solvent-based and Water-based Inks



LDPE: Solvent-based ink	50.4
LDPE: Water-based ink	42.19
PE/EVA: Solvent-based ink	59.08
PE/EVA: Water-based ink	54.09

Heat Resistance/Heat Seal — Solvent-based and Water-based Inks

Only samples printed on OPP and then laminated were tested. Heat resistance/heat seal was measured on blue, green, and/or white printed areas. Table 4.15 presents a summary of the heat seal data. A range of 12 to 24 measurements were taken from each site. The number of measurements depended on where they were taken (e.g., beginning, middle, or end of the run), what ink color was tested, and whether ink transferred to a printed or unprinted substrate.

The solvent-based and water-based inks exhibited mixed results for heat resistance/heat seal. For instance, Solvent-based ink #S2 experienced 100% failure at Site 10 but 100% success at Site L4. These results suggest that other factors, such as the lamination process, might have affected the results.

Table 4.15 Heat Resistance/Heat Seal Results — Solvent-based and Water-based Inks

Ink	Film	Product Line	Site	Number of Passes	Number of Failures	Average Percent of Ink Transfer Per Failure
Solvent-based	OPP	#S1	9B	9	9	10%
		#S2	10	0	18	39%
			L4	12	0	—
Water-based	OPP	#W1	4	9	15	21%
		#W2	1	0	24	26%
			L3	1	11	10%
		#W4	9A	6	12	9%
			L2	0	12	22%

"L" in a site number indicates that the data were taken from a run conducted at Western Michigan University, not from a volunteer printing facility.

Ice Water Crinkle Adhesion — Solvent-based and Water-based Inks

Printed samples from Sites 1, 4, 9, and 10 were not tested because the OPP substrate printed at these sites was laminated. This trapped the ink between the two substrate layers, making it unnecessary to test the ink on the OPP substrate.

Ink adhesion was measured for each color on each substrate. Table 4.16 summarizes the results of this test. The solvent-based ink performed successfully on both the LDPE and PE/EVA substrates. Water-based ink #W3 was evaluated at two sites. At Site 2, the ink performed successfully on both substrates, but at Site 3 the ink failed on both substrates. These results suggest that facility-specific factors other than ink might have affected the results.

Table 4.16 Ice Water Crinkle Adhesion Results — Solvent-based and Water-based Inks

Ink	Film	Product Line	Site	Any Ink Removal?
Solvent-based	LDPE	#S2	5	no
			7	no
			L5	no
	PE/EVA	#S2	5	no
			7	no
			L7	no
Water-based	LDPE	#W3	2	no
			3	yes, less than 5%
			L1	no
	PE/EVA	#W3	2	no
			3	no; less than 5%[a]
			L6	yes, about 30% of the green ink and less than 15% of the blue ink

“L” in a site number indicates that the data were taken from a run conducted at Western Michigan University, not from a volunteer printing facility.

[a] Three of the four samples had complete ink adhesion. The fourth sample had less than 5% removed.

Image Analysis — Solvent-based and Water-based Inks

Due to the shortened run using the PE/EVA substrate at Site 7, samples were taken only from the beginning and 30 minutes into the run. Because Sites 8 and 9 also had shorter runs, samples were taken only from the beginning, 30 minutes into run, and the end of the run.

Table 4.17 presents the image analysis results. Because the purpose of this test was to evaluate screened dot detail as used in process color reproduction, only the magenta and cyan process inks were analyzed. Table 4.17 presents the average dot area and perimeter for these two colors at each performance demonstration site. No statistically significant differences were evident between the two ink systems.

Table 4.17 Image Analysis Results — Solvent-based and Water-based Inks

Ink	Film	Product Line	Site	Color	Average Dot Area (micron^2)	Average Dot Perimeter (microns)
Solvent-based	LDPE	#S2	5	magenta	953.28	125.06
				cyan	725.86	104.26
			7	magenta	1049.71	130.64
				cyan	556.95	107.29
	PE/EVA	#S2	5	magenta	912.18	118.81
				cyan	721.00	104.70
			7	magenta	753.80	123.13
				cyan	323.88	103.58
	OPP	#S1	9B	magenta	620.58	102.60
				cyan	499.75	84.20
		#S2	10	magenta	568.41	122.39
				cyan	967.98	263.90
Water-based	LDPE	#W3	2	magenta	608.53	93.30
				cyan	925.17	120.86
			3	magenta	887.76	127.30
				cyan	608.71	97.16
	PE/EVA	#W3	2	magenta	705.83	107.11
				cyan	911.05	118.63
			3	magenta	649.76	96.93
				cyan	840.34	114.19
	OPP	#W1	4	magenta	837.88	116.53
				cyan	781.21	112.03
		#W2	1	magenta	371.59	97.63
				cyan	338.71	81.61
		#W4	9A	magenta	715.59	108.58
				cyan	748.80	95.80

Jar Odor — Solvent-based and Water-based Inks

Jar odor was evaluated for both printed and unprinted substrates. Table 4.18 presents the results of the jar odor test, listing the strength of the odor present and a description of the odor.

Most of the water-based ink samples had a relatively strong ammonia odor (2 to 3 on a scale of 5). Water-based ink #W1 had a strong, unpleasant odor that was not specifically identified as ammonia. The solvent-based inks had a waxy odor of varying strength (1 to 3 on a scale of 5) on all substrates. The one exception was the sample printed with solvent-based ink #S2 on PE/EVA film at Site 7; this sample had no odor for the control or the printed sample.

Table 4.18 Jar Odor Results — Solvent-based and Water-based Inks

Ink	Film	Product Line	Site	Relative Score[a]	Description of Printed Area	Description of Unprinted Area (control)
Solvent-based	LDPE	#S2	5	3	unpleasant	very slightly waxy
			7	1	waxy, not a big difference from control	waxy, hydrocarbons
			L5	2	mild waxy	very mild waxy
	PE/EVA	#S2	5	1	not very different from control; slightly like ethyl acetate	mild waxy
			7	0	no odor	no odor
			L7		mild waxy	very mild waxy
	OPP	#S1	9B	3	ethyl acetate	mild waxy
		#S2	10	1	waxy, no difference from control	waxy
			L4	1	mild waxy	very mild waxy
Water-based	LDPE	#W3	2	3	strong ammonia odor	very slight waxy
			3	3	strong ammonia odor	no odor
			L1	3	strong ammonia odor	very mild waxy
	PE/EVA	#W3	2	3	strong ammonia odor	very slight waxy
			3	3	strong ammonia odor	very mild waxy
			L6	1	mild waxy	mild waxy
	OPP	#W1	4	4	unpleasant, strong	mild
		#W2	1	2	ammonia odor	mild
			L3	2	ammonia odor	very mild waxy
		#W4	9A	0	no difference from control	mild waxy
			L2	2	ammonia odor	very mild waxy

“L” in a site number indicates that the data were taken from a run conducted at Western Michigan University, not from a volunteer printing facility.

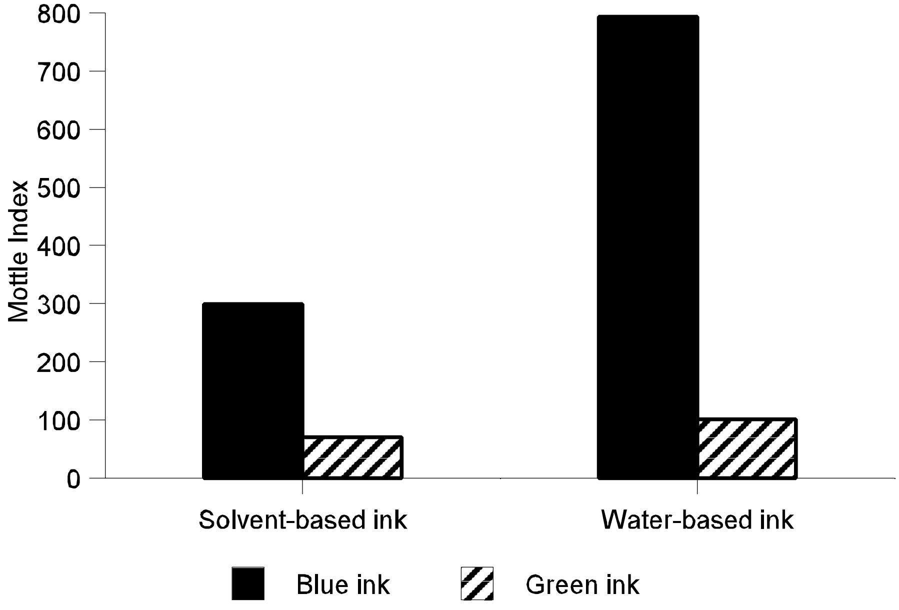
[a] Printed samples were scored on a scale from 0 to 5, with 0 signifying no odor, and 5 signifying an unpleasant, offensive odor.

Mottle/Lay — Solvent-based and Water-based Inks

Mottle was measured on green and blue printed areas. Figures 4.8-4.10 show much higher mottle on the samples printed with water-based inks, especially on LDPE and PE/EVA. Wettability of the substrate plays a role in mottle, and polyethylene substrate surfaces generally do not wet as well as OPP. Corona treatment was employed, however, on all of the LDPE and PE/EVA substrates where water-based inks were used.

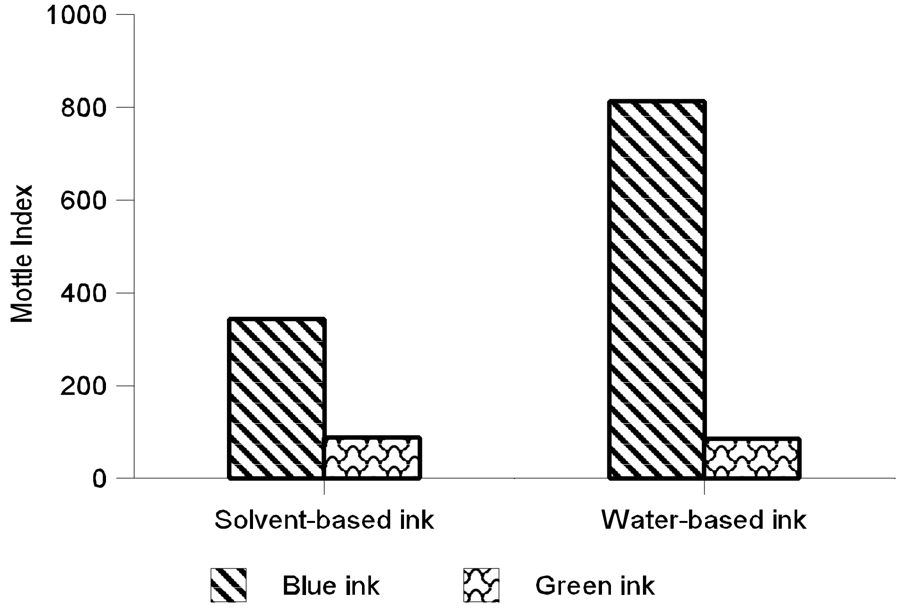
Mottle also was significantly higher on the blue printed areas of all samples tested. None of the variables in this study are thought to account for the differences between the green and blue printed sample results for mottle/lay. Ink formulation and pigment type are most likely the cause for the variations; these variations were evident both ink systems.

Figure 4.8 Average Mottle Index for LDPE — Solvent-based and Water-based Inks



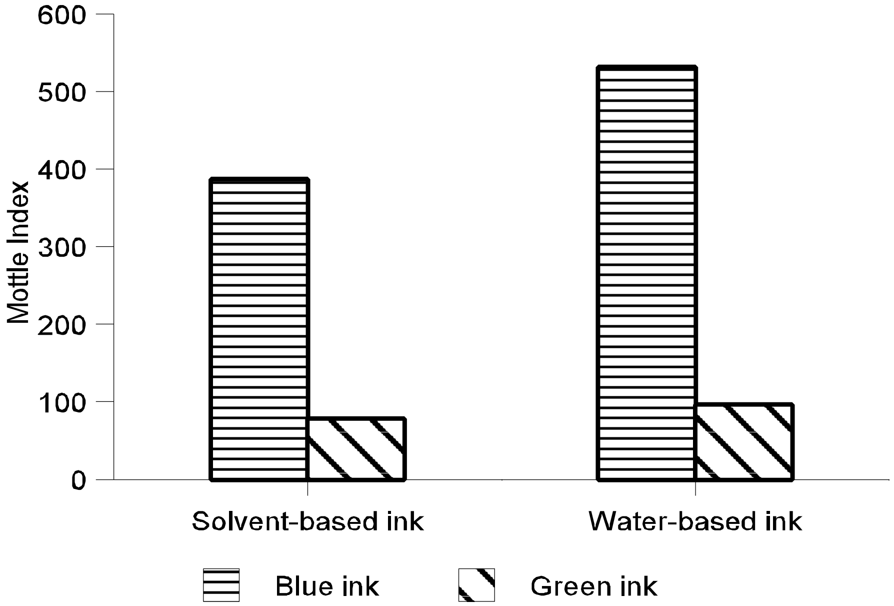
	Solvent-based ink	Water-based ink
Blue ink	298.7	793.75
Green ink	69.8	101

Figure 4.9 Average Mottle Index for PE/EVA — Solvent-based and Water-based Inks



	Solvent-based ink	Water-based ink
Blue ink	343.25	812.25
Green ink	87.5	85

Figure 4.10 Average Mottle Index for OPP — Solvent-based and Water-based Inks



	Solvent-based ink	Water-based ink
Blue ink	386.7	531.5
Green ink	78	96

Opacity — Solvent-based and Water-based Inks

Opacity was measured for samples of white ink on LDPE and OPP. White samples were not printed on PE/EVA because it is a white substrate. The laboratory runs, as well as the runs at Site 9, were shorter in duration than the other demonstration runs; samples were therefore available only from three locations on these runs.

Results for both ink systems were considered acceptable by industry standards (opacity greater than 48%). Results were virtually identical for both ink systems on both substrates.

Rub Resistance — Solvent-based and Water-based Inks

Samples from sites 1, 4, 9, and 10 were not tested in the laboratory, because the OPP substrate printed at these sites was laminated to another substrate. This lamination trapped the ink between the two substrate layers, making it unnecessary to test for rub resistance. Due to the shortened run using the PE/EVA substrate at Site 7, samples were taken only from the beginning and end of the run. Because Site 8 also had a shorter run for the PE/EVA substrate, samples were taken only from the beginning, 30 minutes into the run, and the end of the run.

The blue sample was used for rub testing of the samples taken from the performance demonstration sites. Because blue was not printed during the laboratory runs, the green samples were tested instead.

All inks retained close to 95% of their density after the dry rub test. Table 4.19 presents a summary of the wet rub test results. During the wet rub testing, the water-based ink printed on LDPE performed the best, with “no failure at ten strokes” being reported on the samples from both Sites 3 and L1. The other ink-substrate combinations had mixed results.

Table 4.19 Wet Rub Resistance Results — Solvent-based and Water-based Inks

Ink	Film	Product Line	Site	Failure at Number of Strokes (average)[a]
Solvent-based	LDPE	#S2	5	4.2
			7	5.0
			L5	no failure at 10 strokes
	PE/EVA	#S2	5	2.2
			7	5.0
			L7	5.7
Water-based	LDPE	#W3	2	8.0
			3	no failure at 10 strokes
			L1	no failure at 10 strokes
	PE/EVA	#W3	2	2.5
			3	3.2
			L6	two samples had failures at 6 and 7 strokes; one sample had no failure at 10 strokes

"L" in a site number indicates that the data were taken from a run conducted at Western Michigan University, not from a volunteer printing facility.

[a] A failure represents ink color transferred from the printed substrate to the unprinted substrate. A maximum of 10 strokes were used for the wet rub resistance test. Measurements were taken at four locations and averaged.

Tape Adhesiveness — Solvent-based and Water-based Inks

Tape adhesiveness was measured on LDPE, PE/EVA, and when appropriate, on OPP. The OPP substrates run at the demonstration sites were not tested in the laboratory because these substrates were laminated. Thus, only OPP substrates printed in the laboratory runs were tested for tape adhesiveness. Only the colored inks were tested on the PE/EVA substrate because it is a white substrate.

Table 4.20 presents the results of the tape adhesiveness test. Both inks adhered completely to LDPE. Solvent-based and water-based inks showed good adhesion when printed on OPP during the laboratory runs.

Table 4.20 Tape Adhesiveness Results — Solvent-based and Water-based Inks

Ink	Film	Product Line	Site	Number of Passes	Number of Failures	Comments
Solvent-based	LDPE	#S2	5	4	0	
			7	4	0	
			L5	3	0	
	PE/EVA	#S2	5	2	2	outline of cyan and magenta was removed
			7	0	2	cyan and magenta were slightly removed
			L7	3	0	
	OPP	#S2	L4	3	0	
Water-based	LDPE	#W3	2	4	0	
			3	4	0	
			L1	3	0	
	PE/EVA	#W3	2	2	2	blue was removed
			3	3	1	green was removed
			L6	0	3	all colors were removed
	OPP	#W2	L3	3	0	
		#W4	L2	3	0	

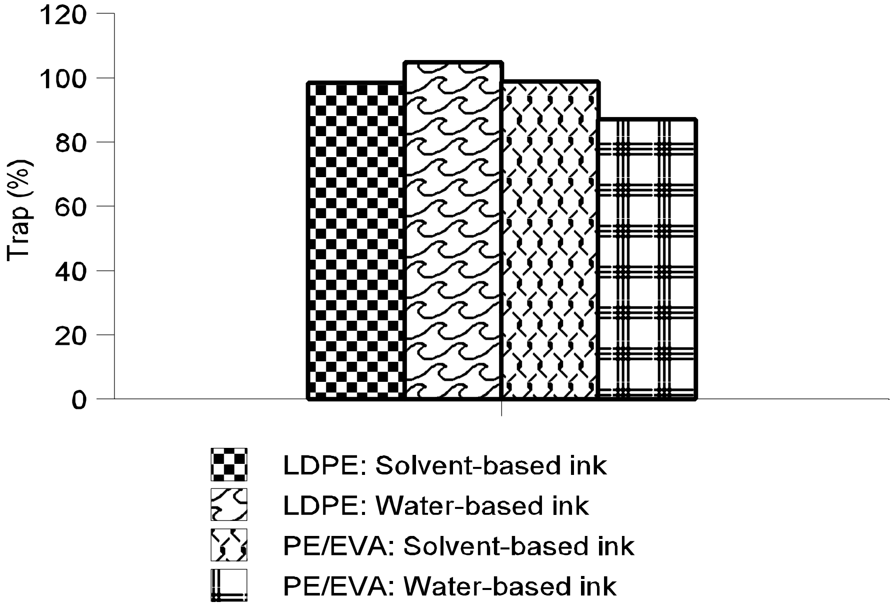
"L" in a site number indicates that the data were taken from a run conducted at Western Michigan University, not from a volunteer printing facility.

Trap — Solvent-based and Water-based Inks

Each site selected its own color sequence for first-down and second-down colors. Trap was measured for both 100% tone (solid) and 80% tone samples printed with magenta and cyan.

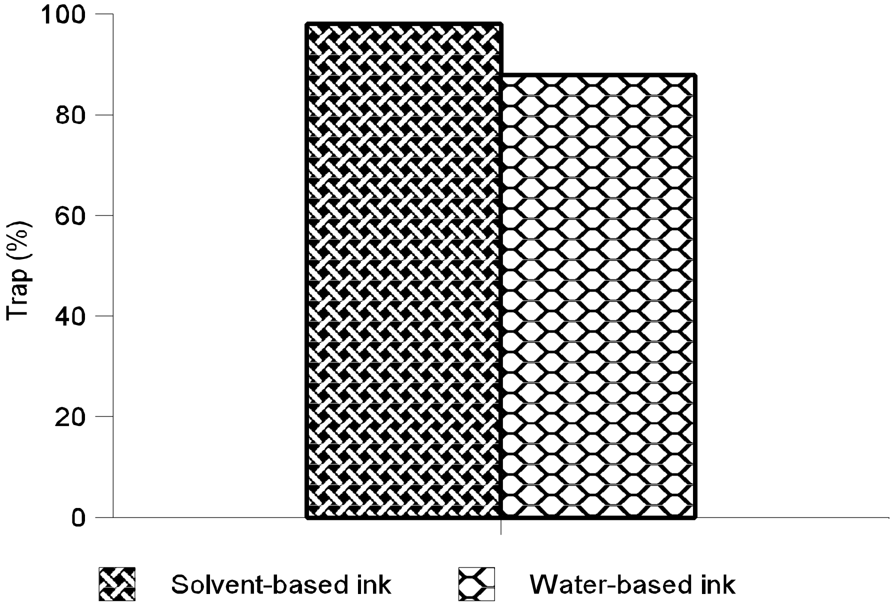
Figure 4.11-4.12 show the average percent trap for these two ink colors on each substrate. The solvent-based inks demonstrated better trap than the water-based inks on the PE/EVA and OPP films. The water-based inks showed slightly better performance than the solvent-based on the LDPE substrate.

Figure 4.11 Average Trap for LDPE and PE/EVA— Solvent-based and Water-based Inks



LDPE: Solvent-based ink	98.4
LDPE: Water-based ink	104.8
PE/EVA: Solvent-based ink	98.7
PE/EVA: Water-based ink	86.9

Figure 4.12 Average Trap for OPP— Solvent-based and Water-based Inks



Solvent-based ink	98
Water-based ink	87.8

Highlights of Performance Results for Solvent-Based and Water-Based Inks

No clear evidence emerged from these tests that either the solvent-based or the water-based system performed better overall. The results of the tests varied widely. On some tests, both ink systems performed comparably well on one substrate and poorly on another. COF, and in most cases density, dimensional stability, image analysis, opacity, and rub resistance, all displayed results that were fairly consistent from substrate to substrate for both ink systems.

On the other hand, other tests showed wide internal variability. Solvent-based inks performed an average of 16% better than water-based inks on the adhesive lamination test. Water-based inks had much better ratings than solvent-based inks on both LDPE and PE/EVA. Gloss was highest for solvent-based inks on PE/EVA. On OPP, heat resistance varied from 9% for one water-based ink to 39% for a solvent-based ink. Odors varied in both strength and type across both ink and substrate type. Mottle was significantly higher for blue inks and water-based inks. Tape adhesiveness and trap varied by substrate and ink system.

These variances point out the importance of a number of factors in the performance of these inks. Substrate type clearly emerged as a critical component of quality. The type and amount of the vehicle (solvent in solvent-based ink and water in water-based ink), as well as press-side solvents and additives, affected the physical properties of ink and substrate. In turn, functional ink-substrate interactions such as wetting and adhesion affected several of the performance results.

The variability of the results indicates that there may not be one best overall choice of an ink system for all performance conditions and applications. One clear conclusion is that a flexographic printer cannot make a simple assumption that any of these ink systems or ink-substrate combinations will be best-suited to the firm's overall needs. Careful testing of a potential ink system on the various substrates that a printer will be using most often is critical to obtaining desired quality on a consistent basis.

4.3 RESULTS OF PERFORMANCE DEMONSTRATION AND LABORATORY RUN TESTS — UV-CURED INKS

This section focuses separately on the ultraviolet-cured ink system, because flexographic printing technology using this UV inks on wide-web presses, particularly using film substrates, was still in a developmental phase at the time this research was performed (November 1996—March 1997). Therefore, the results using UV-cured inks should be viewed as a snapshot of the technology under field conditions during that time period rather than as representative of the capabilities of UV inks now or in general. Since that time, improvements in UV-cured inks have been made that are described in more detail at the end of this section (Technological Developments in UV-cured Inks). Due to technical limitations, no laboratory runs were performed for UV inks.

For the methodology or for more specific information regarding the performance demonstration tests, please see Section 4.1 of this chapter and Appendix 4-E. Table 4.2, near the start of this chapter, describes the purpose, procedure, and interpretation for each test that was performed.

Substrate type played a major role in the performance of UV-cured inks during the tests, showing that the ink-substrate relationship is very important to the performance of printed products. As is true for the solvent-based and water-based ink systems, the UV-cured ink results also varied widely among tests. Printers need to consider the needs of their clients, the type of substrates and products that they most often print, and the desired aspects of quality that are most critical overall, when determining which type of ink system will be most appropriate for the facility.

Block Resistance — UV-cured Inks

Table 4.21 shows the results of this test. On LDPE the ink showed slight blocking. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no block resistance data were available for this ink-substrate combination.

Table 4.21 Block Resistance Results — UV-cured Inks

Ink	Film	Average Rating of Blocking Resistance[a]
UV	LDPE	2.5
	PE/EVA	1.4
UV (no slip)	LDPE	1.0

[a] The following scale was used to assign a numerical score to the test results: 0 = no blocking. 1 = slight cling. 2 = cling. 3 = slight blocking. 4 = considerable blocking. 5 = complete blocking. Table 4-E.1 in Appendix 4-E provides a detailed description of this scale.

CIE L*a*b* — UV-cured Inks

Results for LDPE and PE/EVA are shown in Table 4.22. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no CIE L*a*b* data were available for this ink-substrate combination.

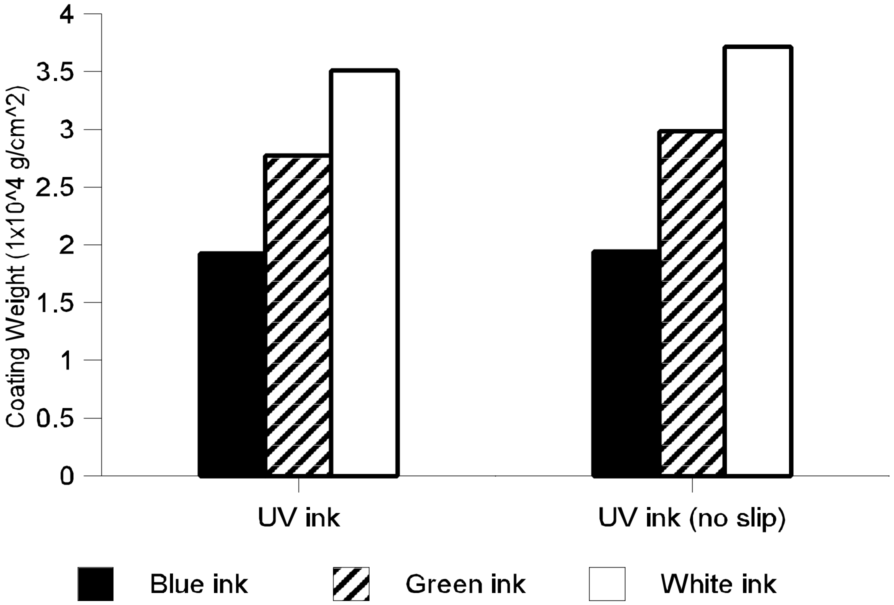
Table 4.22 CIE L*a*b* Results — UV-cured Inks

Ink	Film	Product Line	Site	Color	Average L*	Average a*	Average b*
UV	LDPE	#U2	6	magenta	43.80	49.03	10.90
				cyan	61.17	-37.58	-23.76
				green	65.54	-50.76	32.96
				blue	40.57	2.25	-44.73
	PE/EVA	#U2	6	magenta	47.60	53.85	4.01
				cyan	60.78	-30.65	-38.58
				green	64.47	-57.91	31.73
				blue	38.81	11.30	-50.42
		#U3	8	magenta	53.21	53.50	-2.41
				cyan	62.38	-27.22	-36.98
				green	70.93	-53.83	6.50
				blue	48.64	8.45	-46.77
UV-cured (no slip)	LDPE	#U1	11	magenta	52.71	48.81	-4.70
				cyan	59.88	-33.27	-24.42
				green	63.86	-56.90	10.70
				blue	34.60	15.39	-51.63

Coating Weight — UV-cured Inks

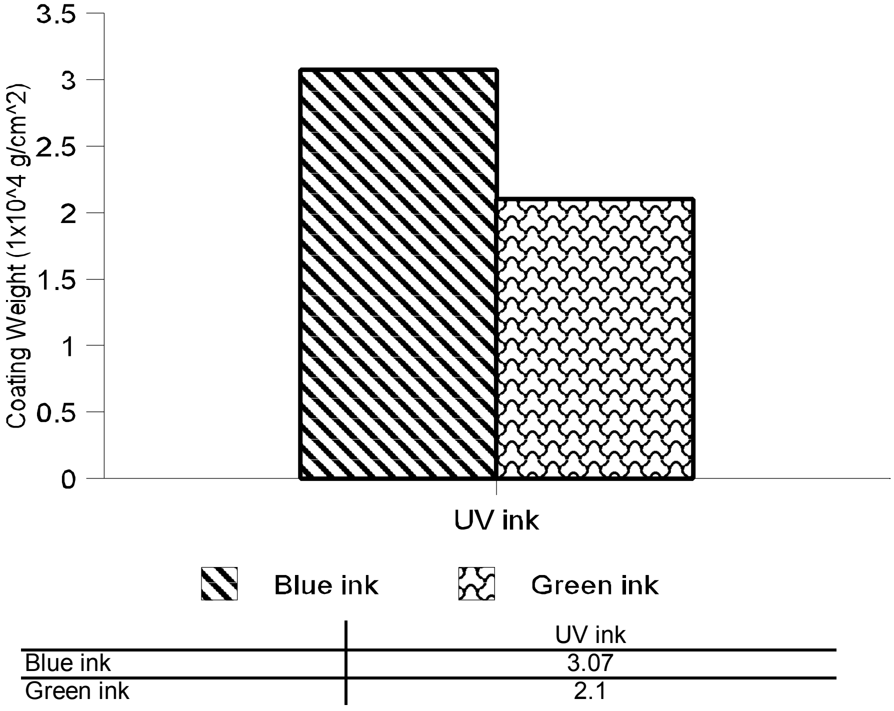
On LDPE, coating weight was lowest for blue and highest for white inks. Figures 4.13 and 4.14 show the results. There were no successful runs of UV-cured ink on OPP, so no coating weight data were available for this ink-substrate combination.

Figure 4.13 Average Coating Weight for LDPE — UV-cured Inks



	UV ink	UV ink (no slip)
Blue ink	1.92	1.94
Green ink	2.77	2.98
White ink	3.51	3.71

Figure 4.14 Average Coating Weight for PE/EVA — UV-cured Inks



	UV ink
Blue ink	3.07
Green ink	2.1

Coefficient of Friction — UV-cured Inks

Results are shown in Table 4.23. UV ink #U3 at Site 11 had the highest COF, as was expected since a no-slip film was used. The COF for UV ink #U2 on LDPE (Site 6) was higher than the other ink-substrate combinations, particularly for two layers of printed substrate. Otherwise, no significant differences between inks tested on the LDPE and PE/EVA substrates existed. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no COF data were available for this ink-substrate combination.

Table 4.23 Coefficient of Friction Results — UV-cured Inks

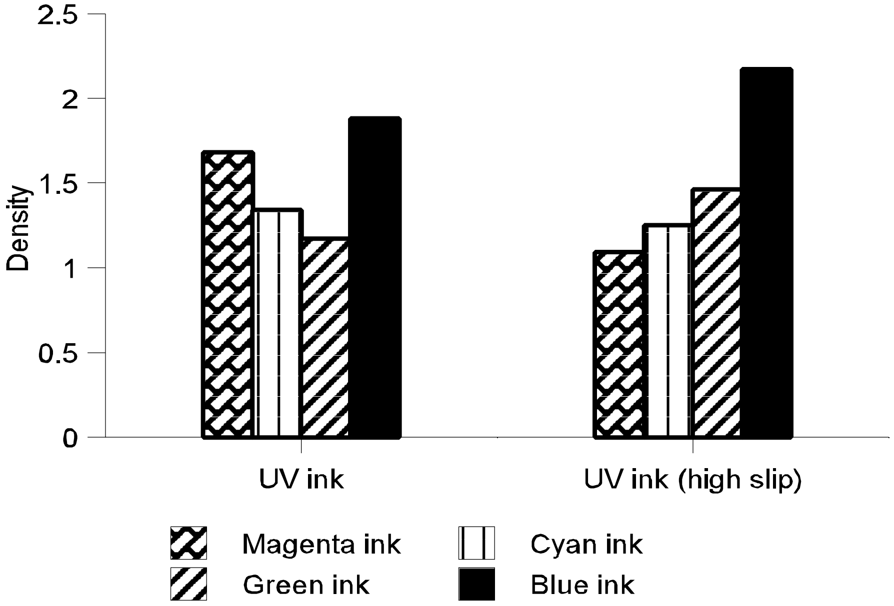
Ink	Film	Product Line	Site	Average Angle of Inclination (degrees)		
				Ink-Un[a]	Ink-Ink[b]	Control[c]
UV	LDPE	#U2	6	31.2	53.8	23.3
	PE/EVA	#U2	6	20.8	21.3	16.7
		#U3	8	25.9	24.7	16.7
UV (no slip)	LDPE	#U1	11	36.9	60+[d]	45.0

[a] "Ink-Un" represents the coefficient of friction for printed substrate on unprinted substrate.
[b] "Ink-Ink" represents the coefficient of friction for printed substrate on printed substrate.
[c] "Control" represents the coefficient of friction for unprinted substrate on unprinted substrate.
[d] The angle of inclination was higher than 60 degrees.

Density — UV-cured Inks

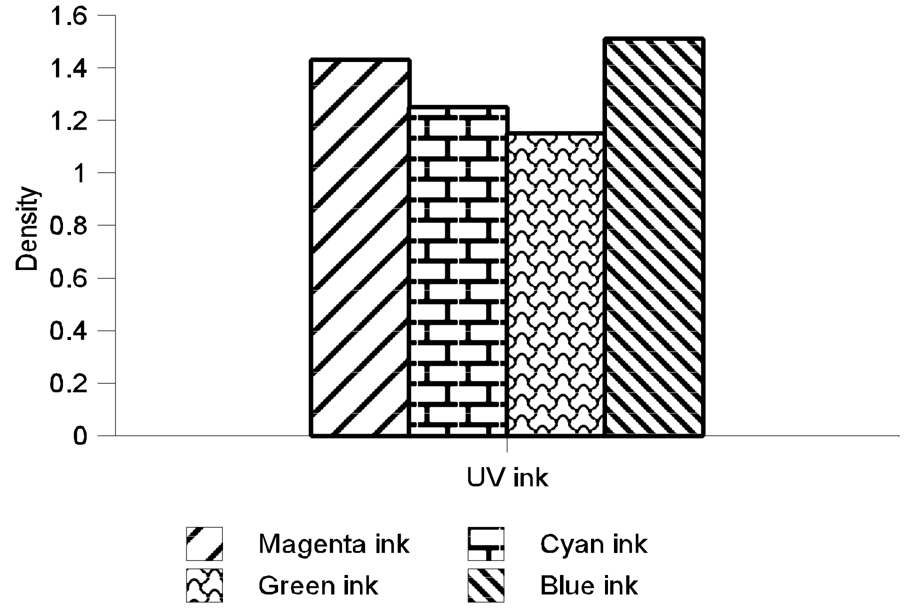
Results are shown in Figures 4.15 and 4.16. On LDPE, the density score for blue ink was substantially higher than that for any other color. Density on LDPE was much lower on the high-slip substrate. Due to a shortened run at site 8, samples were taken only at three of the four planned locations on the runs. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no density data were available for this ink-substrate combination.

Figure 4.15 Average Density for LDPE — UV-cured Inks



	UV ink	UV ink (high slip)
Magenta ink	1.68	1.09
Cyan ink	1.34	1.25
Green ink	1.17	1.46
Blue ink	1.88	2.17

Figure 4.16 Average Density for PE/EVA — UV-cured Inks



	UV ink	UV ink (high slip)
Magenta ink	1.43	n/a
Cyan ink	1.25	n/a
Green ink	1.15	n/a
Blue ink	1.51	n/a

Dimensional Stability — UV-cured Inks

Results are shown in Table 4.24. All three substrates showed similar measurements. Because the run at site 8 was shortened, samples were not taken from all scheduled locations. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no dimensional stability data were available for this ink-substrate combination.

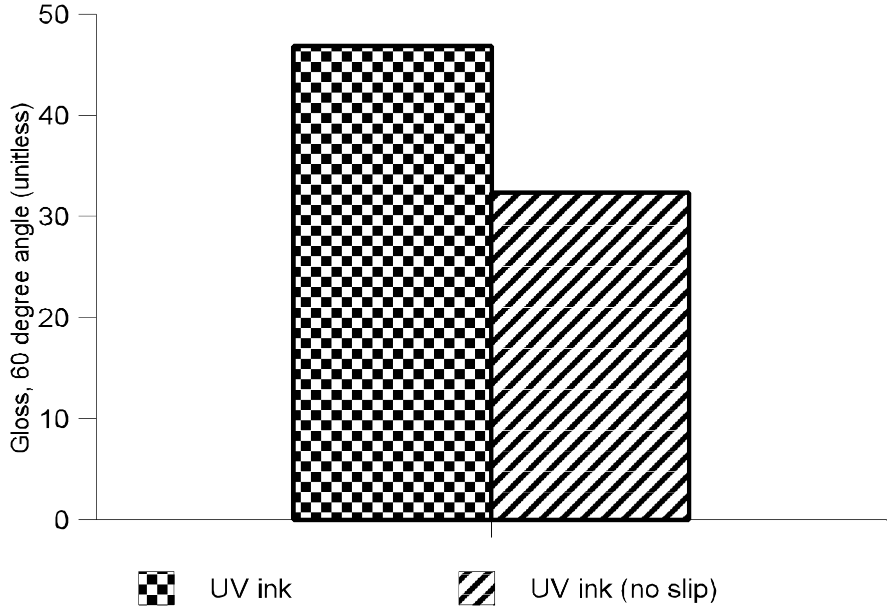
Table 4.24 Dimensional Stability Results — UV-cured Inks

Ink	Film	Product Line	Site	Average Width (mm)	Average Length (mm)
UV	LDPE	#U2	6	54.34	77.24
	PE/EVA	#U2	6	54.24	77.92
		#U3	8	54.08	75.83
UV (no slip)	LDPE	#U1	11	54.25	77.86

Gloss — UV-cured Inks

Figure 4.17 shows the results for UV and UV no slip on LDPE. All readings were below 50%, with UV on LDPE performing the best (46.83%). UV on PE/EVA averaged 42.41%. Limited data were available from Site 8, due to the shortened runs on PE/EVA. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no gloss data were available for this ink-substrate combination.

Figure 4.17 Average Gloss for LDPE — UV-cured Inks



UV ink	46.83
UV ink (no slip)	32.31

Ice Water Crinkle Adhesion — UV-cured Inks

Table 4.25 shows that two of the three UV-cured product lines (UV ink #U1 and UV ink #U3) stayed flexible on both substrates, but UV ink #U2 failed on both substrates.

Table 4.25 Ice Water Crinkle Adhesion Results — UV-cured Inks

Ink	Film	Product Line	Site	Any Ink Removal?
UV	LDPE	#U2	6	yes, less than 15%
	PE/EVA	#U2	6	yes, less than 15%
		#U3	8	no
UV (no slip)	LDPE	#U1	11	no

Image Analysis — UV-cured Inks

Table 4.26 shows the results of the test. Both average dot area and average dot perimeter varied, but not consistently with each other. Dot area showed a range from 384 square microns (cyan on PE/EVA) to 966 square microns (cyan on LDPE). Dot perimeter varied from a low of 80 square microns (cyan and magenta) to a high of almost 139 square microns (cyan). Due to the absence of successful runs of UV-cured ink on the OPP substrate, no image analysis data were available for this ink-substrate combination.

Table 4.26 Image Analysis Results — UV-cured Inks

Ink	Film	Product Line	Site	Color	Average Dot Area (micron^2)	Average Dot Perimeter (microns)
UV	LDPE	#U2	6	magenta	716.28	113.05
				cyan	966.98	134.64
	PE/EVA	#U2	6	magenta	672.38	101.13
				cyan	892.23	138.79
		#U3	8	magenta	480.28	91.78
				cyan	384.78	80.60
UV (no slip)	LDPE	#U1	11	magenta	456.52	80.80
				cyan	571.66	93.08

Jar Odor — UV-cured Inks

Table 4.27 lists the results of this test. The UV-cured inks showed more of a range in scores than did the other ink types. UV ink #U3 had the mildest odor, both in strength (1) and description (mild waxy). The odor from UV ink #U1 was rated 3 in strength and was described as "mild acetic acid." UV ink #U2 had the strongest odors (4 to 5 on a scale of 5) and was described as "very strong bitter almond" on the LDPE substrate, and as "very strong, decayed fish" on the PE/EVA. It should be noted that the controls for these samples were, respectively, "slightly like bitter almond" and "fish." This implies that either the unprinted substrate's odor affected the odor of the ink sample, or that the odor of the ink sample affected the entire roll (both printed and unprinted areas). Due to the absence of successful runs of UV-cured ink on the OPP substrate, no jar odor data were available for this ink-substrate combination.

Table 4.27 Jar Odor Results — UV-cured Inks

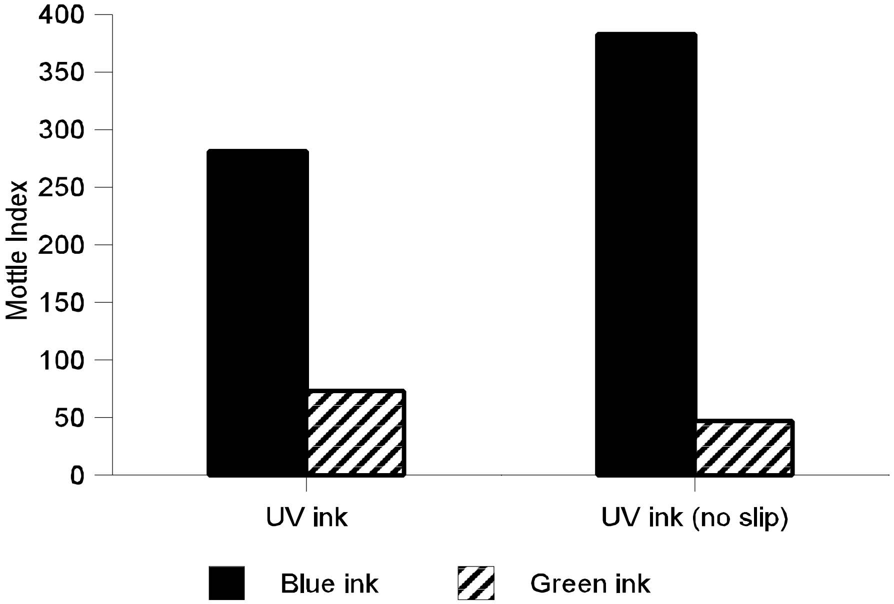
Ink	Film	Product Line	Site	Relative Score[a]	Description of Printed Area	Description of Unprinted Area (control)
UV	LDPE	#U2	6	4	very strong bitter almond	slightly like bitter almond
	PE/EVA	#U2	6	5	very strong, decayed fish	fish
		#U3	8	1	very slight odor	mild waxy
UV (no slip)	LDPE	#U1	11	3	acetic acid, mild	waxy

[a]Printed samples were scored on a scale from 0 to 5, with 0 signifying no odor, and 5 signifying an unpleasant, offensive odor.

Mottle/Lay — UV-cured Inks

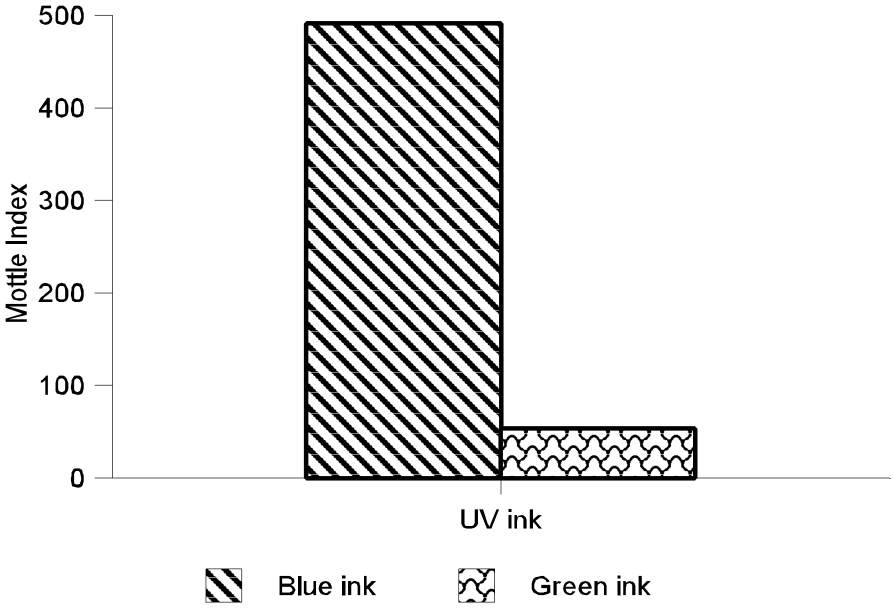
Figures 4.18 and 4.19 display the results of the mottle/lay test. Green ink showed little mottle on either substrate. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no mottle data were available for this ink-substrate combination.

Figure 4.18 Average Mottle Index for LDPE — UV-cured Inks



	UV ink	UV ink (no slip)
Blue ink	281	382.5
Green ink	73	47

Figure 4.19 Average Mottle Index for PE/EVA — UV-cured Inks



	UV ink	UV ink (no slip)
Blue ink	491	n/a
Green ink	53.45	n/a

Opacity — UV-cured Inks

The readings averaged around 55% but showed high standard deviation values, which may indicate poor uniformity of substrate coverage. Only LDPE data were collected for this test. The opacity test was not run on PE/EVA because it is a white substrate, and there were no successful runs of UV-cured ink on OPP.

Rub Resistance — UV-cured Inks

Table 4.28 shows the results of wet rub resistance tests. UV on LDPE performed the best, with failure at an average of 5.2 strokes. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no rub resistance data were available for this ink-substrate combination. For dry rub resistance, the ink used on no-slip LDPE (Site 11) received the only score below 90%.

Table 4.28 Wet Rub Resistance Results — UV-cured Inks

Ink	Film	Product Line	Site	Failure at Number of Strokes (average)[a]
UV	LDPE	#U2	6	5.2
	PE/EVA	#U2	6	4.2
		#U3	8	2.3
UV (no slip)	LDPE	#U1	11	2.2

[a] A failure represents ink color transferred from the printed substrate to the unprinted substrate. A maximum of 10 strokes were used for the wet rub resistance test. Measurements were taken at four locations and averaged. See Appendix 4-E for specifics.

Tape Adhesiveness — UV-cured Inks

Table 4.29 shows the results of the test. Results were mixed. UV no slip on LDPE had no failures and 4 passes, whereas UV on PE/EVA had the reverse showing. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no tape adhesiveness data were available for this ink-substrate combination.

Table 4.29 Tape Adhesiveness Results — UV-cured Inks

Ink	Film	Product Line	Site	Number of Passes	Number of Failures	Comments
UV	LDPE	#U2	6	2	2	white and magenta were removed
	PE/EVA	#U2	6	0	4	blue, green, and magenta were removed
		#U3	8	1	2	cyan was slightly removed
UV (no slip)	LDPE	#U1	11	4	0	

Trap — UV-cured Inks

This system averaged approximately 90% for trapping. UV inks on PE/EVA scored an average of 93%, whereas on LDPE the inks scored an average of 87%. Due to the absence of successful runs of UV-cured ink on the OPP substrate, no trap data were available for this ink-substrate combination.

Uncured Residue — UV-cured Inks

The uncured residue test was performed only for UV-cured inks. The uncured residue test was measured in the laboratory with samples collected from Sites 6, 8 and 11. UV ink was not run at any other sites.

Uncured residue was measured only for green, blue, and white ink, since these colors had the largest areas of coverage. Results are presented in Table 4.30 as average percent (by weight) of ink removed. The averages are based on four measurements taken at different locations from each site sample. Uncured residue was found only on the blue ink samples. Due to the absence of successful runs of UV ink on the OPP substrate, no uncured residue data were available for this ink-substrate combination.

Table 4.30 Average Uncured Residue Results — UV-cured Inks

Ink	Film	Product Line	Site	Average Percent of Ink Removed (by weight)[a]
UV	LDPE	#U2	6	0.00
	PE/EVA	#U2	6	0.00
		#U3	8	6.97
UV (no slip)	LDPE	#U1	11	10.42

[a] Uncured residue was found on the blue ink samples only.

Summary of Performance Test Results for UV-Cured Inks

These performance demonstrations were completed in 1997, since which time flexographic printing technology for UV-cured inks has made significant advances. The test results recorded in this CTSA provide a snapshot of UV technology early in its technical development but do not necessarily lead to any conclusions about current or potential abilities of UV inks. In fact, just as for solvent-based and water-based inks, no one test can provide a reliable or accurate indicator of overall quality for any printer. Printers need to consider a variety of different factors in determining acceptable quality. These factors — among them cost, health and environmental risks, energy use, and pollution prevention opportunities — are discussed in other chapters of this CTSA.

UV-cured inks performed well on some tests. The inks displayed good resistance to blocking, particularly on PE/EVA and no-slip LDPE. The inks displayed relatively good trapping. Mottle was better than that of the water-based inks and comparable to that of the solvent-based inks. For the ice water crinkle test, only one UV-cured ink (#U2) displayed evidence of removal. Also, the coating weight was greater than that for solvent- and water-based inks, despite lower ink consumption as measured in Chapter 6.

The test results on these particular UV product lines also showed a need for improvement, particularly some physical adherence tests. The rub resistance and tape adhesiveness results were unimpressive for inks #U1 and #U3; these results may have been caused by the incomplete curing observed with these two product lines. The opacity level (measured for white inks only) showed a high standard deviation, which indicated a lack of uniformity. In addition, gloss was low, despite the fact that high gloss is considered to be a strength of UV finishes.

Technological Development in UV-cured Inks

With any new technology, changes can occur rapidly, and UV-cured inks are no exception. Recent formulation and equipment improvements are addressing some of the limitations for UV-cured inks seen in the performance demonstrations for this CTSA. For example, cationic inks (as opposed to the free-radical UV inks in the CTSA) may have lower shrinkage rates and improved flexibility, which may help with adherence. Other adjustments in chemistry are being made to reduce viscosity and improve the curing rate of UV inks. Furthermore, improvements in equipment may lead to overall better coatings. This section describes significant developments and the improvements they could yield, and discusses aspects of the technology that continue to pose difficulties.

Many advances have been made in the past few years that improve the quality of UV inks for wide-web flexography. New cationic inks might offer an alternative for printers who use porous substrates, need a more thoroughly cured ink, or print items for which odor must be minimized. Improvements have been made with free-radical UV-cured inks; some inks can be used on several substrates, the viscosity has been reduced, and the ink is more durable when applied. Equipment improvements have led to better heat management, which in turn has provided printers with better energy efficiency, improved equipment durability, and high-quality products. Furthermore, technologies such as improved UV bulbs are improving curing rates while at the same time requiring that less photoinitiator be included in the ink.
Although UV wide-web flexography still faces obstacles, technological developments indicate that UV will continue to improve and grow in the future.

Cationic Inks

Currently, most UV-cured ink is based on free radical curing, which involves acrylate monomers that, when exposed to high-energy ultraviolet light, undergo a chain reaction to bind together in a large polymer. (For more information on the free-radical curing process, see Chapter 2.) This free radical reaction is beneficial in several ways, most prominently that the reaction (or “drying”) is almost instantaneous when the polymer is exposed to the UV light. Early concerns with cationic inks included 1) that the reaction process causes the ink to shrink, which can affect the ability of the ink to bind to the substrate, 2) the reaction can be inhibited by the presence of oxygen for some applications, and 3) unreacted epoxide molecules can have an unpleasant odor.[1] These concerns have largely been addressed through formulation and equipment improvements.[2]

The evolution of cationic inks is one of the most significant recent developments in UV-cured ink technology. Cationic inks work in a similar fashion to free-radical inks, in that small monomers react to form a cohesive polymer in the presence of UV rays. This process differs from free radical curing in that the monomer in the ink is usually an epoxide rather than an acrylate, and that the reaction occurs due to the reaction of electron-deficient ions, rather than the binding of electronically-neutral but unstable radicals.

One benefit of the cationic system over the free radical system is that the reaction is not inhibited by oxygen; therefore, the curing is usually more complete. However, the reaction can be limited if bases, such as amines, are present in the ink or substrate.[3]

Cationic inks have several other advantages. The epoxide shrinks less than acrylate when it polymerizes, and therefore adheres to the substrate better. Cationic inks have less odor, because the material dries more thoroughly and because epoxides are inherently less odorous than acrylics. Furthermore, cationic inks are less viscous. As a result, they flow well without heating, they require corona treatment less frequently, and the applied layer is more evenly spread for solid colors. Ink densities are also stronger for cationic inks than they might be for free radical inks.[4] In addition, cationic inks can produce a high gloss and good adhesiveness, and thus can prevent the need for costly lamination on certain products.[5]

Several disadvantages, however, currently make cationic inks a less popular option than the more established free radical system. Even though cationic inks may dry more thoroughly, the drying process takes longer. This has implications for press speed, because additional colors cannot be added until the first color cures.[6] The final product printed with cationic inks does not have as much solvent resistance as free radical inks.[7] The drying of cationic inks are can be affected by moisture and high humidity, so that until the problem is resolved, cationic inks cannot be used universally in all geographic locations.[8] Finally, cationic inks might not cure effectively on high-pH substrates, such as paper.

Other Ink Developments

Significant advances have been made in adjusting the properties of both free radical and cationic inks. One such property is the ability to be printed on more than one substrate. Early UV-cured inks were specially formulated for a given substrate, and several sets of UV ink chemistries had to be stored on-site if a printer worked with multiple substrates. This practice was inconvenient and increased inventory costs. Newer UV-cured inks are more universal and perform consistently on most substrates. However, these inks may damage the photopolymer plates, which then require more frequent changing.[9]

Ink suppliers are now developing UV-cured inks that have less odor, either by reducing the amount of photoinitiator and monomer needed, or modifying the chemical structure of the monomer so that it is less pungent.[10] Skin irritation sometimes caused by UV-cured inks has been mitigated by using water to reduce the viscosity of the inks rather than traditional diluents.[11] Also, the resistance of inks to water damage has been improved by developing additives that make the ink more durable.[12]

Temperature Control

Temperature management with central impression drum presses (which include most wide-web presses) equipped with UV curing equipment has been a challenge. If the conditions are not managed properly by the press manufacturer, some UV rays reflect off of the drum and heat it in the process. When the press temperature is raised above the standard 32°C, the drum is vulnerable to warping. In addition, heat can damage some substrates, including films.

Adjusting the energy input to the curing lamps has been one approach to reducing press temperatures. One study found that with most UV-cured inks, smaller diameter bulbs cured the inks at the same rate but used significantly less energy and thus generated less heat. In addition, specialized bulbs (e.g., D bulbs containing iron for pigmented inks and V bulbs containing gallium for white inks) can reduce the required energy.[13]

Lowering ink viscosity also helps lower temperatures. Viscous inks often require heating in order to make the ink flow well. Cationic inks, which generally are less viscous and do not require heating, are a possible solution for printers faced with difficulties in heat management.

Equipment suppliers are also improving power supply and ventilation systems used in curing UV inks. Devices can be installed that allow for variable power supply; the press operator can adjust the power so that only the minimum amount of energy is used to cure the ink. Heat can be removed more efficiently from the bulb and substrate surface by making improvements in ventilation, such as improved lamp housing aerodynamics and variable-speed blowers.[14] Another recent improvement has been the development of special dichroic reflectors, which absorb infrared energy while directing UV rays to the desired coating.[15]

Ultraviolet/Electron Beam (UV/EB) Hybrid Press

A combination of a UV press with a final electron beam (EB) curing station is still considered experimental, but might improve drying and reduce energy demands. An EB curing station emits a higher energy wave than UV lamps, and therefore penetrates thicker layers better. Because EB lamps cure so much more thoroughly at the end, the intermediate UV lamps do not have to be as powerful, and fewer photoinitiator are needed in the inks.[16] It has been estimated that a UV/EB hybrid press consumes 35 percent less energy and produces less heat.[17] In addition, the UV/EB technology can be used with porous substrates, which standard UV technology cannot since it does not thoroughly cure ink on such substrates. Currently, the major limitation for UV/EB technology is the large capital expenditure required for equipment. In addition, performance properties of the ink might be altered.[18]

Remaining Technical Challenges

Despite the advances made during the past few years, several difficulties still remain with UV technology. One that is particularly evident in film applications is inadequate adhesion. Much of the difficulty stems from the shrinkage that free radical UV-cured inks undergo as they cure. Because shrinkage is less of an issue with cationic inks, further development of cationic inks may help solve this problem. Ink suppliers are also developing free radical UV-cured inks with improved adhesion.

Another issue is the application of even ink layers. Historically, the thick viscosity of UV-cured inks has created discontinuous ink layers and pinholing. The reduced viscosity of current UV inks reduces pinholing but could affect dot gain.[19, 20, 21]

4.4 SITE PROFILES

The site profiles provide background information for each of the volunteer printing facilities that participated in the performance demonstrations. This section provides information about each facility, as well as technical information about each press.

Table 4.31 summarizes the press speed, run time, and run length for each of the performance demonstration sites.

Table 4.31 Summary Information about the Performance Demonstration Sites

Site	Ink	Substrate	Average press speed (ft/min)[b]	Run time (minutes)[a]	Run length (feet)
1	Water-based	OPP	430	129	51,000
2	Water-based	LDPE	403	93	37,053
		PE/EVA	403	102	37,868
3	Water-based	LDPE	218	126	26,927
		PE/EVA	430	131	47,884
4	Water-based	OPP	450	123	13,160
5	Solvent-based	LDPE	400	57	21,924
		PE/EVA	400	56	20,858
6	UV	LDPE	344	92	32,431
		PE/EVA	354	95	27,691
		OPP	344	38	6,853
7	Solvent-based	LDPE	450	148	42,000
		PE/EVA	—	—	8,069
8	UV	LDPE	262	65	2,559
		PE/EVA	262	63	15,912
		OPP	262	15	4,265
9A	Water-based	OPP	425	66	34,434
9B	Solvent-based	OPP	415	80	33,641
10	Solvent-based	OPP	600	90	56,700
11	UV	LDPE	400	153	38,400

[a] Run time included changing of substrate rolls and getting the press back up to speed.
[b] Based on the maximum speed attained during the run.

Site 1: Water-based Ink #W2 on OPP

Table 4.32 Facility Background Information for Site 1

Item	Description
Ink type used	100% water-based
Control equipment	None
Annual production	1.5 million pounds of clear and metallized polypropylene, polyethylene, and polyester; cellophane and paper flexographic-printed products
Operating hours	24 hours per day, 363 days per year
Avg. production run	Four hours

Table 4.33 Press Information for the Performance Demonstration at Site 1

Item	Description
Press	Amber Press, Central Impression
Size of press	55 inches wide, eight-color
Printing type	Reverse
Typical production speed	500 feet/minute
Plates	0.067" Dupont EXL photopolymer: 1) Two process plates (magenta and cyan) mounted using 0.020 hard stick back 2) Three line plates (green, blue, and white) mounted using 0.020 hard stick back
Corona treater (yes / no)	Pillar, Model DB5673-16
Ink metering system	Chambered
Type of doctor blade	Steel
Ink pumping and mixing system	Peristaltic air pump, pumping from semi-covered five-gallon buckets

Table 4.34 Color Sequence and Anilox Configurations for Site 1

Sequence	Color	Anilox lpi[a]	Anilox BCM[b]
Deck 1	Blue	280	7.0
Deck 2 — Not Used	—	—	—
Deck 3	Cyan	800	1.7
Deck 4	Green	280	6.4
Deck 5 — Not Used	—	—	—
Deck 6	Magenta	800	1.7
Deck 7 — Not Used	—	—	—
Deck 8	White	280	7.5

[a] lines per inch
[b] billion cubic microns per square inch

Table 4.35 Summary Information from the Performance Demonstration at Site 1

Substrate	Press speed	Run time	Run length
OPP	430 ft/min	129 minutes	51,000 feet

Observations and Comments

Due to site-specific circumstances, a surface ink was used for the blue in place of a reverse ink at the start of the run. The correct reverse ink was added to the surface ink in the ink pan after approximately 38,000 impressions. While a press speed of 500 ft/min might have been possible with this press and ink, bounce on the white plate limited the maximum obtainable speed to 430 ft/min. The bounce on the white plate occurred due to mounting.

Overall, the makeready and demonstration run were completed with no uncontrollable complications. The printing problems encountered were considered normal and the press operators were easily able to adjust the printing environment to obtain the desired quality result and achieve production printing speeds and conditions.

Site 2: Water-based Ink #W3 on LDPE and PE/EVA

Table 4.36 Facility Background Information for Site 2

Item	Description
Ink type used	100% water-based
Control equipment	None
Annual production	10,465,000 pounds of polyethylene flexographic-printed products
Operating hours	24 hours per day, 363 days per year
Avg. production run	Five hours, including makeready

Table 4.37 Press Information for the Performance Demonstration at Site 2

Item	Description
Press	UTECO, Quarz 140
Size of press	54 inches wide, six-color
Printing type	Surface
Typical production speed	500 feet/minute
Plates	0.107” Dupont EXL photopolymer: 1) Two process plates (magenta and cyan) mounted using Tessa hard stick back 2) Three line plates (green, blue, and white) mounted using Tessa hard stick back
Corona treater	Enercon
Ink metering system	Chamber
Type of doctor blade	Daetwyler 0.006
Ink pumping and mixing system	Peristaltic pump with air monitors in each five-gallon bucket

Table 4.38 Color Sequence and Anilox Configurations for Site 2[a]

Sequence	Color	Anilox lpi[b]	Anilox BCM[c]
Deck 1	White	360	5.05
Deck 2	Green	300	6.90
Deck 3 — Not Used	—	—	—
Deck 4	Magenta	360	5.13
Deck 5	Blue	280	6.00
Deck 6	Cyan	360	4.90

[a] Deck 1 (white ink) not used for the PE/EVA substrate
[b] lines per inch
[c] billion cubic microns per square inch

Table 4.39 Summary Information from the Performance Demonstration at Site 2

Substrate	Press speed	Run time	Run length
LDPE	403 ft/min	93 minutes	37,053 feet
PE/EVA	403 ft/min	102 minutes	37,868 feet

Observations and Comments

LDPE

Pinholing occurred in all colors, and the trap was poor. No blocking or apparent problems with dimensional stability occurred. The pinholing and poor trap were considered acceptable and typical for this site. The press operator made minor impression adjustments in an effort to compensate for the pinholing.

PE/EVA

The green and blue samples taken at the beginning of the run failed the adhesiveness test, while the magenta and cyan passed. The printing quality of all colors was poor, and the printing appeared dirty, but the lay was acceptable with no blocking. The trap was variable depending on position across the web and impression. There appeared to be no dimensional stability concerns.

At the end of the run, the green and blue samples continued to fail the adhesiveness test, but the magenta and cyan samples passed with no failure or ink removed. The printing still appeared to look dirty. Trap was acceptable and lay was improved.

Overall, the makeready and run were completed with no serious complications. The printing problems encountered were considered normal for this site.

Site 3: Water-based Ink #W3 on LDPE and PE/EVA

Table 4.40 Facility Background Information for Site 3

Item	Description
Ink type used	100% water-based
Control equipment	None
Annual production	10 million pounds of flexographic-printed flexible packaging products
Operating hours	24 hours per day, seven days per week
Avg. production run	Eight hours including makeready

Table 4.41 Press Information for the Performance Demonstration at Site 3

Item	Description
Press	Faustel
Size of press	50 inches wide, six-color
Printing type	Surface
Typical production speed	Not given
Plates	0.067” Polyfibron photopolymer plates: 1) Two process plates (magenta and cyan) mounted using compressible stick back 2) Three line plates (green, blue, and white) mounted using hard stick back
Corona treater	Enercon
Ink metering system	Chambered doctor blade, except for white, which is a two-roll without doctor blade
Type of doctor blade	Not given
Ink pumping and mixing system	Peristaltic air pump in five-gallon bucket

Table 4.42 Color Sequence and Anilox Configurations for Site 3[a]

Sequence	Color	Anilox lpi[b]	Anilox BCM[c]
Deck 1	White	300	5.2
Deck 2	Magenta	500	3.2
Deck 3	Cyan	500	3.2
Deck 4	Green	240	7.8
Deck 5	Blue	240	7.8
Deck 6 — Not Used	—	—	—

[a] Deck 1 (white ink) not used for the PE/EVA substrate
[b] lines per inch
[c] billion cubic microns per square inch

Table 4.43 Summary Information from the Performance Demonstration at Site 3

Substrate	Press speed	Run time	Run length
LDPE	218 ft/min	126 minutes	26,927 feet
PE/EVA	430 ft/min	131 minutes	47,884 feet

Observations and Comments

LDPE

Toward the end of the run, pinholing was evident in the blue and the green samples. Also, there was indication of ink drying on the edge of the magenta plate. The pinholing was considered minimal and typical. The press operator made minor impression adjustments to compensate. Trap and dimensional stability were not considered to be a factor in overall quality.

PE/EVA

The samples taken at the beginning of the run passed the adhesiveness test, although some light dusting occurred in the green and blue. No trap or dimensional problems occurred. Poor wetting of the green on white, and pinholing of the blue on white, were evident.

At the end of the run, the cyan and magenta samples passed the adhesiveness test with no ink removed, but the green and blue failed. The demonstration team noted that these two colors should be tested again later after they had more time to dry. When tested again, the blue passed the adhesiveness test, but the green still failed. Increased pinholing was noted for both the green and the blue. Trap and dimensional stability were not considered to be a factor in overall quality.

Overall, the makeready and demonstration run were completed with no uncontrollable complications. The printing problems encountered were considered normal for this site.

Site 4: Water-based Ink #W1 on OPP

Table 4.44 Facility Background Information for Site 4

Item	Description
Ink type	100% water-based
Control equipment	None
Annual production	3 million pounds of polyethylene and polypropylene flexographic-printed products
Operating hours	24 hours per day, five days per week
Avg. production run	One week

Table 4.45 Press Information for the Performance Demonstration at Site 4

Item	Description
Press	Kidder Stacey
Size of press	46 inches wide, six-color
Printing type	Reverse
Typical production speed	400 feet/minute
Plates	0.067” Dupont EXL photopolymer plates: 1) Two process plates (magenta and cyan) mounted using Foam NY20 stick back with foam lining 2) Three line plates (green, blue, and white) mounted using Foam NY20 stick back with foam lining
Corona treater	Enercon
Ink metering system	Chambered
Type of doctor blade	Unknown
Ink pumping and mixing system	Air powered pump from five-gallon buckets covered with cardboard

Table 4.46 Color Sequence and Anilox Configurations for Site 4

Sequence	Color	Anilox lpi[a]	Anilox BCM[b]
Deck 1	Blue	250	6.1
Deck 2	Cyan	800	2.2
Deck 3	Green	250	6.8
Deck 4	Magenta	600	2.7
Deck 5 — Not Used	—	—	—
Deck 6	White	250	6.3

[a] lines per inch

[b] billion cubic microns per square inch

Table 4.47 Summary Information from the Performance Demonstration at Site 4

Substrate	Press speed	Run time	Run length
OPP	450 ft/min[a]	123 minutes	13,160 feet

[a]The press speed varied between 400 ft/min and 450 ft/min.

Observations and Comments

The press was initially ramped to 400 ft/min for the demonstration run. The speed was then increased to 450 ft/min, after 7,500 feet of film had been consumed. Press speed was later slowed to 435 ft/min, and then to 415 ft/min for the last roll of substrate due to drying concerns.

During the run, the pinholing became worse for the green sample, and was also appearing in all the other colors. Both pinholing and plugging occurred in the blue. The pinholing and contamination were considered minimal and typical for this site. The press operator made minor impression adjustments to compensate during the run. Trap and dimensional stability were not considered to be factors in overall quality.

Site 5: Solvent-based Ink #S2 on LDPE and PE/EVA

Table 4.48 Facility Background Information for Site 5

Item	Description
Ink type used	100% solvent-based
Control equipment	Four catalytic oxidizers for nine presses
Annual production	14 million pounds of polyethylene and polypropylene flexographic-printed products
Operating hours	24 hours per day, six days per week
Avg. production run	Two hours

Table 4.49 Press Information for the Performance Demonstration at Site 5

Item	Description
Press	Windmöller & Hölscher, Central Impression
Size of press	24 inches wide, six-color
Printing type	Surface
Typical production speed	400 feet/minute
Plates	0.107” Dupont EXL photopolymer: 1) Two process plates (magenta and cyan) mounted using compressible stick back 2) Three line plates (green, blue, and white) mounted using hard stick back
Corona treater	None
Ink metering system	Enclosed doctor blade
Type of doctor blade	Stainless steel
Ink pumping and mixing system	Closed-loop, air-powered

Table 4.50 Color Sequence and Anilox Configurations for Site 5[a]

Sequence	Color	Anilox lpi[b]	Anilox BCM[c]
Deck 1	White	300	6.2
Deck 2 — Not Used	—	—	—
Deck 3	Green	240	4.2
Deck 4	Blue	240	4.2
Deck 5	Magenta	550	2.0
Deck 6	Cyan	550	2.0

[a] Deck 1 (white ink) was not used for the PE/EVA substrate.
[b] lines per inch
[c] billion cubic microns per square inch

Table 4.51 Summary Information from the Performance Demonstration at Site 5

Substrate	Press speed	Run time	Run length
LDPE	400 ft/min	57 minutes	21,924 feet
PE/EVA	400 ft/min	56 minutes	20,858 feet

Observations and Comments

LDPE

Some slight plate contamination was evident in the blue sample. Minor pinholing was apparent in the green sample. The pinholing and contamination were considered minimal and typical. The press operator made minor impression adjustments to compensate. Trap and dimensional stability were not considered to be a factor in overall quality.

PE/EVA

The samples taken at the beginning of the run passed the adhesiveness test, with no trap or dimensional problems. The lay was acceptable and tones appeared clean and open in the light end highlights. At the end of the run, the samples passed the adhesiveness test with no failure of ink removed. There were, however, some slight problems with solid formation, which may have been related to impression. The tones were beginning to plug in the light end highlights. The press team suggested that the ink drying speed was fast. Trap and dimensional stability were not considered to be a factor in overall quality.

Overall, the makeready and demonstration run were completed with no uncontrollable complications. The printing problems encountered were considered normal and the press operators were easily able to adjust the printing environment to obtain the desired quality result.

Site 6: UV Ink #U2 on LDPE, PE/EVA, and OPP

Table 4.52 Facility Background Information for Site 6

Item	Description
Ink type used	60% solvent-based inks, 35% water-based inks, and 5% UV inks
Control equipment	Charcoal adsorption
Annual production	8 million pounds of polyethylene, polypropylene, and paper flexographic-printed products
Operating hours	24 hours per day, 4.5 days per week
Avg. production run	Six to eight hours

Table 4.53 Press Information for the Performance Demonstration at Site 6

Item	Description
Press	Cobden Chadwick
Size of press	32 inches wide, six-color
Printing type	Surface and reverse
Production speed	250 to 350 feet/minute
Plates	0.107” Dupont EXL photopolymer: 1) Two process plates (magenta and cyan) mounted using 0.020 compressible stick back 2) Three line plates (green, blue, and white) mounted using 0.020 hard stick back
Corona treater	Q.C. Electronics
Ink metering system	Chambered
Type of doctor blade	Unknown
Ink pumping and mixing system	ARO, model 65736-003, air-powered, with diaphragm

Table 4.54 Color Sequence and Anilox Configurations for Site 6[a]

Sequence	Color	Anilox lpi[b]	Anilox BCM[c]
Deck 1	White	250	7.5
Deck 2	Magenta	600	2.8
Deck 3	Cyan	600	2.8
Deck 4	Green	360	4.7
Deck 5	Blue	360	4.7
Deck 6 — Not Used	—	—	—

[a] Deck 1 (white ink) not used for the PE/EVA substrate

[b] lines per inch

[c] billion cubic microns per square inch

Table 4.55 Summary Information from the Performance Demonstration at Site 6

Substrate	Press speed	Run time	Run length
LDPE	344 ft/min[a]	92 minutes	32,431 feet
PE/EVA	354 ft/min	95 minutes	27,691 feet
OPP[b]	344 ft/min	38 minutes	6,853 feet

[a] Press speed was averaged between the two rolls (337 ft/min and 351 ft/min).

[b] The run was aborted due to sample failure of the adhesiveness test and overheating of the chill roller.

Observations and Comments

LDPE

Some slight plate contamination and minor pinholing were evident in the white. The pinholing and contamination were considered minimal and typical. The press operator made minor impression adjustments to compensate. Although there was still some wrinkling of the substrate noted, trap was not considered to be a factor in overall quality.

PE/EVA

The samples taken at the beginning of the run revealed that the ink lay was good, but the print quality appeared dirty. These problems were also noted on the samples taken at the end of the run. It was also noted that the density of the magenta had increased during the run, and the attempts to reduce it were unsuccessful. Trap and dimensional stability were not considered to be a factor in overall quality.

Samples taken at the beginning of the run failed the adhesiveness test in all colors. Adhesiveness tests were performed on samples taken mid-run, at which time the green and blue both passed, but the other colors failed. By the end of the run, all colors again failed the adhesiveness test except cyan.

OPP

The samples taken at the beginning of the run failed the adhesiveness test. The white appeared to have low opacity, evidence of pinholing, and the print quality appeared dirty. The other colors appeared to have good printability with fair trap. No major problems with dimensional stability or blocking were noted; however, heat from the lamps caused wrinkles to form.

The main (final) UV lamp was overheating the chill roller during the run, and the demonstration team decided that the chill roller was not functioning properly. The temperature of the chill roller was 155°F, and the chill roller was smoking. The decision was made to abort the run, and no samples were taken for measurement or analysis.

Site 7: Solvent-based Ink #S2 on LDPE and PE/EVA

Table 4.56 Facility Background Information for Site 7

Item	Description
Ink type used	100% solvent-based
Control equipment	Two-unit catalytic oxidation
Annual production	10 million pounds of oriented polypropylene flexographic-printed products
Operating hours	24 hours per day, five days per week plus every other weekend
Avg. production run	60 to 60,000 pounds

Table 4.57 Press Information for the Performance Demonstration at Site 7

Item	Description
Press	Kidder
Size of press	45.5 inches wide, six-color
Printing type	Surface
Typical production speed	500 feet/minute
Plates	0.067” Dupont FAH photopolymer: 1) Two process plates (magenta and cyan) mounted using 0.20 compressible stick back 2) Three line plates (green, blue, and white) mounted using 0.20 compressible stick back
Corona treater	None
Ink metering system	Chamber
Type of doctor blade	Unknown
Ink pumping and mixing system	Greymill, electric

Table 4.58 Color Sequence and Anilox Configurations for Site 7[a]

Sequence	Color	Anilox lpi[b]	Anilox BCM[c]
Deck 1	White	200	8.5
Deck 2 — Not Used	—	—	—
Deck 3	Cyan	700	2.0
Deck 4	Magenta	700	2.0
Deck 5	Green	500	4.0
Deck 6	Blue	500	4.0

[a] Deck 1 (white ink) was not used for the PE/EVA substrate
[b] lines per inch
[c] billion cubic microns per square inch

Table 4.59 Summary Information from the Performance Demonstration at Site 7

Substrate	Press speed	Run time	Run length
LDPE	450 ft/min	148 minutes	42,000 feet
PE/EVA[a]	—	—	8,069 feet

[a] The run was aborted due to problems with the substrate.

Observations and Comments

LDPE

The printing quality of the tones and the lay of the inks were acceptable. The trap was very good, and no blocking occurred. No problems with dimensional stability were noted.

PE/EVA

It was intended that the PE/EVA substrate also be run at this location. The substrate was mounted on the press, and the "makeready check" was begun. After only 8,069 feet of film were consumed, the run was aborted. The demonstration team decided that the roll of substrate they were running was not the correct project control film, due to a supplier mix-up. In addition, the substrate had wrinkles from poor extrusion, the cores were not the correct size, and the cores were crushed.

No samples were taken from the PE/EVA run, and no measurements were made.

Site 8: UV Ink #U3 on LDPE, PE/EVA, and OPP

Table 4.60 Facility Background Information for Site 8

Item	Description
Ink type used	This facility is a press manufacturing facility in Germany; it is not a commercial printing facility. Therefore, no production data are available.
Control equipment	
Annual production	
Operating hours	
Avg. production run	

Table 4.61 Press Information for the Performance Demonstration at Site 8

Item	Description
Press	Windmöller & Hölscher, Soloflex 2
Size of press	25 inches wide, four-color
Printing type	Surface and reverse
Production speed	450 feet/minute
Plates	0.067" Dupont photopolymer: 1) Two process plates (magenta and cyan), mounting unknown 2) Three line plates (green, blue, and white), mounting unknown
Corona treater	Kalwar
Ink metering system	Chambered
Type of doctor blade	Steel
Ink pumping and mixing system	Air-powered

Table 4.62 Color Sequence and Anilox Configurations for Site 8[a]

Sequence	Color	Anilox lpi[b]	Anilox BCM[c]
Deck 1 — PE/EVA	Magenta	724	4.5
Deck 1 — LDPE, OPP	White	200	8.4
Deck 2	Green	724	4.5
Deck 3	Blue	724	4.5
Deck 4	Cyan	724	4.5

[a] Deck 1 changed between PE/EVA and LDPE because this site used only a four-color press.

[b] lines per inch

[c] billion cubic microns per square inch

Table 4.63 Summary Information from the Performance Demonstration at Site 8

Substrate	Press speed	Run time	Run length
LDPE	262 ft/min	65 minutes	16,643 feet
PE/EVA	262 ft/min	63 minutes	15,908 feet
OPP[a]	262 ft/min	15 minutes	4,264 feet

[a] The run was aborted due to sample failure of the adhesiveness test and the discoloration of the OPP to a greenish tint.

Observations and Comments

The performance demonstration at Site 8 was conducted on a press manufacturer's pilot line, which was not a commercial printing press.

LDPE

The samples taken at the end of the run failed the adhesiveness test. The printing appeared dirty in the solid areas of the blue ink, but the other colors had good printability. The trap was good. No problems with dimensional stability were noted, and there was no evidence of blocking.

PE/EVA

Dirty printing was more evident in the blue solid area on the end of run samples, and the green was also starting to appear dirty. The tones were inspected for cleanliness and transfer. Trap and dimensional stability were not considered to be a factor in overall quality.

OPP

At the end of the run, the samples failed the adhesiveness test. The printing appeared dirty in the blue solid area, and was beginning to appear dirty in the green as well. The visual quality of the other colors was good. Trap was acceptable, there was no blocking, and there were no problems with dimensional stability. During this run, the OPP substrate turned a greenish tint. It is believed that the UV lamps caused a photo-reaction in the substrate.

Site 9A: Water-based Ink #W4 on OPP

Table 4.64 Facility Background Information for Site 9A

Item	Description
Ink type used	100% water-based
Control equipment	None
Annual production	300 million linear feet
Operating hours	Two 12-hour shifts per day
Avg. production run	8 to 12 hours

Table 4.65 Press Information for the Performance Demonstration at Site 9A

Item	Description
Press	Kidder Stacey
Size of press	45.5 inches wide, eight-color
Printing type	Reverse
Typical production speed	500 feet/min
Plates	0.067” Dupont PQS photopolymer: 1) Two process plates (magenta and cyan) mounted using 3M 1020, 0.020 compressible stick back 2) Three line plates (green, blue, and white) mounted using 3M 1020, 0.020 compressible stick back
Corona treater	Enercon
Ink metering system	Chamber
Type of doctor blade	White steel
Ink pumping and mixing system	Powerwise, air-powered

Table 4.66 Color Sequence and Anilox Configurations for Site 9A

Sequence	Color	Anilox lpi[a]	Anilox BCM[b]
Deck 1 — Not Used	—	—	—
Deck 2	Blue	400	4.0
Deck 3	Cyan	550	2.7
Deck 4 — Not Used	—	—	—
Deck 5	Magenta	550	2.7
Deck 6	Green	400	4.0
Deck 7 — Not Used	—	—	—
Deck 8	White	300	5.5

[a] lines per inch

Table 4.67 Summary Information from the Performance Demonstration at Site 9A

Substrate	Press speed	Run time	Run length
OPP	425 ft/min	66 minutes	34,434 feet

Observations and Comments

The samples taken at the end of the run revealed good printability, good trap, no problems with dimensional stability, and no blocking. Overall, the makeready and demonstration run were completed with no uncontrollable complications.

Site 9B: Solvent-based Ink #S1 on OPP

Table 4.68 Facility Background Information for Site 9B

Item	Description
Ink type used	100% water-based
Control equipment	None
Annual production	300 million linear feet
Operating hours	Two 12-hour shifts per day
Avg. production run	8 to 12 hours

Table 4.69 Press Information for the Performance Demonstration at Site 9B

Item	Description
Press	Kidder Stacey
Size of press	45.5 inches wide, eight-color
Printing type	Reverse
Typical production speed	500 feet/min
Plates	0.067” Dupont PQS photopolymer: 1) Two process plates (magenta and cyan) mounted using 3M 1020, 0.020 compressible stick back 2) Three line plates (green, blue, and white) mounted using 3M 1020, 0.020 compressible stick back
Corona treater	None
Ink metering system	Chamber
Type of doctor blade	White steel
Ink pumping and mixing system	Powerwise, air-powered

Table 4.70 Color Sequence and Anilox Configurations for Site 9B

Sequence	Color	Anilox lpi[a]	Anilox BCM[b]
Deck 1 — Not Used	—	—	—
Deck 2	Blue	400	4.0
Deck 3	Cyan	550	2.7
Deck 4 — Not Used	—	—	—
Deck 5	Magenta	550	2.7
Deck 6	Green	400	4.0
Deck 7 — Not Used	—	—	
Deck 8	White	300	5.5

[a] lines per inch
[b] billion cubic microns per square inch

Table 4.71 Summary Information from the Performance Demonstration at Site 9B

Substrate	Press speed	Run time	Run length
OPP	415 ft/min	80 minutes	33,641 feet

Observations and Comments

Site 9B is normally a 100% water-based ink facility. Facility staff agreed to do a demonstration run with solvent-based inks on OPP for this project. Overall, the makeready and demonstration run were completed with no uncontrollable complications. The samples taken at the end of the run revealed good printability, good trap, no problems with dimensional stability, and no blocking.

Site 10: Solvent-based Ink #S2 on OPP

Table 4.72 Facility Background Information for Site 10

Item	Description
Ink type used	100% solvent-based
Control equipment	One thermal oxidizer for three presses
Annual production	10.5 million pounds — 95% medium-density polyethylene (MDPE), 5% low-density polyethylene (LDPE)
Operating hours	24 hours per day, 5 days per week, plus 25 Saturdays
Avg. production run	24 hours

Table 4.73 Press Information for the Performance Demonstration at Site 10

Item	Description
Press	Paper Converting Machine Company, model 7067
Size of press	61 inches wide, eight-color
Printing type	Reverse
Typical production speed	750 to 850 feet/minute
Plates	0.107" BASF photopolymer: 1) Two process plates (magenta and cyan) mounted using 3M 1120 compressible stick back 2) Three line plates (green, blue, and white) mounted using 3M 939 hard stick back
Corona treater	None
Ink metering system	Chambered — two-blade
Type of doctor blade	Unknown
Ink pumping and mixing system	Powerwise, Underwriters Laboratory, electric, 5 hp, 3450 rpm, 115 to 230 volts

Table 4.74 Color Sequence and Anilox Configurations for Site 10

Sequence	Color	Anilox lpi[a]	Anilox BCM[b]
Deck 1 — Not Used	—	—	—
Deck 2	Green	250	9.8
Deck 3	Blue	250	10.1
Deck 4	Cyan	800	1.75
Deck 5 — Not Used	—	—	—
Deck 6	Magenta	800	1.6
Deck 7 — Not Used	—	—	—
Deck 8	White	250	9.0

[a] lines per inch

[b] billion cubic microns per square inch

Table 4.75 Summary Information from the Performance Demonstration at Site 10

Substrate	Press speed	Run time	Run length
OPP	600 ft/min	90 minutes	56,700 feet

Observations and Comments

This site normally prints LDPE, but agreed to print the OPP with a reverse ink system. The samples taken at the end of the run showed poor solid formation in the magenta, with all other colors having good printability. The magenta also appeared weak, attributed to high anilox line count and low volume. Trap and dimensional stability were not considered to be factors in overall quality.

Overall, the makeready and demonstration run were completed with no uncontrollable complications. The printing problems encountered were considered normal and the press operators were easily able to adjust the printing environment to obtain the desired quality result.

Site 11: UV Ink #U1 on LDPE (no slip)

Table 4.76 Facility Background Information for Site 11

Item	Description
Ink type used	80 to 85% water-based, 15 to 20% UV
Control equipment	None
Annual production	50 million pounds of polyethylene flexographic-printed products
Operating hours	24 hours per day, five days per week
Avg. production run	Three hours to two weeks

Table 4.77 Press Information for the Performance Demonstration at Site 11

Item	Description
Press	UTECO, Amber 808
Size of press	61 inches wide, ten-color
Printing type	Surface
Production speed	820 feet/minute
Plates	0.107” Dupont EXL photopolymer: 1) Two process plates (magenta and cyan) mounted using compressible stick back 2) Three line plates (green, blue, and white) mounted using hard stick back
Corona treater	None
Ink metering system	Chambered
Type of doctor blade	Unknown
Ink pumping and mixing system	Arrow, air-powered, diaphragm

Table 4.78 Color Sequence and Anilox Configurations for Site 11

Sequence	Color	Anilox lpi[a]	Anilox BCM[b]
Deck 1	White	300	6.0
Deck 2	Magenta	500	2.7
Deck 3 — Not Used	—	—	—
Deck 4 — Not Used	—	—	—
Deck 5	Cyan	500	2.7
Deck 6	Green	360	5.6
Deck 7 — Not Used	—	—	—
Deck 8	Blue	360	5.6
Deck 9 — Not Used	—	—	—
Deck 10 — Not Used	—	—	—

[a] lines per inch
[b] billion cubic microns per square inch

Table 4.79 Summary Information from the Performance Demonstration at Site 11

Substrate	Press speed	Run time	Run length
LDPE[a]	400 ft/min	153 minutes	38,400 feet

[a] The LDPE was extruded with no-slip additives.

Observations and Comments

This site chose to print its normal production LDPE substrate instead of the DfE-control LDPE. This site-standard LDPE substrate was extruded with no slip additives. Overall, the makeready and demonstration run were completed with no uncontrollable complications. The printing problems encountered were considered normal and the press operators were easily able to adjust the printing environment to obtain the desired quality result.

The samples taken at the end of the run continued to show good printability in all colors, with continued blade streaking in the cyan. Dry ink was continually evident on the blue anilox roll. Trap and dimensional stability were not considered to be factors in overall quality.

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