FTROP
Flexographic Tone Reproduction Optimization Program

REPORT

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Electronically Printed By The Banta Prepress Group

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THE MOTHER OF ALL EXPERIMENTS
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Flexographic Tone Reproduction
Optimization Program
Graduated Scales

**TEST IMAGE**

This image was used in the first subexperiment, printed with magenta ink on white polyethylene film. It was repeated 16 times across the web in each of 16 bands of anilox roll screens ranging from 360 to 800 lines per inch.

Three graduated scales are included for measuring percent dots at halftone line screens of 120, 150, and 175 LPI.

The boxes at the top were used for measuring slur.

The square at the bottom was used for visual evaluation of ghosting and to measure density of a solid.

Regular and reverse type samples from 4 to 12 points were printed in each band.
EXECUTIVE SUMMARY

THE MISSION
Help film printers have a process that’s repeatable and of improved quality by identifying variables within the system and understanding their interactions in printing.

Improving control of process color is the goal of the Flexographic Tone Reproduction Optimization Program (F-TROP). F-TROP was initiated by W.R. Grace & Company and Eastman Kodak Company in 1992 and has expanded to include a volunteer research team of industry leaders (listed below), with Clemson University’s Printing/Converting Research Center playing a major role.

The goal is to establish a systematic method for optimizing print quality, which can be applied by flexo printers. A four-step approach is being pursued.

1) OPTIMIZE PRINTING CONDITIONS
2) FINGERPRINT THE PRESS
3) OPTIMIZE COLOR SEPARATIONS FOR THE PRESS
4) VERIFY REPEatability ON THE PRESS

**Step 1:**
(Described in the first two sections of this report.)

By consensus, the F-TROP team agreed that all test runs would be printed on the same press, a wide web Carint press at Clemson, and all runs would be printed on white opaque polyethyline film. Only one ink color was considered necessary to optimize printing conditions (Step1), and magenta was selected as the color most prone to show effects of variability in density and dot gain. A solvent-based ink was used with a one-sheet capped photopolymer plate.

The following factors and their inter-relationships have been tested and analyzed in a FIRST SUBEXPERIMENT.

<table>
<thead>
<tr>
<th>FLEXO PROCESS FACTOR</th>
<th>NO. TESTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stickybacks</td>
<td>5</td>
</tr>
<tr>
<td>Anilox Roll Screens</td>
<td>3</td>
</tr>
<tr>
<td>Anilox Depth-to-Opening Ratios</td>
<td>5</td>
</tr>
<tr>
<td>Ink Viscosities</td>
<td>5</td>
</tr>
<tr>
<td>Halftone Screen Rulings</td>
<td>120/150/175 LPI</td>
</tr>
<tr>
<td>Dot Shapes</td>
<td>Round/Square/Elliptical</td>
</tr>
</tbody>
</table>

Changes in these factors were related to measurements from test samples using computer-aided statistical analysis. For key attributes of print quality were measured and analyzed statistically.

- Solid Ink Density (SID)
- Highlight Dot Gain @ 3%
- Midtone Dot Gain @ 50%
- Slur

Data was also gathered for “delta dot gain” (the difference between gain in 25% and 75% dots) and “print contrast” (the difference between the density of a solid and 70% tints divided by density of the solid), which are described in Appendix 2.2A.
The purpose of the first subexperiment was to define the optimum anilox cell configuration, stickyback and ink viscosity which would yield the best possible print quality. Conclusions include the following:

- **Selected stickybacks** were a significant factor, yielding different average values for SID, dot gain, delta dot gain, and slur.

- **As anilox lines per inch** goes up, SID, dot gain, delta dot gain and slur go down.

- **As depth to opening ratio** goes up, SID, dot gain, delta dot gain, and slur go up.

- **Ink viscosity** appeared to have little or no effect on delta dot gain, midtone dot gain, print contrast, and slur. SID was not affected by viscosity, except when the stickyback varied, implying an interaction between ink viscosity and stickyback type.

Data for halftone screen ruling and dot shape were collected but were not analyzed. They offer opportunities for future study.

After analyzing and discussing results of the first test run, **quality aim points** were selected by consensus for a subsequent VERIFICATION TEST RUN.

<table>
<thead>
<tr>
<th>QUALITY ATTRIBUTE</th>
<th>AIM</th>
<th>TOLERANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Ink Density</td>
<td>1.40</td>
<td>± 0.05</td>
</tr>
<tr>
<td>Highlight Dot Gain @ 3%</td>
<td>9%</td>
<td>15% Max.</td>
</tr>
<tr>
<td>Midtone Dot Gain @ 50%</td>
<td>40%</td>
<td>Minimize</td>
</tr>
<tr>
<td>Slur</td>
<td>5%</td>
<td>+ 5%</td>
</tr>
</tbody>
</table>

Results of the first run were also used to establish “operating windows” (acceptable ranges of values) for ink viscosity, for anilox roll screens and depth to opening ratios, and for stickybacks which would produce the best results **under the test conditions**. In evaluating results, experienced printers served as consultants to help define “acceptable” print quality.

The verification run was successful, confirming findings from the first run. At this point, printing conditions had been optimized to produce acceptable results (within quality aim point tolerances) repeatably when running within the “operating windows.”

**Step 2:**

FINGERPRINTING THE PRESS, was begun with a process color test run at Clemson on June 28, 1993 using optimum conditions identified in Step 1. Analysis is under way and findings will be reported when available. Step 2 will characterize press performance, relating input (dot values in color separation films) to output (dot values printed with ink on film). Theoretically, aim points can then be derived for color separations (Step 3) which will produce acceptable process color printing repeatably (Step 4).

**IMPORTANT NOTE:** The goal of F-TROP is to identify a method by which printers can optimize process quality. It is not our intent nor is it possible to specify products or universal values, because **results will vary based on test conditions**.
1.1 - The Initiative

It all started for me with a phone call from Bruce Capriotti of W.R. Grace. He inquired of Clemson’s interest in working together on a research project to gain an understanding of selected variables in the flexographic printing process. He and Dick Bucknam from Eastman Kodak were moving forward with the concept of carrying out a study, the parameters of which were undefined. I was enthusiastic and hoped that a project would evolve.

Several weeks later, representatives from Clemson, Eastman Kodak and W.R. Grace met during the FTA Forum in Chicago at the Kodak facilities. It was a meeting to get acquainted and brainstorm, while gaining a feel for the questions that might be addressed. It was agreed that a need existed for a serious investigation of color reproduction by the flexographic process.

At this initial meeting, a list was developed of other potential participants who might have all of the needed expertise to delve into such a study. Criteria for partners included genuine expertise in color reproduction, the flexographic process, and each of the specific elements or ingredients involved in flexographic color reproduction. In addition were considerations for potential commitment both in time and expense. It was also considered imperative that parties be identified who would assure the “external validity” of such a project. Simply said “printers” had to be involved as well as separators if the project would hold up to the test of practical application upon its completion. The intent was to carry out a sophisticated and well-designed experiment but with conditions in tune with daily manufacturing factors.

A list of excellent printers experienced with top quality process printing on film was considered for this part of the undertaking. As the effort developed, it was further strengthened by the involvement of individuals and organizations outside the confines of flexography. They brought other perspectives and the constant reminder that flexo must compete and compare favorably with all printing methods.

1.2 - Participants

Within a few short weeks of the initial meeting in Chicago, the partners were identified. They were: W.R. Grace and Co., representing the plate system and expertise; Eastman Kodak, with a long history of color science and imaging, as well as expertise in statistical design; Sun Chemical with all its expertise in ink; Clemson University with a good broad understanding of all elements of the process, formulation and control; Harper Corporation of America for its expertise in anilox roll technology; Graphics Microsystems, Inc. for its expertise in print quality evaluation cutting across process lines; Color Response for its expertise in customizing prepress for specific press conditions in all printing methods; and printers selected from “the best” included Paramount Packaging, Printpack, Inc., and Princeton Packaging. Assistance with the supply of white opaque polyethylene, the substrate, came from C.T. Film, and bases for anilox rolls were provided by Atlanta Grinding. It was felt that true expertise was on board in all elements of the process and that it was time to put the thoughts and experiences together in the design of an experiment which would be appreciated, both as a demonstration of the value of this experimental process, and in the advancement of knowledge regarding the flexographic printing method.

1.3 - Mission

On May 21, 1992, just a month after the first meeting, the entire group of partners came together for a meeting at Clemson University. While there was certainly strength in numbers and expertise on hand, the process of making decisions, identifying variables and delimiting the experiment was, needless to say,
both interesting and challenging. It was successful, as the project was launched and plans drawn for its execution.

At the first meeting, the mission was defined. It reads as follows:

*Help film printers have a process that is repeatable and of improved quality by identifying variables within the system and understanding their interactions in printing.*

It is important to note that in the statement the substrate was limited to film and the benefits targeted to printers themselves. Repeatability was a mandate, and quality, of course, a must. Interactions among variables were of keen interest and at the very heart of the entire program.

The goals of the effort were:
1) to achieve the highest quality printing possible on film, as determined by density, dot gain, print contrast and clean printing;
2) to achieve repeatability.

### 1.4 - Variables Tested

The variables to be tested were **stickyback, ink, anilox rolls** and **images**. The only type of stickyback to be evaluated was cushion stickyback and a .020" thickness was chosen. This decision was made because it represented the most widely accepted practice in current high quality film printing applications. The object was to evaluate five commercially available products and select one for continuance in the study. It is important to note that the purpose was not to identify a single “best,” but one type which accommodated the quality requirements for tone reproduction.

Solvent-based ink was the type of ink chosen because it has continued to be preferred system for top quality film printers. Initially, two types of solvent based inks were tested and each at five viscosities, with the objective to identify a window of optimum viscosity for one of the two inks. In making decisions on anilox rolls, it was determined that only laser engraved ceramic rolls would be tested since the use of reverse angle doctor blades was considered essential. There were 15 bands of different cell configuration defined by the project team, the purpose being to ultimately select one specification for the final demonstration of the process color printed image. The bands varied widely in screen count and depth to opening ratio to assure that the optimum window would be clearly defined by the statistical evaluation process. Depth to opening ratio is that relationship between the depth of the cell and its diameter or measurement across the opening. A ten percent depth to opening ratio would mean that cell with an opening of ten units would have a depth of one unit.

The entire effort was to be executed in a series of experiments with early experiments intended to reduce the number of variables to be included in subsequent experiments. It is important to note that there are many ways that a team could go about executing a study of this type and that the one reported in this article, and the articles to follow, is simply that process determined best by this specific project team.

Other variables were defined and fixed. They included the selection of a “capped” plate .067“ thick with .028” relief depth.

**Press speeds** were initially to be 500, 750 and 1000 ft. per minute. It was also felt to be Important that the press be allowed to run and stabilize for at least five minutes before taking samples. Early in the first experimental run, it became quite evident that the volume of material and the burden of expense would necessitate selecting one press speed, which was done. That was 500 feet per minute.

The choice of **white opaque polyethylene** was based upon previous work done by the FTA Color
Committee, where it was found that this particular substrate was remarkably stable in its specifications for whiteness, brightness and opacity.

1.5 - First Subexperiment: Variables

The objectives of the first experiment were to define the optimum anilox cell configuration, stickyback and ink viscosity for best possible tone reproduction. Two types of solvent based inks were tested with viscosities run in three-second increments from 27 to 41 seconds on a No. 2 Zahn cup. The ink color chosen was magenta, since it was agreed by the printers and other partners that it was generally the most difficult ink to run. The decision was made to confirm the correlation of yellow, cyan and black in a later run, after magenta had been analyzed.

Three impressions were used during the first subexperiment. The optimum was set by the press operator, Marc Edlein, and agreed to by two or more printers for each setting. Two over-impressions were evaluated: +.001” and +.008”. (Later tests used a single impression setting made by the press operator and confirmed by on-site printer / advisors.)

The anilox roll contained 16 bands including a duplicate control band to assure that impression could be checked from the same anilox roll configuration on both sides of the press. All bands were engraved at a 60-degree angle. This decision was made after convincing evidence was shared by the anilox roll manufacturer and several printers. Three anilox line counts were specified. The low count was 360 lines per inch, chosen because of its common use in tone reproduction on film. The highest cell count was 800 lines per inch, considered a relatively fine cell count at the time the study was undertaken. The middle count was 565, selected as a mathematical midpoint for statistical purposes.

Five depth to opening ratios were evaluated at each line count. They were 10 percent, 15.5, 25, 32.5 and 40 percent. The images defined for the first set of experiments were three lines screens: 120, 150 and 175; three dot shapes: round, elliptical and square; and all screens were run at 52.5 degree angles, conforming to the industry practice of running 7 _ degrees off of the standard 45 degree halftone angle considered least visible to the naked eye.

Evaluation of impression included the testing of five commercially available stickybacks. No bearers were run on the plates since they were determined to be impractical for the market to which this study would be generalized. To minimize bounce, the test images were staggered, a technique accepted as standard by quality flexographers. Dial indicators were used to assure accuracy and repeatability on the over-impression settings.

1.6 - First Subexperiment: Measurements

From the first experimental press run, 170 samples were taken. Each contained 54 tone scales plus a solid. This resulted in 9,000 measurements. Al measurements were taken independently by a standard procedure at Graphics Microsystems. A scanning densitometer was programmed to the test form and used to obtain all of the densitometer readings. The Murray Davies equation using standard measurement procedures was employed to calculate dot percentages. No evaluations or adjustments were made in the measurement process. It might be described as a “blind procedure” to assure objectivity. Results of the measurements, the data, were forwarded to Peter Bartell, the statistician at Eastman Kodak who carried out the statistical analyses. (NOTE: A thorough explanation of the statistical design and analysis follows in 2.0).

One of the recommendations resulting from this research came from the measurement procedures which have been established primarily for commercial and publication offset and substrates used in those applications. The translucent qualities of white opaque polyethylene and other nonporous substrates used in packaging suggest that different measurement procedures might be necessary. This topic will be
discussed in follow-up reports.

The measurements taken on the 16 band test form were: solid ink density, slur, midtone dot gain, three percent dot gain, delta dot gain the calculated difference between the dot gain at the 25 percent and 75 percent level, print contrast the difference between the density of a solid and a 70 percent tint divided by the density of the solid. The observations of delta dot gain, sometimes used in other printing analyses, were deleted from further study.

Following the first subexperiment since analysis confirmed the nature of the flexographic print curve which is characterized by more dot gain in the highlight tones, including the 2.5 percent area, than in the shadows.

1.7 - First Subexperiment: Conclusions

Observations of the data on the first experiment were very positive. However, unless the second phase “the verification process” was successful, the project team could not be satisfied. These early data revealed a very clear picture of the interrelationships of the variables being studied. To those project team members not previously exposed to statistical analysis, the pictures drawn by the numbers were most impressive and gave a great deal of confidence to things which otherwise have been felt to be “truths” but not documentable. A great deal of comfort also came the printers themselves.

The first examination of data was reported by Peter Bartell at a meeting in Rochester, NY. He assured the F-Troop project team that the results observed, if verified, would be expected to repeat themselves in manufacturing production which, of course, is the entire net value of this work.

Conclusions from the first subexperiment include the following:

- Selected stickybacks were a significant factor, yielding different average values for solid ink density, dot gain, delta dot gain and slur.
- As anilox lines per goes up, solid ink density, dot gain, delta dot gain and slur go down.
- As depth to opening ratio goes up, solid ink density, dot gain, delta dot gain and slur go up.
- There is an interaction between lines per inch and depth to opening ratio.

1.8 - The Verification Test: Variables

The second press run was carried out for the purpose of verifying the findings of the first experiment. Remember, “repeatability” was one of the key objectives at the outset of the F-TROP endeavor. Analysis and discussion of the first trial run led to the definition of narrower “operating windows” within which good print quality could be achieved repeatably.

The second trial involved the production of a new anilox roll. This time, there were seven experimental bands with an eighth control band to provide visual assistance in setting impressions on press. Simply put, the bands on each end of the roll were the same. One of the questions was whether or not anilox roll specifications could be repeated, and then, of course, will the repeated results also appear in print. In the verification run, all anilox roll specifications from the original roll which fell outside of the quality criteria were eliminated. If the second trial was to be successful, it would produce eight bands that all basically looked the same to the naked eye, but the eight bands would differ in cell count and depth to opening ratio. This process should theoretically find even a smaller window within which top quality process printing would be achieved.

Other changes made in the second run were that only 120, 150 and 175 line per inch round dots were used in the test image. It was agreed by consensus that different dot shapes did not produce significantly results in the first experiment.
In addition to stepped dot percent scales, continuous graduated scales were added to the *test image* for the verification test. This was done to identify any possible bridging phenomena which might take place in dot percentages falling between those on the step scales. The choice of *stickyback* was narrowed to compare only two, and the anilox roll specifications were as follows: 550, 600, 700, 800, 900 and 1000 *line cell counts* with *depth to opening ratios* of 20, 22, 25 and 30 percent. Higher screen counts were added to be sure to identify the limits of the window of anilox specifications. The first subexperiment did not show the “end” of the high screen counts that might achieve the quality criteria specified in the study. All volumes fell between 1.5 and 2.0 BCMs (Billion Cubic Microns per square inch). Only optimum *impression* was evaluated during the verification run.

The *quality aim points* selected after the first trial and used for the verification run were solid ink densities between 1.35 and 1.45. Maximum acceptable dot gain in the 3 percent dot was 15 percent, with the least possible as the ideal. Maximum gain in the 50 percent dot was 40 percent, with the least possible gain as the ideal. The aim point for slur was 5% allowing plus or minus 5%. Obviously, zero slur would be the goal. Slur was significantly affected by stickyback selection, and had positive effects on the appearance of shadows and solids, while having negative effects on the dot percentages in the highlights.

### 1.9 - The Verification Test: Conclusions

The results of the verification run were exciting and rewarding. They did indeed result in the same findings as the first experiment. A window was defined from which anilox rolls could be selected for process printing. This window contained a range of screens and depth to opening ratios, all of which delivered nearly the same amount of ink, as determined by solid ink density. The data on selected stickybacks were repeated leaving the team with a choice of two or three possible stickybacks to pursue the final color press test and production run. An operating window for ink viscosity was verified.

In summary, sufficient information was now available to pursue a process color press trial. The verification process was successful. Rolls were engraved again, to demonstrate the repeatability of the laser engraving method. Plates, inks and impression all combined to achieve print quality measurements depicting a controlled process and a set of specifications which repeatably resulted in the quality targets established by the F-TROP team.

### 1.10 Process Color Trial Run

A preliminary four-color test image was assembled with a variety of test targets for a color press trial. A run was made. However, it was considered a first look, with considerable evaluation of the images on the target needed before the actual fingerprint trial would be run for analytical purposes.

The first test target will include both continuous gradations and stepped scales in all four colors and combinations, gray balance charts, a Kodak Q-60 color test target, selected pictorials and other images to provide a complete “picture” of the four color process capability of the total system.

### 1.11 Observations

While the interest from the industry in this study and others of its type is in understanding the technology, it is almost of equal importance for the reader to appreciate the many other benefits to be realized by partnering with others having common mutual interest to execute efforts of this type. It is also of major importance to understand that commitment to participation in work of this sort is a major commitment of time and expense. The Appendix (1.11A) includes a list of meetings attended by nearly all parties throughout the course of this effort.

Of course, there were individuals who had to be absent from time to time but, for the most part, all partners were represented. The investment was clearly a significant one.
Some special benefits came from the unique selection of partners in this particular effort. While many examples could be noted, the involvement of Kodak and Graphics Microsystems, Inc. brought many experiences from outside the flexographic industry. This was also true in the participation by Color Response, a supplier to all major printing processes. When outsiders are involved, they always come without the paradigms which exist within a specific technology. Interesting questions were raised, and interesting approaches were suggested and sometimes taken in the observations and evaluation of print quality. Furthermore, the active participation of top quality printers dealing in varieties of substrates and market areas brought the various perspectives and experiences that they have had in their own efforts to optimize quality by the flexographic method. It was clear at press side that there were multiple approaches to be aken and sometimes several options in terms of decisions that might have been made. While this certainly didn’t simplify the process of running experiments, it did tremendously strengthen the validity and consequently the value which is anticipated to be realized by the partners, and the industry at large, as these findings are shared in their entirety.

As is always the case when a detailed and controlled study is undertaken, numbers of limitations or new questions are identified. At this point, it would be fair to say that while there are excellent stickyback products, none was found to be "ideal" when evaluated throughout the range of graphic effects from fine highlights to solids. Also the measurements systems which have been developed around the offset lithographic process and primarily for commercial and publication applications seem to lack somewhat in their utility when employed on polyethylene and other translucent substrates. This is an experience of the F-TROP as well as that of numerous advanced students working in the Clemson program conducting experiments on their own on a wide variety of materials. The selection of the spot to be read for solid ink density is another open question. Of course, the natural thing to do would be to read a "true solid". However, it has been observed and it is repeatable that high dot percentages after gain on press will generally produce a higher solid ink density than an actual solid due to the "gravure effect" of the 90 or 95 percent dot which carries ink in the "nonprinting" area as a gravure cell carries ink. This "negative dot" transfers more than the amount of ink which can be carried on a flat plate, a solid. Close examination of many high quality flexographic print jobs, including numerous FTA award winners, will reveal that indeed the solids are reproduced with a dot, and many creative techniques have been applied to try to maximize the benefits of this technique.

There is also need to examine the output of various imagers, since a great deal of technological change and development is taking place at a rapid pace in that area. One might even consider the possibility of the change of dot shapes as one moves from highlight to shadow dot percentages to further optimize the printing process. Data exist in the F-TROP findings to enable further study. However, this was not one of the areas chosen to pursue beyond the selection of one dot shape, as commonly found available today.

In summary, the procedures employed in this effort are procedures that can be followed in any printing application, regardless of whether the substrate is corrugated board, flexible packaging material or folding carton stock. The printer and the substrate and various suppliers will bring different specifics in their ingredients and the numbers resulting from study will be different. However, the process will be the same, and there is no reason why any converter, large or small, can not undertake an effort of this type. It certainly does not have to involve as many partners as this did. Of course, it would be done for internal purposes in most cases and not for the "good of the industry." It is a logical, sound and very workable process with major benefits for all who participate.

Follow-up articles will detail the findings with the actual data so that others might put their thoughts to its evaluation. The partners of the F-TROP will continue this effort through the final color press trial and may undertake other efforts as they have become quite a cohesive group having raised numbers of new questions that have inspired debate and curiosity.
There were seven steps involved in the execution of a statistically designed experiment for optimizing print quality. In order, they were brainstorming, rationalization, design selection, experimental execution, statistical analysis of experimental results, optimization and finally, verification. Each step has inputs necessary for the execution of the step, activities that are undertaken to complete the step, and results from the step. Often time’s execution of these steps is part of the iterative process of learning about a system's behavior in small incremental steps.

2.1 - Step 1: Brainstorming

The only inputs necessary for brainstorming were people. These people had knowledge of the process under study, flexographic printing. The group was asked two questions.

1. “What print quality characteristics are important to customers?”
2. “What factors in the flexographic imaging process influence print quality?”

The result of the brainstorming step were two large lists that contained answers to these two questions.

2.2 - Step 2: Rationalization

The second step was rationalization. Resource constraints prevented the team from studying everything listed in the brainstorming session. The objective of rationalization was to reduce the number of quality characteristics and the number of factors in the flexo printing process to a manageable size. The inputs to the rationalization process are the same people that performed the brainstorming and the lists created during brainstorming. Negotiation and discussion narrowed the focus of the study down to six print quality characteristics and four flexo printing process factors.

These six print quality characteristics and four flexo printing process factors were then restated as experimental goals and objectives. The goal of the experiment was to optimize print quality as assessed by densitometry for solid ink density, highlight dot gain (measured at 3%), midtone dot gain (measured at 50%) and % slur. After the first subexperiment, optimal print quality for magnaeta ink was defined as solid ink density 1.40 +/- 0.05, highlight dot gain ( 15%, midtone dot gain ( 40% and % slur ( 10%. The objective of the experiment was to test the hypothesis that solid ink density, print contrast, highlight dot gain, midtone dot gain, delta dot gain and slur are a function of anilox roller lines/inch, anilox roller cell depth to opening ratio, ink viscosity and type of stickyback.
Delta dot gain is defined in equation (1):

\[
\text{Delta dot gain} = \text{Dot gain at 25\%} - \text{Dot gain at 57\%} \tag{1}
\]

Print contrast is defined in equation (2):

\[
\text{Print contrast} = \frac{(D_s - D_{70\% \text{ tint}})}{D_s} \tag{2}
\]

Where:

- \(D_s\) = density of solid
- \(D_{70\% \text{ tint}}\) = density of 70\% tint

(Note: Delta dot gain and Print Contrast are described in Appendix 2.2B.)

Percent slur was calculated using a procedure and equations (3) through (8) described in the Appendix (2.2B).

In addition, press impression level, halftone screen ruling, and halftone dot shape were included in the design of the experiment. No print quality optimization work was done using these factors. Incorporating these factors into the print quality optimization process represents an opportunity for future study.

2.3 - Step 3: Design Selection

Inputs into the design selection activity are the experimental goals and objectives from the rationalization step and subject matter experts. Two questions are answered to aid in design:

1. “What information do you want from the experiment?” and 2. “What experiment resources can you afford?” The design selection activity consists of choosing a design or family of design that accommodates the answers.

Frequently, the resources necessary to satisfy the answer to question 1 are not available. Experimental resources typically are money, people, equipment, materials and time. Time is very frequently the most restrictive. It is the only resource that experimenters can’t, by themselves, get more of.

The answer to question 1 led to discussion and negotiation between the subject matter experts, culminating in agreement to estimate all main effects, interactions and curvilinear effects for the print quality characteristics.

A candidate design to satisfy question 1 was a \(2^3\) full factorial, plus central composite, with a replicated center point. In addition, there was a class variable (stickyback type) at 5 levels. Table 1. Lists the factors and levels chosen for the design. Stickyback types are coded A through E for confidentiality purposes.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anilox Lines/inch</td>
<td>380, 585, 800</td>
</tr>
<tr>
<td>Anilox Depth/Opening Ratio</td>
<td>10, 17.5, 25, 32.5, 40</td>
</tr>
<tr>
<td>Ink Viscosity</td>
<td>27, 30, 33, 37, 41</td>
</tr>
<tr>
<td>Stickyback</td>
<td>A, B, C, D, E</td>
</tr>
</tbody>
</table>

Table 1: Experimental Factors and Levels
Table 2. shows a portion of the total design, trial by trial. The full design included this pattern in LPI, D/O Ratio and Ink Viscosity repeated for all 5 stickybacks.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Anilox LPI</th>
<th>Anilox D/O Ratio</th>
<th>Ink Viscosity (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>360</td>
<td>17.5</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>800</td>
<td>17.5</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>360</td>
<td>32.5</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>800</td>
<td>32.5</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>360</td>
<td>17.5</td>
<td>37</td>
</tr>
<tr>
<td>6</td>
<td>800</td>
<td>17.5</td>
<td>37</td>
</tr>
<tr>
<td>7</td>
<td>360</td>
<td>32.5</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>800</td>
<td>32.5</td>
<td>37</td>
</tr>
<tr>
<td>9</td>
<td>360</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>10</td>
<td>800</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>11</td>
<td>565</td>
<td>10</td>
<td>33</td>
</tr>
<tr>
<td>12</td>
<td>565</td>
<td>10</td>
<td>33</td>
</tr>
<tr>
<td>13</td>
<td>565</td>
<td>40</td>
<td>33</td>
</tr>
<tr>
<td>14</td>
<td>565</td>
<td>25</td>
<td>41</td>
</tr>
<tr>
<td>15</td>
<td>565</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>16</td>
<td>565</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>17</td>
<td>565</td>
<td>25</td>
<td>33</td>
</tr>
</tbody>
</table>
Table 2: The Core Design

The full design called for the production of 85 printed samples. An experimental plan was assembled detailing resources and responsibilities for execution of the design.

2.4 - Step 4: Experimental Execution

Inputs for the experimental execution step are the experimental plan from the design selection step and the resources needed to execute the experiment. Resources included ink, substrate, press, press time, people to run press and other things.

The experiment was run on press and 85 printed samples were used to generate print quality characteristic measurements for subsequent statistical analysis. Densitometric measurements were made for all print quality characteristics on 85 printed samples. These measurements were the key input into the statistical analysis step.

2.5 - Step 5: Statistical Analysis of Experimental Results

Statistical analysis of a designed experiment can contain many elements and different analytical techniques. Nevertheless some general themes and issues are found in most statistical analyses of designed experiments. When, as ours was the primary goal of an experiment is optimization, two fundamental questions are addressed:

1. “Have I demonstrated, beyond a reasonable doubt, a cause and effect relationship between a flexo printing process factor and a print quality characteristic?”

2. “Can I make useful predictions of print quality characteristics resulting from specific printing process factor?”

An example of the first question is “Have I proved beyond a reasonable doubt that there is a cause and effect relationship between anilox roll lines/inch (LPI) and solid ink density?”

An example of the second question is “What value can I expect to see for solid ink density if I set LPI at 725 LPI?”

An important element of the prediction issue is the usefulness of the predictions. Usefulness is often times related to accuracy of the prediction compare to actual results. Only the subject matter expert can determine if the predictive results of the statistical analysis are useful.

Inputs into answering these two questions were print quality characteristic values for magenta solid ink density (SID), dot gain (highlight and midtone), slur, delta dot gain and print contrast and proposed mathematical models (Appendix 2.5A) which would be used to make print quality characteristic predictions.

Looking at SID, Figure 1. shows a scatter plot of SID values by stickyback type. The diamonds illustrate 95% confidence interval estimates for the average SID for a particular stickyback type. The horizontal lines inside the diamonds are plotted at the average value for SID for a specific stickyback. Figure 1. illustrates that it’s reasonable to assume there are indeed different average values for SID among the five stickyback types. Type C’s average SID is higher than all others. Types B, D and E have the same average value, which is about 0.12 density unit higher type A.
Figure 2. is a scatter plot of SID as a function of anilox LPI for one specific stickyback type. It illustrates that as LPI increases SID decreases. This relationship was consistent across all stickyback types. The stickyback used in figures 2 – 4 was the same.

![Figure 2. Solid Ink Density by Anilox LPI](image)

Figure 3. is a scatter plot of SID by anilox cell depth to opening ratio (D/O ratio) for a specific stickyback. It illustrates that when D/O ratio increases so does SID, but SID begins to level off and actually decrease beyond a certain level of D/O ratio. This behavior of SID by D/O ratio was consistent for all stickybacks.

![Figure 3. Solid Ink Density by Anilox Cell Depth to Opening Ratio](image)

Figure 4. is a scatter plot of SID by ink viscosity (in seconds) for a specific stickyback. It illustrates that for all intents and purposes, over the range of viscosities selected, there is no apparent effect on SID as a function of ink viscosity. In general this “lack of relationship” was not consistent across all stickyback types. This implies an interaction between ink viscosity and stickyback type.

![Figure 4. Solid Ink Density by Ink Viscosity](image)
Turning to dot gain at the highlight (3%), the same graphical approach to interpreting the data was used. Figure 5. Shows a scatter plot of highlight dot gain by stickyback type. The diamonds illustrate 95% confidence interval estimates for the average dot gain for a particular stickyback type. The horizontal lines inside the diamonds are plotted at the average value for dot gain for a specific stickyback. Figure 1. illustrates that it’s reasonable to assume there are indeed different average values for dot gain among the five-stickyback types. Type C is higher than all but type D. Type A is lower than types C and D.

Figure 5. Highlight Dot Gain by Stickyback Type

Figure 6. is a scatter plot of dot gain as a function of anilox LPI for one specific stickyback type. It illustrates that as LPI increases dot gain decreases. This relationship was consistent across all stickyback types.

Figure 6. Highlight Dot Gain by Anilox LPI
Figure 7 is a scatter plot of highlight dot gain by anilox cell depth to opening ratio (D/O ratio) for a specific stickyback. It illustrates that when D/O ratio increases so does dot gain, but dot gain begins to level off and actually decrease beyond a certain level of D/O ratio. This behavior of highlight dot gain by D/O ratio was consistent for all stickybacks.

![Figure 7. Highlight Dot Gain by Anilox Depth to Opening Ratio](image)

Figure 8 is a scatter plot of highlight dot gain by ink viscosity (in seconds) for a specific stickyback. It illustrates there is an apparent effect on dot gain as a function of ink viscosity. On closer examination though it was discovered that for all other stickyback types, there was no apparent relationship between dot gain and viscosity. This implies an interaction between ink viscosity and stickyback type.

![Figure 8. Highlight Dot Gain by Ink Viscosity](image)

The same process of scatter plotting, analysis of variance followed by regression analysis was used to identify significant effects on print quality characteristics for delta dot gain, midtone dot gain, slur and print contrast. In general the scatter plots and general relationships seen for SID and highlight dot gain were repeated for delta dot gain, midtone dot gain and slur. That is, as LPI increased, delta dot gain, midtone dot gain and slur decreased. As D/O ratio increased delta dot gain, midtone dot gain and slur increased to a point and then level off. Ink viscosity in general appeared to have little or no effect on delta dot gain, midtone dot gain, print contrast and slur. Stickyback type effected the average for delta dot gain, midtone dot gain, print contrast and slur.

The statistical analysis activity concluded with an agreement among subject mater ex-
perts that the models proposed for solid ink density, highlight and midtone dot gain, delta dot gain and slur provided useful predictions of the performance of the printing system.

The model for print contrast did not predict print system performance to a degree of accuracy deemed useful. Print contrast analysis provides an opportunity for subsequent study. For example, in some instances, the density of the 70% tint very near the density of the solid. Yet visual inspection of the 70% tint indicated there should have been a larger difference. The reasons for this would make an interesting follow-up study.

2.6 – Step 6: Co-optimization

Co-optimization is a collection of activities that result in finding settings for the key flexo print factors that will yield optimal print quality characteristics. Inputs into co-optimization are useful models for print quality characteristics and targets/tolerances for the same print quality characteristics. A Nelder-Medal polytype co-optimization routine was used to find the optimal settings for flexo print factors. Table 3. Details the four print quality characteristics contained in the experimental goals and objectives coupled with their co-optimization targets and tolerances. All co-optimization work was done with the 120 line round dot halftone screen print quality characteristics.

<table>
<thead>
<tr>
<th>Print quality characteristic:</th>
<th>Aim</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Solid ink density</td>
<td>1.4</td>
<td>+/- 0.05</td>
</tr>
<tr>
<td>2. Highlight dot gain (@3%)</td>
<td>9%</td>
<td>(15%)</td>
</tr>
<tr>
<td>3. Midtone dot gain (@50%)</td>
<td>40%</td>
<td>Minimize</td>
</tr>
<tr>
<td>4. Slur</td>
<td>5%</td>
<td>+/- 5%</td>
</tr>
</tbody>
</table>

Table 3: Co-optimization Aims and Tolerances

Table 4. shows one set of optimal solutions for two different stickyback types. The co-optimization results for stickyback B were acceptable for SID and midtone dot gain. The co-optimization results for stickyback B were at the edge of the upper tolerance for highlight dot gain and slur tolerances. The co-optimization results for stickyback A were slightly below tolerance for SID, but acceptable for highlight and midtone dot gain and slur. There was no acceptable solution for stickyback type C because dot gain and slur were too high for their respective tolerances.
<table>
<thead>
<tr>
<th>Settings</th>
<th>Optimal</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stickyback B:</td>
<td>Density</td>
<td>Gain</td>
</tr>
<tr>
<td>LPI:</td>
<td>625</td>
<td>1.36</td>
</tr>
<tr>
<td>D/O Ratio:</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Visc:</td>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Settings</th>
<th>Optimal</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stickyback A:</td>
<td>Density</td>
<td>Gain</td>
</tr>
<tr>
<td>LPI:</td>
<td>640</td>
<td>1.31</td>
</tr>
<tr>
<td>D/O Ratio:</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Visc:</td>
<td>41</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Co-optimization Results

The co-optimization solutions, combined with contour plots of predicted responses, provided direction for the next verification step.

2.7 – Step 7: Verification

The purpose of the verification step was to confirm the belief that the team could successfully predict flexo print quality characteristics resulting from specific settings of print process factors. Inputs into activity were the print quality characteristic’s models, equipment, materials and time.
Figure 9 through 12 are contour plots of SID, slur highlight dot gain and midtone dot gain, respectively, as a function of LPI and D/O Ratio for stickyback type B at 33 seconds viscosity. The plots were used to provide guidance for the creation of another anilox roll for use in the verification step.

In general the contour plots suggest exploring an area between 600-800 LPI and D/O ratio of from 20 to 30 optimal print quality. Another anilox roll engraved and used for printing additional samples to verify predictive accuracy.
Table 5. summarizes predictions (in the “Pred” position) and verification press run measurements (in the “Veri” position) for SID, highlight dot gain, midtone dot gain and slur. There are no predictions for the 900 and 1000 LPI combinations because these combinations were outside the original experimental space.

<table>
<thead>
<tr>
<th>LPI</th>
<th>D/O Ratio</th>
<th>SID (Pred/Veri)</th>
<th>3% Dot Gain (Pred/Veri)</th>
<th>50% Dot Gain (Pred/Veri)</th>
<th>Slur (Pred/Veri)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Band</td>
<td>700</td>
<td>25</td>
<td>1.43/1.46</td>
<td>16/18</td>
<td>35/31</td>
</tr>
<tr>
<td>B Band</td>
<td>700</td>
<td>25</td>
<td>1.43/1.4</td>
<td>16.24</td>
<td>35/37</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>20</td>
<td>1.44/1.35</td>
<td>18/19</td>
<td>35/35</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>22</td>
<td>1.44/1.44</td>
<td>17/20</td>
<td>35/37</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>30</td>
<td>1.45/1.41</td>
<td>17/21</td>
<td>36/33</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>30</td>
<td>NA/1.33</td>
<td>NA/18</td>
<td>NA/34</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>30</td>
<td>NA/1.36</td>
<td>NA/18</td>
<td>NA/33</td>
</tr>
</tbody>
</table>

Stickyback A:

<table>
<thead>
<tr>
<th>LPI</th>
<th>D/O Ratio</th>
<th>SID (Pred/Veri)</th>
<th>3% Dot Gain (Pred/Veri)</th>
<th>50% Dot Gain (Pred/Veri)</th>
<th>Slur (Pred/Veri)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Band</td>
<td>700</td>
<td>25</td>
<td>1.28/1.27</td>
<td>13/15</td>
<td>36/34</td>
</tr>
<tr>
<td>B Band</td>
<td>700</td>
<td>25</td>
<td>1.28/1.22</td>
<td>13/15</td>
<td>36/36</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>20</td>
<td>1.31/1.14</td>
<td>15/17</td>
<td>37/39</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>22</td>
<td>1.26/1.29</td>
<td>14/17</td>
<td>36/31</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>30</td>
<td>1.26/1.27</td>
<td>13/16</td>
<td>37/36</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>30</td>
<td>NA/1.22</td>
<td>NA/16</td>
<td>NA/36</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>30</td>
<td>NA/1.16</td>
<td>NA/15</td>
<td>NA/34</td>
</tr>
</tbody>
</table>

Table 5: Comparison of Verification Press Run Results To Predictions

2.8 - Summary

The team felt that, based on verification press run results, they had sufficient understanding of the required print process factors and settings for optimizing print quality. And most importantly, they could now intelligently configure the flexo printing process for optimal results.

The team was convinced that statistical experimental design is an efficient, powerful tool which can be used to assist in optimization of the flexographic imaging process.
APPENDIX

1.11A F-TROP MEETINGS AND PRESS TRIALS as of August-1993

1992
April 27 Chicago, IL.
May 21 Clemson University, Clemson, SC
June 11 Clemson University, Clemson, SC
August 20-21 Harper Corporation, Charlotte, NC
September 17-18 FIRST SUBEXPERIMENT at Clemson University
October 28-29 Eastman Kodak, Rochester, NY.
December 5-6 Orlando, FL. (FTA Ink Conference)

1993
February 2-3 Clemson University
March 1 “OTHER COLORS” CONFIRMATION TRIAL at Clemson University
March 2-3 Color Response, Charlotte, NC
March 18 7-BANDED ROLL VERIFICATION TEST at Clemson University
April PROCESS COLOR TRIAL RUN at Clemson University
April 20 W.R. Grace, Atlanta, GA.
May 4 Report to FTA Forum, Dallas, TX
May 25 Clemson University
June 28-29 FINGERPRINT TEST RUN
August 5 W.R. Grace, Atlanta, GA

2.2A DELTA DOT GAIN is determined by subtracting dot gain at the 25% dot from dot gain at the 75% dot. Delta dot gain can be helpful to color separators in assigning dot values to compensate for dot gain throughout the tone scale, particularly in the quarter-tone areas.

In offset lithography, when dot gain is plotted from highlight through shadow dots, it tends to follow a common pattern: a dome-shaped curve peaking at the 50% dot (where gain is greatest) and sloping down to zero relatively symmetrically toward both highlight and shadow dots. Therefore, there is little difference between gain at the 25% and 75% dots (low delta dot gain). In flexography, however, there tends to be a marked difference, with far more gain at the 25% dot and less at the 75% dot.

PRINT CONTRAST is calculated using the equation shown in 2.2. It indicates the ability to hold detail in shadow areas. The higher the value for print contrast, the greater the ability to reproduce shadow detail. A higher value also affords the color separator more flexibility in assigning dot values that will produce successful tone reproduction.
2.2B Percent slur calculation was performed using the following procedure and equations (3) through (8):

1. Three test patches of a 50% ruling were printed. Each pair of lined rulings are different by 120%.

2. Collect optical density ($D_i$) above paper for 3 patches 1 through 3.

3. Convert density of all three patches to effective printed area, $a_i$, equation (3) using the Yule-Nielsen equation solved for $a$.

\[
a_i = \frac{1-10^{-\left(\frac{D_i}{n}\right)}}{1-10^{-\left(\frac{D_s}{n}\right)}}
\]

Where: $a_i$ = effective dot area for $i$ samples 1 through 3.

$D_i$ = optical density of sample patch $i$ samples 1 through 3.

$D_s$ = optical density of solid patch

$n = 1.7$

4. Compute total dot gain, $G_i$, for each sample patch:

\[
G_i = a_i - 0.50
\]

5. Rank order $G_i$:

$G_{\text{max}}$ = largest $G_i$

$G_{\text{mid}}$ = second largest $G_i$

$G_{\text{min}}$ = smallest $G_i$

6. Calculate $F$ (symmetrical dot gain) and $S$ (asymmetrical dot % slur):

\[
F = G_{\text{mid}} + G_{\text{min}} - G_{\text{max}}
\]

\[
S_1 = 2(G_{\text{max}}) - G_{\text{mid}} - G_{\text{min}}
\]

\[
S_2 = \left(\frac{3}{3}(G_{\text{mid}} - G_{\text{min}})\right)
\]

\[
S = 100\left[\left(S_1^2 + S_2^2\right)^{\frac{1}{2}}\right]
\]
The general form of the models proposed were:

\[ \text{PQC}_y = b_0 + b_1(\text{Stickyback}) + b_2(\text{LPI}) + b_3(\text{D/O Ratio}) + b_4(\text{Ink Viscosity}) + b_{12}(\text{Stickyback})(\text{LPI}) + b_{13}(\text{Stickyback})(\text{D/O Ratio}) + b_{14}(\text{Stickyback})(\text{Ink Viscosity}) + b_{23}(\text{LPI})(\text{D/O Ratio}) + b_{24}(\text{LPI})(\text{Ink Viscosity}) + b_{34}(\text{D/O Ratio})(\text{Ink Viscosity}) + b_{11}(\text{Stickyback})^2 + b_{22}(\text{LPI})^2 + b_{33}(\text{D/O Ratio})^2 + b_{44}(\text{Ink Viscosity})^2 + e \]

Where:
1. \( \text{PQC}_y \) are the print quality characteristics: solid ink density, % slur, highlight dot gain, midtone dot gain, print contrast, delta dot gain.
2. \( b_0 \) is an intercept term.
3. \( b_{ij} \) are estimated regression coefficients.
4. \( e \) is error.