# High-Quality Inkjet Color Graphics Performance on Plain Paper

Realizing the color graphics performance of the HP DeskJet 1200C printer required simultaneous optimization of many interacting parameters of the ink and the architecture to deliver significant improvements in print quality, color gamut, throughput, and cost per copy.

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The HP DeskJet 1200C printer is a 300-dpi, plain paper printer that provides vivid, bright, true colors with consistent print quality on all media (plain and special papers, transparency and glossy films).

The color print cartridges (cyan, magenta, yellow) for the DeskJet 1200C represent a significant advance in HP thermal inkjet printing technology. The major contributors to the improved performance, print quality attributes, and throughput are the ink and the architecture. Both the ink and the architecture were optimized to deliver significant improvements in print quality, color gamut, throughput, and cost per copy. One major customer benefit of the DeskJet 1200C cartridge is the small drop volume, which provides industry-leading color cost per copy at any use rate.

During the color development phase of the DeskJet 1200C printer, the HP DeskJet 500C[1] and HP PaintJet XL300 printers were used as benchmarks for color graphics. The team learned a great deal from these products and leveraged some of the acquired knowledge in developing a significantly better product. However, leveraging from these products did not make the development easy; a major effort was still required since new issues emerged as design modifications were made. Test qualification became very important, and since time was a limiting factor, the design-build-test-fix cycle became a challenge. Throughout the project, optimization was done within aggressive schedule objectives.

### Addressing Customer Needs

Early in the DeskJet 1200C printer and pen cartridge development, the QFD (Quality Function Deployment) method of addressing customer needs was used.[2] This established a foundation of customer focus throughout the project for both the printer and the print cartridge.

A QFD team was formed to gather customer needs, link one or more engineering metrics to the customer needs, and determine what technical factors engineers could control and measure to satisfy the customer needs. This team was composed of representatives from different areas of the project.

Based on the QFD customer research studies, several fundamental characteristics that define color graphics quality were identified:

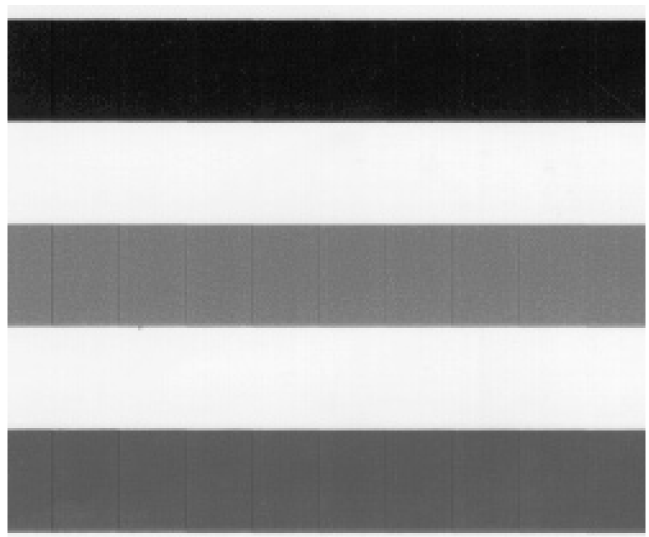

**Fig. 1.** Drop placement errors caused by swath advance.

- Color quality
- Area fill quality
- Line and edge quality
- Cockle
- Curl
- Whiteness
- Archivability.

### Engineering Metrics

Color quality of a printed output is determined using the Munsell color measurement system.[3] Chroma is a measure of the vividness or brightness of the color. Hue refers to the shade or tone of the color. Value is a measure of the darkness or lightness of the color. The color gamut describes this three-dimensional color space:

$$\text{Color Gamut} = \text{Value} \times \text{Chroma}^2 \times \text{Hue}.$$

Customer survey results indicate that smooth area fills are very desirable. The parameters that can affect area fill quality are:

- Drop placement errors caused by swath advance (see Fig. 1) and theta-Z (printhead rotational misalignment) errors

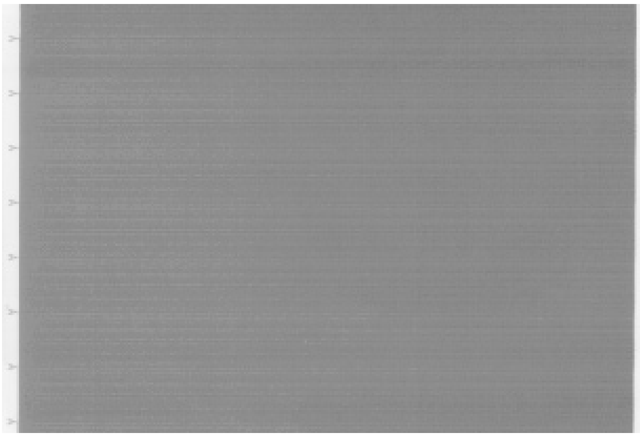

**Fig. 2.** Banding caused by misdirection.

- Banding caused by pen defects such as misdirection (see Fig. 2) and variations in drop volume or dot size
- Wait time banding (see Fig. 3)
- Mottling (see Fig. 4)
- Bleed caused by different penetration rates of the ink into the media (see Fig. 5)
- Coalescence caused by drops pulling together before the printing surface is wetted
- Print rendering methods.

Mottling, coalescence, and wait time banding are evaluated visually. Several algorithms using a machine vision system were developed to measure swath advance and theta-Z errors, directionality, dot size, and bleed.

Artifacts such as spray (see Fig. 6), feathering, and jaggy horizontal and vertical lines (see Fig. 7) caused by dot placement errors or paper shrinkage can deteriorate the line and edge quality of the printed image. Spray is inherent in thermal inkjet technology and it is made worse by the presence of the vapor removal system in the printer. The vapor removal system consists of the fan and the plenum. Its primary function is to remove local moisture from the writing system area.

Flat paper output is another customer want. Paper cockle is a distortion in which bumps or ridges are randomly produced

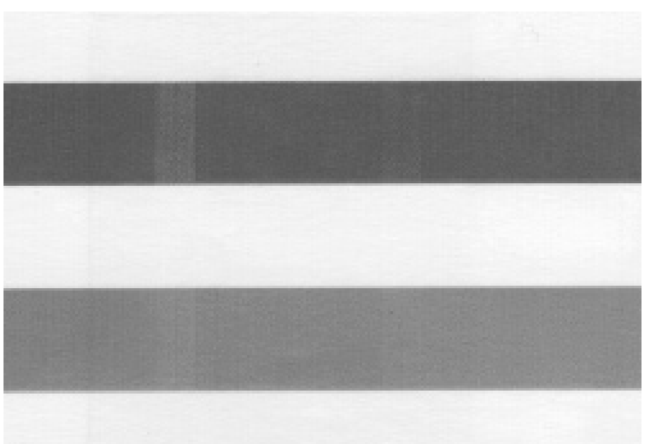

**Fig. 3.** Wait time banding.

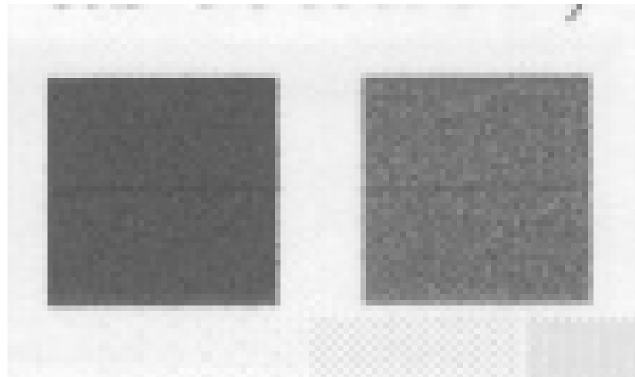

**Fig. 4.** Mottling.

on the printed paper. Paper flatness is lost and the output has a wavy appearance. This is a side effect of high-density inkjet printing with aqueous inks. Visual measurement is done on paper cockle. Curl is a phenomenon in which the edges of the paper migrate towards the center of the paper (see Fig. 8). In worst-case environmental and printing conditions, the output may take the form of a tube. Curl measurements involve measuring the height of all four corners of a sample resting on a flat surface. This problem can be a major customer dissatisfier since paper curl affects media stacking and curled sheets are difficult to display or store. Cockle and curl get worse as the throughput increases. These print quality defects are inversely related. The more cockle a solid area fill output has, the less curl it has. The cockle appears to reinforce the paper so that it does not curl.

Fig. 9 shows one of the engineering test plots used to evaluate some of the print quality attributes such as dot size, line width, color quality, banding, and mottling.

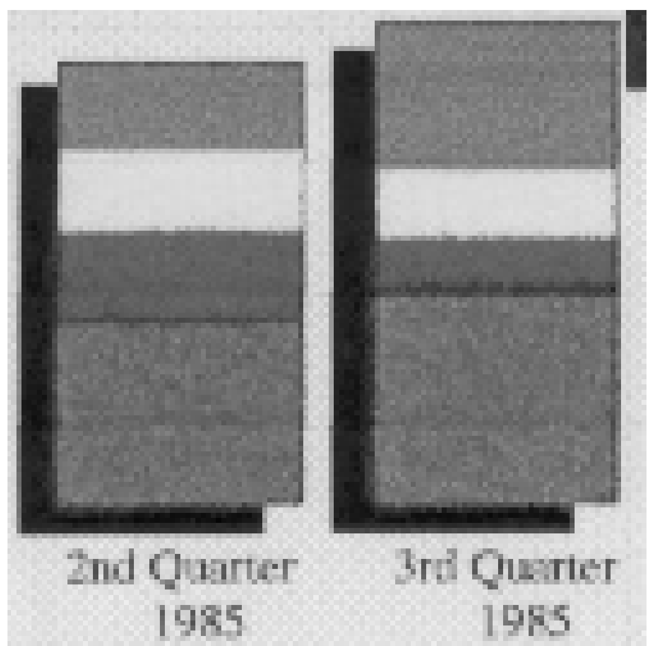


**Fig. 5.** Bleed.

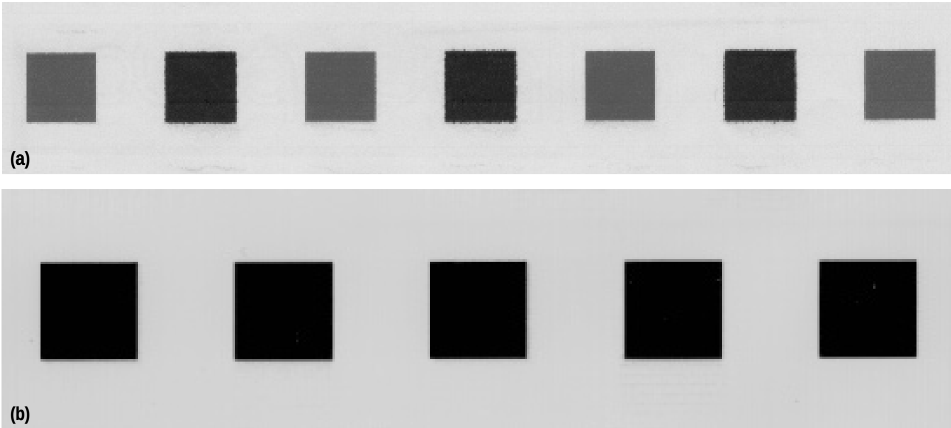


**Fig. 6.** (a) Spray. (b) Shim spray.

The amount of ink placed on the media is a very important parameter to control since it affects several print quality attributes such as bleed, transparency film bleed and blocking,* glossy film bleed and color transfer, cockle, curl, and banding. To achieve acceptable edge acuity and area fill quality for color graphics, the size, shape, and consistency of the drops fired from the printhead generator need to be controlled. Drop volume is an engineering measurement used to determine the amount of ink delivered by the print cartridge in a single drop. Dot size and shape are engineering measurements used to determine the size and shape of the spot made by a drop of ink when it lands on the paper. The print cartridge architecture is an important print cartridge parameter that, in conjunction with the ink, controls these attributes.

### Color Architecture and Drop Volume

Selecting the target drop volume was an important part of the architecture design process. This was critical to system testing to determine ink, media, heater, blower, and print-mode interactions. Several product and print cartridge variables were considered in selecting the target drop volume. The product variables were:

- Heater settings. Higher temperatures increase the delivered volumes but decrease the dot size for a given drop volume.
- Print cartridge temperature. The print cartridge temperature increases with continuous printing and this increases the delivered volume.
- Print mode. The amount of ink placed in different passes changes the dot size and the area fill coverage.
- Swath advance accuracy. Larger dot sizes are required if swath advance errors are large.
- High-density versus low-density plots. High-density plots hide artifacts such as directionality, but induce problems such as curl, cockle, bleed, transparency film bleed and blocking, and glossy film bleed and image transfer.
- Special paper versus plain paper. Special paper must typically print in the same print modes as plain paper. The challenge was to obtain the same dot size as closely as possible for both media.

The print cartridge variables that were considered are:

- Ink. Different inks have different dot size characteristics because of heater settings, ink penetration rates, and print cartridge temperatures.
- Directionality. Larger spots are needed to cover larger errors.
- Manufacturing variability. Large drop volumes affect the area fill quality, cockle, bleed, transparency film bleed and blocking, and glossy film bleed and image transfer. Low drop volumes show artifacts such as misdirection and improper color saturation.

As mentioned earlier, the small drop volume delivered by the HP DeskJet 1200C color print cartridge provides very low color cost per copy. When pulse warming was implemented in the DeskJet 1200C as explained in the article on page NO TAG, the nominal drop volume was lowered by about 5

* Blocking is a phenomenon in which the ink and media stick to the plastic sleeves used to protect transparencies, causing pockets of air that cause distorted images when the film is projected.

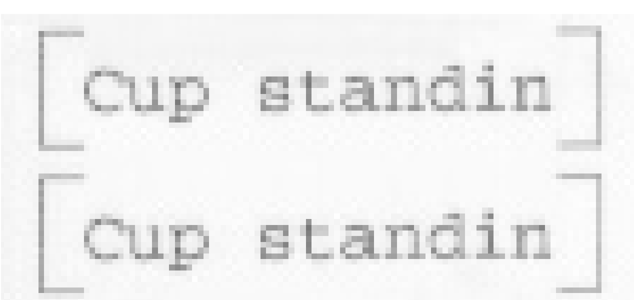


**Fig. 7.** Jagged lines.

**Fig. 8.** Curl.

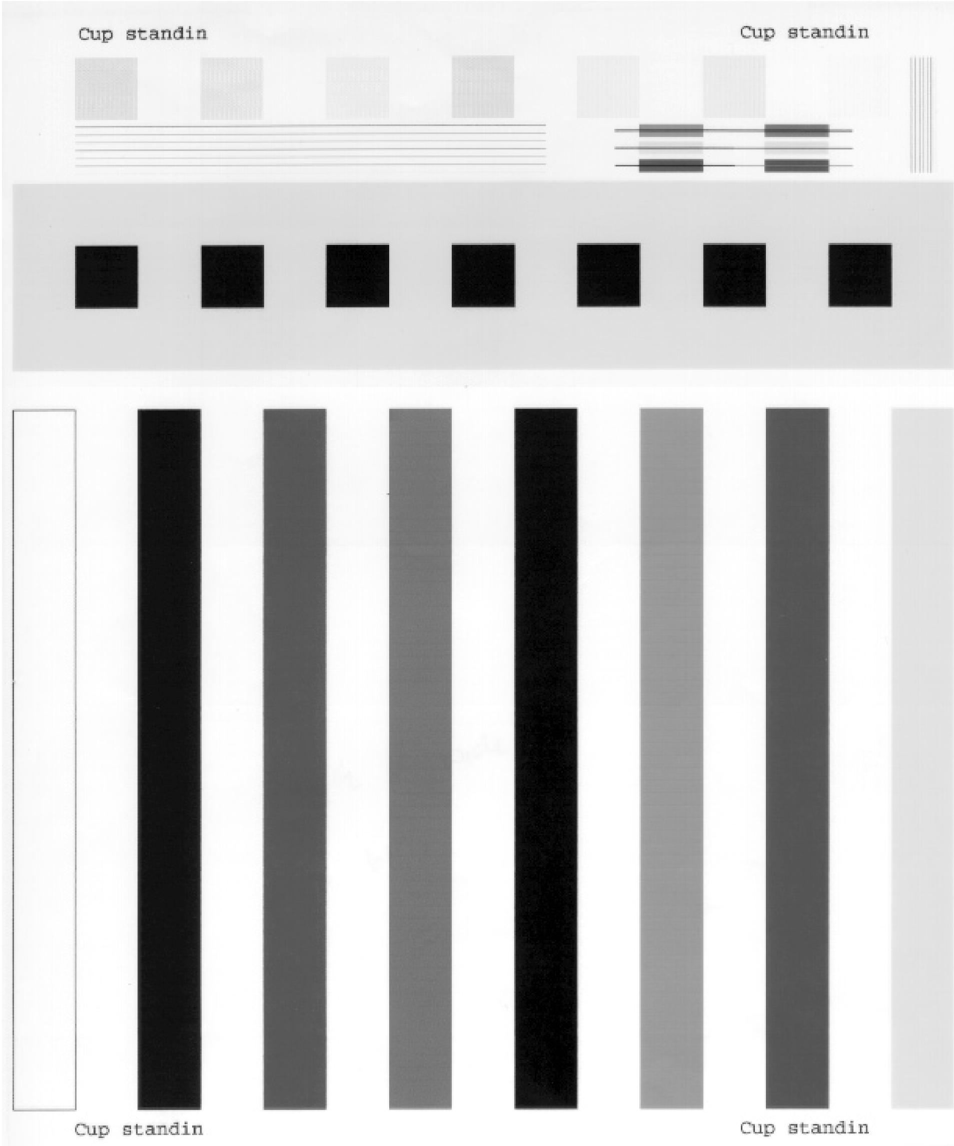


**Fig. 9.** Print quality metric plot.

picoliters. Changes in the orifice diameter, resistor size, and barrier geometry were required to implement and compensate for this change.

One of the challenges of designing the color architecture was to be able fire the print cartridge at a higher frequency. This was driven by the customer need for increased throughput. As the frequency was increased, puddling also increased (see Fig. 10), and ink accumulated on the surface of the top plate, causing misdirected drops called streaks (see Fig. 11). To correct these problems, a balance between refill speed and fluid damping was incorporated in the architecture design by adjusting the dimensions of the channel.

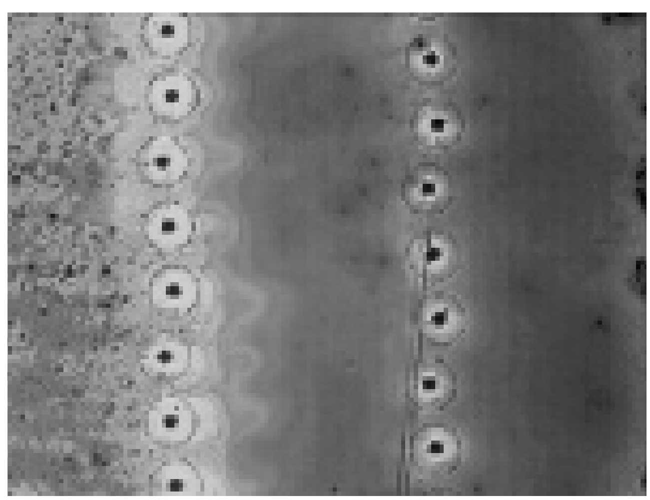

**Fig. 10.** Puddling.

### Print Mode

Achieving high color graphics throughput (less than two minutes per page for high-quality print mode on a range of plain papers and three minutes per page for transparency and glossy films) was a very challenging customer demand. To achieve this aggressive goal, the amount of ink placed on the media per dot location, the speed with which the ink is placed, and the number of passes required to complete the

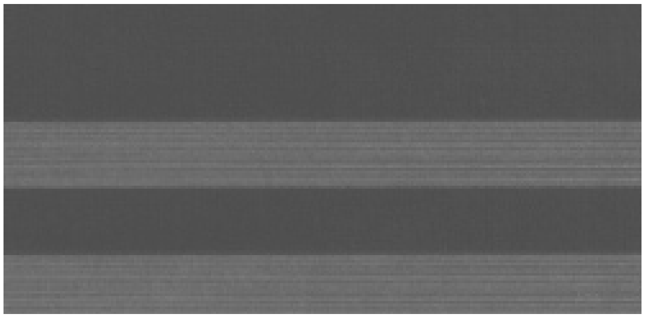

**Fig. 11.** Streaks.

image became very critical factors. The print mode is the mechanism used to control these factors. The choice of print modes had a large impact on certain key design decisions such as swath advance distances for greatest accuracy, swath advance accuracy goals, and electronic architecture. The print mode has a tremendous effect on print quality attributes such as bleed, cockle, banding, edge acuity, spray, color saturation, curl, transparency bleed and blocking, and glossy film bleed and image transfer.

Two print modes were considered for high-quality special and plain media printing: four-pass at a higher scan speed and three-pass at a slower scan speed. The three-pass mode was chosen because it has several advantages over the four-pass mode. The slower scan speed produces less spray and smaller ink-drop tails because the print cartridge is fired at a lower frequency. This also avoids streaks or misdirectionality since puddling is reduced. Paper curl is better since the paper spends more time over the heater. One advantage of the four-pass print mode is to reduce cockle, since the ink density per pass is lower.

One of the biggest decisions in print mode development was the implementation of transparency and glossy print modes. Transparency film bleed and blocking and glossy film bleed and image transfer were major problems faced by the color technical teams. These problems are accelerated at high temperatures and humidities. The print mode developed for glossy and transparency film uses six passes with one third of the ink density placed per pass, completing 100% area fill density after the third pass and 200% density after the sixth. A special print mode algorithm varies the amount of ink placed per pixel for primary and secondary colors. For example, to print green on transparency film, one drop each of yellow and cyan are used in each of two opposite corners of a pixel and one drop of yellow and two drops of cyan are used in each of the remaining corners of the pixel.

### System Test Strategy

The color development team was constantly battling to improve print quality, reliability, throughput, and cost. The challenge of providing the best print quality with high performance at a reasonable price to attract both home and business customers was constantly faced. These customer demands became increasingly difficult to meet. Any design modifications made to improve one of these areas was bound to affect one or more other areas adversely. The technical team needed to ensure that the components of the system were properly integrated.

The DeskJet 1200C writing system is complex. Its major components are the printer, the cartridge, and the media. The printer consists of the heater, the blower, the electrical system, the print algorithms in firmware, and the service station. The print cartridge cartridge consists of the ink, the architecture, and the ink delivery system. The media types include special and plain paper and transparency and glossy film.

A system approach to setting objectives and problem solving was the key to optimizing system performance while minimizing time to market. Understanding component-level design issues and how they affected the system as a whole was important since it saved time, effort, and resources. As mentioned earlier, time was a limiting factor in the development of the DeskJet 1200C printer and print cartridge. Shortening the design-build-test-fix cycle and meeting the design objectives became a real challenge. Any design changes required a series of design iterations, each with a long lead time, followed by an intense qualification phase. System test development became a vital part of the development phase.

### Ambient and Environmental System Test

The purpose of the system test was to screen new designs, processes, or ink and media formulations quickly and identify failures or areas of concern. The test was designed not only to test for conformance to specifications but also to test for failures. This test measured the print quality and reliability of the system. It was important to monitor both print quality and reliability since a system with poor reliability can lead to unacceptable print quality.

The test consisted of both user and diagnostic plots using different print modes and media. The print quality attributes evaluated were dot size, line width, drying time, water fastness, smear fastness, archivability, color quality, bleed, cockle, spray, feathering, banding, and curl. The reliability attributes evaluated were intervention rate, failure rate, short-term decap time,* and start-up.

### Print Quality Evaluation

During color development, we found it necessary and beneficial to use our HP division's internal print quality committee. The print quality committee represents the end user's opinions, and research has been done to show that the print quality committee correlates very well with our end users in most cases. The committee was initially used to determine how the DeskJet 1200C compared to the benchmark products. It was also used to judge the acceptability limit of a single print quality attribute at a time. This provided quick feedback on improvements without extensive outside market research, which adds cost.

A vision system tool was also used to measure dot size, directionality, bleed, line width, and color quality (chroma, hue, gamut). As new problems emerged, it became necessary to develop tests and metrics to determine the severity of the problems.

* Short-term decap time is the amount of time that a print cartridge can be left uncapped and still recover. When a cartridge is left uncapped the water in the ink evaporates, leaving very viscous ink around the nozzles. This can cause nozzles to drop out (fail to function).

### Issues and Trade-offs

The color graphics seam team faced many issues and trade-offs during the development phase.

To achieve the throughput goals that were set for the HP DeskJet 1200C printer, a heater was added to accelerate the drying of the ink on the surface of the media. This minimizes the amount of cockle and bleed on the output. However, the use of the heater has the disadvantage of making paper curl worse. After extensive investigation, the ink was found to be the major factor that could be controlled to solve the problem. The DeskJet 1200C ink contains an anticurl agent to provide curl-free high-density output at high throughput.

The introduction of the new ink was not without its set of other problems. After a series of system test qualifications, one of the major problems found was an archival problem. The mechanism that helps reduce paper curl had a negative effect on transparency and glossy film. Transparency bleed and blocking and glossy film bleed and color transfer were unacceptable, especially at worst-case environmental and printing conditions. The problem also got worse over time. During our ink vehicle optimization investigation, we found that there were no margins for changing the ink to achieve acceptable print quality on both film and curl issues. In our investigation, we had identified several possible solutions: (1) adjust the heat, (2) modify the time over the heater, (3) change the drop volume, (4) change the inks, (5) change the films, and (6) use a different print mode that places less ink on the film. To improve the film issue without compromising curl and other print quality attributes, the film and the amount of ink on the film were found to be the major controllable factors. A major film development effort was spearheaded by the media team (see article, page NO TAG) and print mode development was put into place to control the amount of ink on the film without compromising color quality.

### Color Ink Development Process

The aggressive schedule for the DeskJet 1200C required quick development of color inks that met all design objectives. The approach was to follow three relatively simple principles: listen to the customer, communicate changes, and don't try to do everything yourself. The development of the DeskJet 1200C color inks followed the QFD approach[2] to listen to the needs of the customer. Key attributes for color ink design were:

- Large color gamut
- Excellent red chroma on plain paper
- Bright colors
- High-speed printing
- Excellent quality on a variety of media
- Low ink cost per page.

Meeting aggressive time-to-market goals required selecting a technical path for color ink development without knowing all of the possible problems associated with that path. The approach taken was to divide ink requirements into "must" and "want" objectives. Musts were things that the product had to have and were nonnegotiable, while wants were important but not essential. Examples of musts are reliability and nontoxicity. Examples of wants are low cost per copy, light fastness, high throughput, and low cost. Some attributes had both must and want objectives. For example, the must objective for color gamut was to equal the gamut of printers on the market, while the want objective was to exceed other printers.

Several color ink development pathways were evaluated to see if they met the must objectives. Pathways that failed to meet one or more musts were rejected and the surviving pathways were evaluated to see how well they met the want objectives. A problem was encountered because all wants were not equal—some were more important than others. Instead of relying on the technical team's ability to prioritize want objectives, the QFD approach was used. QFD not only ranks customer needs by order of importance, but can also be used as a tool to see how well technical tests match the attributes that customers care about. For example, instruments can be used to measure color coordinates in CIE color space, but this wouldn't have any meaning to the average customer. What the customer understands are terms such as bright colors, saturated images, and vividness. By looking at the matrix of how customer needs are ranked and how well analytical tests match those needs, want objectives were prioritized and the correct ink development path was chosen.

As ink improvements were made during the DeskJet 1200C program, it was important to communicate ink changes clearly to the rest of the project teams. There was always a default color ink set, which allowed the program to move forward. As new ink formulations were evaluated, their performance was compared to the default ink. When a new ink had been thoroughly tested and exceeded the performance of the default, the default ink was changed to the next ink revision. To avoid confusion, the entire set of three color inks was changed to a new revision, even if only one of the three inks was changed.

Hewlett-Packard's ink development resources were leveraged by working closely with a partner for ink development and manufacturing. Having a partnership as opposed to a vendor-customer relationship had numerous advantages and provided a few additional challenges. Some of the advantages included the ability to carry out custom synthesis of new compounds, access to facilities and equipment, and the availability of a large chemistry knowledge base to help solve problems.

By working with the same partner for both R&D and manufacturing, the team was able to achieve a smooth transition from development to production. Many of the same people involved in ink design were also involved in setting up the manufacturing facility. This increased the focus on using manufacturable processes as the inks were developed. The same or similar manufacturing equipment was used to provide ink for R&D and for full-scale production. This greatly simplified scaling up to production levels and the transition from R&D to manufacturing.

Some of the challenges of working with a partner as opposed to a vendor were more frequent travel and meetings and a greater need for clear communication of goals and expectations. Different corporate cultures were also encountered and each group had to learn the other's terminology. The advantages of a partnership clearly outweighed the disadvantages and allowed the team to meet customer needs.

### Color Ink Design

In designing an ink, one begins by setting its performance requirements based on user needs and the restrictions imposed by the printer's hardware and operating conditions. For the DeskJet 1200C printer, the user needs were low cost and high-quality graphics at fast throughput rates. The ink that was designed to meet these user needs consists of dyes and a vehicle. The dyes impart a gamut of bright, saturated colors. The vehicle provides:

- A carrier for the colorant into the paper fibers
- Fast drying time to allow faster throughput
- Anticrusting properties to prevent clogging of the nozzles in the print cartridge
- Dot spread for lower cost per copy
- Anticurl properties to allow printing of high-density graphics
- Fluid dynamics for reliable drop ejection
- Biocides for control of microbial growth.

Ideally, each functional requirement would be uniquely influenced by one component in the ink formulation, but in reality, any given component can play multiple roles, both positive and negative. A further complication is that the functional requirements place conflicting demands on the ink, and the hope is that the individual operating windows will overlap with sufficient latitude. The concentration of each component is optimized and an operating window is assigned through rigorous system testing. The optimized formulation and the tolerances are then translated into a set of measurable physical properties of the ink. In the beginning, this set may be incomplete and have wide specification ranges, but as the project matures, more parameters enter into the picture and the ranges tighten. The resulting formulation and specifications are then passed on to manufacturing which formulates the production quality plan.

### Dye Selection

The dye choices for cyan, magenta, and yellow were driven by the customer expectations of vivid, bright colors on varied media, as well as by the need for more color. The initial choice for these three dyes was to use the well-established dyes already in use in HP plotter print cartridges and in already released HP DeskJet printers such as the DeskJet 500C. These anionic dyes have well-characterized archival properties, and when coupled with the appropriate counterion (cation), can be made compatible with all the performance and reliability requirements of the new cosolvent ink writing system.

Purity of the dye sources can effect color significantly. To ensure purity, physical properties of the inks, such as conductivity, pH, anion and cation concentrations, viscosity, surface tension, and UV-visible spectra must be tightly specified and monitored.

### Color Optimization

The customer need for vivid, bright colors on varied media determined the choice of color metrics to be used in determining dye loads.

First of all, it was decided that the metric should be based on a visual system such as the Munsell system[3] rather than an instrumental system such as L*a*b*[4] (more about this later). Therefore, all instrumental measurements were transformed from L*a*b* coordinates to Munsell coordinates.

Second, the metric was further refined by scaling Munsell color differences according to the Balinkin transformation,[5] which reflects the actual human response to the variables. The Balinkin-scaled chroma difference is $20\Delta C/\pi$, where $\Delta C$ is the Munsell chroma difference, while the Balinkin-scaled hue angle difference is $2C\Delta H/5$, where $\Delta H$ is the Munsell hue difference.

The method used in optimizing dye loads was as follows:

- Identify a set of focal colors to be used for measurements.
- Determine the Munsell coordinates of the focal colors chosen.
- Adjust dye loads to exceed the Munsell chroma of the focal colors while matching the Munsell hue and value of the standard colors.

Focal colors are colors for which people, independent of culture, identify a one-to-one correspondence between the color names and definite regions in 3D color space. The centroids of focal color regions such as red, orange, green, yellow, purple, pink, and brown have been determined.[6,7] The intersection of the focal colors with the color secondaries RGB (red, green, blue) and the color primaries CYM (cyan, yellow, magenta) results in four colors: RGBY. These were selected as the colors to be measured for dye load optimization. In Munsell color coordinates the focal color centroids are as shown in Table I.

**Table I**
**Focal Color Centroids in Munsell Coordinates**

| | Hue | Value | Chroma |
|---|---|---|---|
| Red | 5.6R | 4.6 | 13.2 |
| Green | 2.8G | 5.2 | 10.3 |
| Blue | 6.4PB | 4.1 | 9.2 |
| Yellow | 6.4Y | 9.0 | 12.8 |

Note: The Munsell hue spectrum is circular and is divided into ten regions, each of which is divided into ten angle units called hundredths. A color's hue is specified by a letter code identifying the region and a number between 0 and 10 indicating the number of hundredths within that region.

The color metric used to measure the goodness of each ink color was:

$$\text{Metric} = 20\Delta C/\pi - |2C\Delta H/5|,$$

where $\Delta C$ is the chroma excess, or the amount by which the chroma of the ink color exceeds the chroma of the focal color centroid, and $\Delta H$ is the hue angle deficiency, or the amount by which the ink color differs from the hue of the focal color centroid. Thus the metric is the Balinkin-scaled chroma excess minus the absolute value of the Balinkin-scaled hue angle deficiency. This metric reflects the relative importance of chroma excess and hue angle deficiency relative to the centroids.

However, selection of a metric was only the beginning. Because the results could be expected to be influenced both by the type of media and by the specific color, the optimization procedure also needed to reflect the relative weightings of the focal colors and of the various required media. Using QFD and Kepner-Tregoe[8] approaches suggested the following rankings of importance from the customer standpoint:

Media: Office Papers > Transparency Film > Special Papers

Focal Colors: Red > Yellow > Green > Blue.

Dye loads were optimized by maximizing the metric for the focal colors using these relative weightings to make trade-offs where necessary.

### Other Optimizations

In addition to this quadratic design optimization of the Balinkin-scaled metric (excess chroma minus hue difference) by adjustment of dye loads, a second factorial design optimization was performed. Optimal concentrations of red magenta dye to be mixed with the original violet magenta dye to obtain the optimum chroma-hue balance in the red and blue focal colors were determined. The original magenta dye, when used alone, created reds that were too violet in hue but created excellent blues. The second magenta dye, when used alone, created reds that were too orange in hue and created blues that were both too dark and too achromatic. The factorial optimization coupled with the quadratic optimization simultaneously created the best balance in both the red and the blue focal color regions.

Optimization of the third coordinate of color, which is value, or lightness/darkness, is implicit in the optimization described above, since the chroma optimization can only be made after an initial dye load approximation to give proper optical density, adjusting for drop volume, dot spread, print mode, heater settings, and media differences. However, increasing dye load to increase chroma also tends to increase value. This was only a problem with the blue focal color, which came out slightly too dark, but the result was judged to be within the acceptable range.

Another useful metric for optimization is the Munsell gamut number, which has the dimensions (value $\times$ chroma$^2$ $\times$ hue) and is an acceptable metric describing the entire 3D accessible color space using a black print cartridge and white media difference to describe the extreme value difference. The disadvantage in the use of this metric is that the color gamut is dependent upon the black ink and may not reflect the customer need for more vivid, bright colors. We used the Munsell gamut as a check on our other methods and found, as expected, that gamut was increased by our optimization methods.

### Results of Color Optimization

To illustrate the success of these techniques of optimization, consider the focal color coordinates of the optimized DeskJet 1200C color ink on just one of the copy papers, as shown in Table II. Singling out one type of media is representative of the solution, but of course, the weighting factors for all media were considered in the total optimization.

This oversimplified analysis points out that the metric is positive for R, G, B. Only the value of the blue focal color is very different from target (2.9 in Table II versus 4.1 in Table I). The red and the green hues on this type of media are very slightly yellow, but the added chroma benefit more than exceeds that slight hue error (less than one hundredth of a Munsell hue circle). Furthermore, dithering a slightly orange red with a magenta of the same value to obtain optimum reds is less obtrusive than dithering too bluish a red with a yellow of far higher value to obtain optimum bright reds.

**Table II**
**HP DeskJet 1200C Ink Coordinates and Focal Color Differences on One Copy Paper**

| | Hue | Value | Chroma | ΔC | ΔH | Scaled Metric |
|---|---|---|---|---|---|---|
| Red | 6.5R | 4.8 | 14.4 | 7.6 | 5.2 | 2.4 |
| Green | 1.7G | 5.1 | 12.0 | 10.8 | 5.3 | 5.5 |
| Blue | 8.6PB | 2.9 | 12.0 | 17.8 | 10.6 | 7.2 |
| Yellow | 6.9Y | 9.1 | 13.0 | 1.3 | 2.6 | –1.3 |
| Magenta | 3.1RP | 5.0 | 17.0 | | | |
| Cyan | 7.2B | 5.9 | 12.0 | | | |

The yellow hue is slightly greenish, but the resulting scaled hue error is too small to be significant.

Since the primaries and secondaries all exceed the requirements for chroma, the resulting gamut of available colors compares very favorably to the gamuts of competitive inkjet and thermal transfer products (see Fig. 12).

### L*a*b* versus Balinkin Coordinates

The need to transform from L*a*b* coordinates to Balinkin coordinates is illustrated by Fig. 13, which shows the dependency of the L*a*b* color difference metric $\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$ on the hue, value, and chroma of all six color primaries and secondaries. For convenience, a constant delta Balinkin of 6 has been chosen as a frame of reference, and fading of each of these six colors has been simulated in each of the separate three coordinates of color: hue, value, and chroma. Note that human observers are most sensitive to changes in ΔE* resulting from chroma loss and least sensitive to changes resulting from value gain (lighter). ΔE* changes resulting from hue shifts are very dependent upon initial hue, being most sensitive in yellow and least sensitive in blue and magenta. In summary, ΔE* as a metric is more of a historical and instrumental convenience than it is a consistent metric for human visual response.

### Vehicle Design

In addition to providing high-quality graphics, the HP DeskJet 1200C printer had to be faster than the HP PaintJet

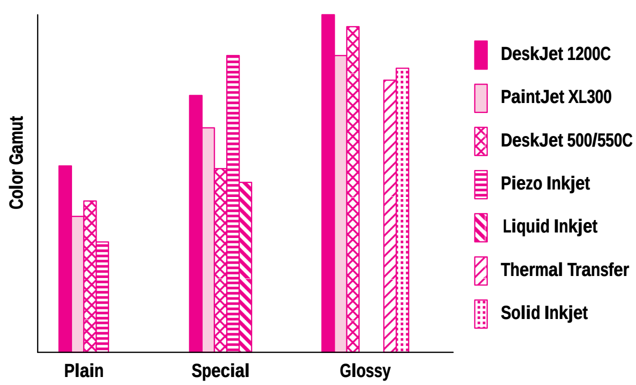


**Fig. 12.** Relative color gamut of the HP DeskJet 1200C printer and other color printers.

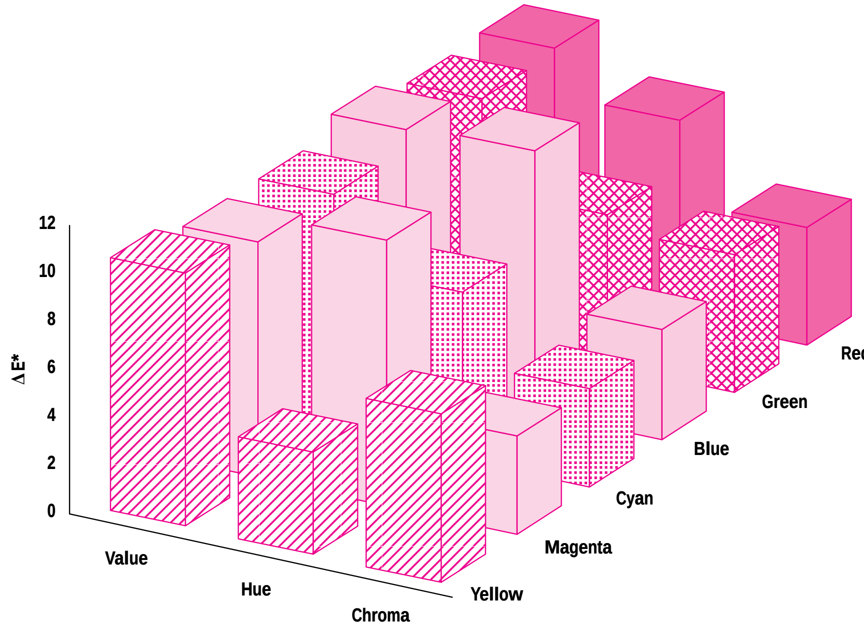


**Fig. 13.** Relative effect on the L*a*b* metric ΔE* of constant perceptual changes in value only, hue only, or chroma only as a function of original color for the primaries C,M,Y and secondaries R,G,B.

XL300 printer. The throughput goal was specified at less than two minutes for a high-density plot on office paper. The throughput for the HP PaintJet XL300 printer at equivalent density is three minutes per page. To meet this goal required a system approach involving the ink, print cartridge, media, and product. However, this section will focus mainly on changes to the ink.

To achieve the throughput goals, the color inks had to be designed for faster penetration into the paper to avoid bleeding or mixing of colors between adjacent drops. The penetration is usually driven by capillary pressure, although in some papers penetration is controlled by diffusion. The classical Lucas-Washburn[9] model is used to first order to describe the water transport in the pore system of the paper:

$$L = \left(\frac{r\sigma\cos\theta}{2\eta}\right)^{1/2} t^{1/2}$$

where L is the penetration distance after time t, r is the pore radius, σ is surface tension, θ is the contact angle, and η is viscosity.

However, this equation does not take into account the dynamic nature of capillary pressure (surface tension and contact angle) or of pore radius which changes because of swelling of the paper fibers upon absorption of water. Nonetheless, it does provide an important piece of information: that faster penetration can be achieved by reducing the contact angle* (increase wettability) between the ink and the paper surface as well as by reducing the viscosity of the fluid.

Most paper surfaces are hydrophobic (they repel water). Thus, surface-active agents (surfactants or cosolvents) were added to improve the wettability of the ink to the paper. Reducing the wetting delay time allows faster penetration into the paper. However, it was later discovered that an adverse consequence of faster penetration is severe paper curl on high-density color plots. It was subsequently determined to be caused by interaction of the printer's heater and the ink. Initially, the issue of paper curl was addressed mainly by the printer design group because significant changes to the inks at this phase of the product cycle was viewed as risky. When the plausible printer fixes were unsuccessful in eliminating paper curl, the inks became involved in the solution.

Knowing that paper curl results from stresses caused by differential shrinkage (from water absorption and subsequent evaporation) of paper fibers between the wet printed side and the undisturbed fibers on the back side, the ink strategy for fixing curl focused on replacement of the water in the ink with alternate additives or cosolvents. Soon it was learned that compounds with a particular type of attraction with the paper fiber were most effective. The higher the concentration of organic additives, the lower the amount of paper curl.

However, the amount of organics that could be added was constrained by the performance on transparency film. These constraints, especially at high temperature and high humidity, were the amount of bleed or mixing between adjacent drops and film blocking. Therefore, an ideal compound was not only effective but more efficient in controlling paper curl. However, even with the best anticurl substance, an acceptable trade-off between paper curl and transparency film performance required modifications to the film coating.

In addition to the paper curl issue, the use of surface active agents to lower surface tension and increase wettability created another issue known as puddling (see Fig. 10). These puddles are formed by overshoot of the ink meniscus in the print cartridge chamber during drop firing. As the puddles accumulate on the nozzle plate, they interfere with drop ejection, leading to misdirected or missing drops. Print cartridge architectures with increased damping combined with inks containing special polymers to reduce puddling were incorporated for reliable printing in high-quality mode (2-kHz firing rate).

## Dot Spread

Low ink cost per copy is increasingly becoming an important competitive advantage. The HP DeskJet 1200C goal was less than U.S. $0.10 per copy at 15% density. To achieve this goal

* See page NO TAG for the definition of contact angle.

required a print cartridge drop volume range half that of previous HP printers with 300 dots/inch (dpi) resolution (about 120-μm dot diameter). To attain the same dot size for 300 dpi but at half the typical drop volume required a significant change in ink properties. It turned out that, in addition to providing improved bleed performance on paper as mentioned earlier, surface-active agents provide an added benefit. In a given print cartridge architecture, an ink containing a surface-active agent produces a larger dot than an ink with no surface-active agent. The greater lateral spreading of these drops is a direct result of greater wettability of the ink to the paper fibers. A negative side effect is a slight loss in text edge acuity on some papers.

**Acknowledgments**

A project of this breadth and complexity had many contributors. The success of this project was mainly because of the great team effort exhibited by the group. We would like to thank the DeskJet 1200C printer team and the inkjet R&D and production teams for their dedication and support. We would like to acknowledge our management team for providing a creative, productive, and supportive environment. We would also like to acknowledge the members of the QFD and seam teams for a job well done. Special thanks to Chuck Hutchison, Dave Vasti, Dale Frank, and their groups for providing the support to build and test the print cartridges. Finally, thanks to John Stoffel, Loren Johnson, Mark Hickman, John Rich, Corinna Hall, Frank Drogo, Michele Shepard, Don Bergstedt, Lance Cleveland, and John Moffit.

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