Laser-Comparable Inkjet Text Printing

The HP DeskJet 1200C printer achieves laser quality by means of pigmented black ink and precise, mode dependent control of drop volume. Contributing to laser printing speed are an intelligent print mode forecaster, a large memory capacity, heated drying, improved media handling, a larger printhead, and a high firing rate made possible by careful attention to refill dynamics.

by Jaime H. Bohórquez, Brian P. Canfield, Kenneth J. Courian, Frank Drogo, Corrina A.E. Hall, Clayton L. Holstun, Aneesa R. Scandalis, and Michele E. Shepard

The mission of the HP Deskjet 1200C print cartridge and product development team was to deliver text quality and speed that meets the expectations of the office printer market. The office standard for text printing has been set by the HP LaserJet series of printers. To be a general-purpose office printer, a printer must provide text quality, output speed and connectivity comparable to LaserJet printers, along with LaserJet language compatibility. This article discusses how two of those objectives—text quality and speed—were achieved. The article on page NO TAG discusses the compatibility and connectivity solutions.

Text Quality Fundamentals

Several attributes define the text quality of a printed page, regardless of whether its source is a serial impact dot matrix printer, a thermal inkjet printer, a laser printer, or a printing press. The fundamental characteristics that define print quality are:

- Character hue and darkness
- Edge smoothness or roughness
- Character edge contrast
- Presence of artifacts
- Uniformity of area fills.

Character darkness, or optical density, is a measure of the blackness (lack of lightness) of the printed image. In general, most surveys indicate that customers prefer darker characters over lighter characters. Hue refers to the tone of the color used to print the character. Even black characters can be slightly cold (bluish) or warm (brownish). The ability of the eye to distinguish small differences in hue diminishes at high optical densities.

In text printing, edge roughness is determined by several factors including printer resolution (often measured in dots per inch), dot placement accuracy, rendering algorithms, and the interactions between the colorant (e.g., the laser toner or the inkjet ink) and the paper. In general, higher resolutions produce smoother edges because they allow smaller changes in dot placement and the individual picture elements (pixels) correspond to smaller areas. Fig. 1 illustrates the improvement obtained by increasing resolution from 150 to 300 dpi with a binary printer. Firmware and hardware-based algorithms can be used to enhance edge smoothness further by judiciously placing dots between the basic grid points or by changing the dot size.

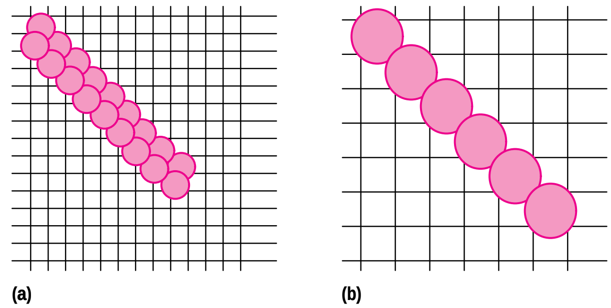

Fig. 1. Comparison of edge smoothness at two resolutions. (a) Line drawn at 300 dpi resolution. (b) Line drawn at 150 dpi resolution.

The contrast between the printed character and the background paper is affected by the optical density of the ink and toner, the color and brightness of the paper, and the edge transition sharpness of the printed area. For high-quality, high-contrast printing, the dark printed zones must transition sharply into unprinted zones. If the printed area slowly fades into unprinted paper, the characters appear fuzzy and soft.

Unwanted artifacts, such as inkjet spray and laser background scatter, can also make characters appear fuzzy. Inkjet spray is the presence of small, unwanted dots near the printed zones. In laser printing a similar phenomenon, called scatter, sometimes occurs, leaving undesirable toner particles near the printed zones.

Solid area fills, used for graphics and large font rendition, should be uniform and dark. Nonuniformity of area fills can occur in a variety of ways, such as the mottle (light and dark areas) caused by the uneven penetration of an inkjet ink, the uneven gloss seen on many laser prints, banding, and density gradients.

Text Speed

Typical inkjet printers have text throughput ratings of one to three pages per minute. Laser print engines deliver four pages per minute in their low-end designs, 8 to 10 pages per minute in the midrange designs, and as much as 16 to 20 pages per minute in the relatively expensive shared network devices. Our market target matched the low-end to midrange lasers, so we made our minimum throughput goal for

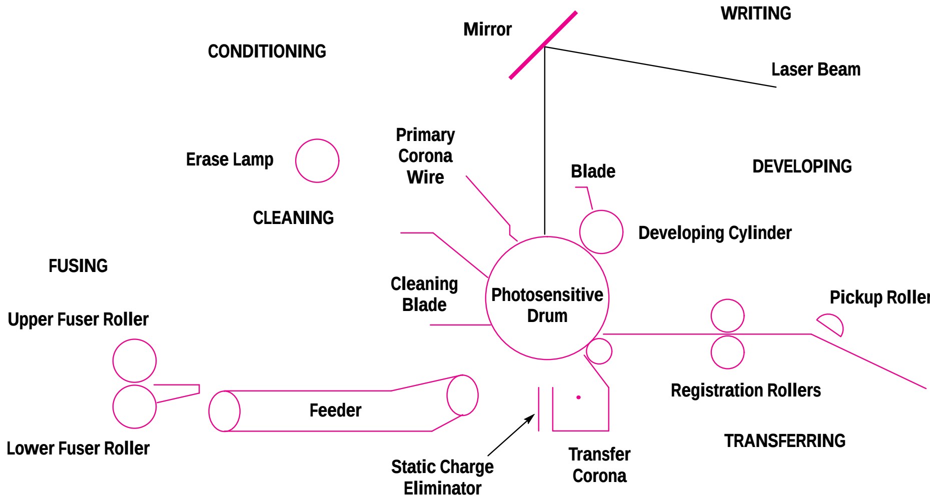

Fig. 2. HP LaserJet IIIP electrophotographic print engine.

high-quality text a true four pages per minute as measured by industry analysts' latest printer text benchmarks.

Comparing the Technologies

HP LaserJet printers and HP thermal inkjet printers use significantly different printing technologies. Each process has inherent advantages and engineering challenges. Fig. 2 illustrates the electrophotographic printing process and Fig. 3 shows the inkjet drop generation process. The basics of the thermal inkjet printing engine are described in "An Inside View of the Drop Generation Process" on page 11.

Laser printing has several high-value attributes. It provides a high degree of media independence, it is a high-speed page printing process, it is a dry process that doesn't wet the paper so physical distortions of the media are minimized, and it produces durable print unaffected by water and highlighters. Excellent character edge smoothness is achieved by the fusing process and the small toner particle size. Dot size can be adjusted, and customers perceive the process to be highly reliable.

Thermal inkjet printing also has attributes that have been engineered to deliver customer value. It uses a low-cost print engine (the disposable inkjet cartridge). Printer mechanism simplicity is possible for low-end designs. It can do single-pass full-color printing and has fewer limitations in producing graphic area fills. The requirements for producing good inkjet text quality and speed can be summarized as follows:

- Pick a high resolution (300 dpi minimum)
- Eject uniform drops of the correct size, shape, and velocity at a high frequency
- Place the dots precisely on the paper
- Control the ink-media interaction
- Make the printer mechanism fast and intelligent.

The rest of this article will describe how the design teams achieved these goals during the Deskjet 1200C printer and black ink cartridge development.

Controlling Drop Size and Shape

To provide text and images that are as sharp and crisp as laser output, the size, shape, and consistency of the drops must be controlled. Since the drops are the result of a nucleated bubble, nucleation must be repeatable from firing to firing. One way to ensure this is to use very narrow heating pulse widths. By transferring energy to a thin layer of ink over the heating resistor rapidly, defects on the resistor surface that trap gas do not have a chance to alter the nucleation, so each drop looks like the others.[1]

The print cartridge also needs to be fired very fast (8 kHz) so that the printer will have laser-comparable throughput. It is easy to make a print cartridge refill this fast, but the trick

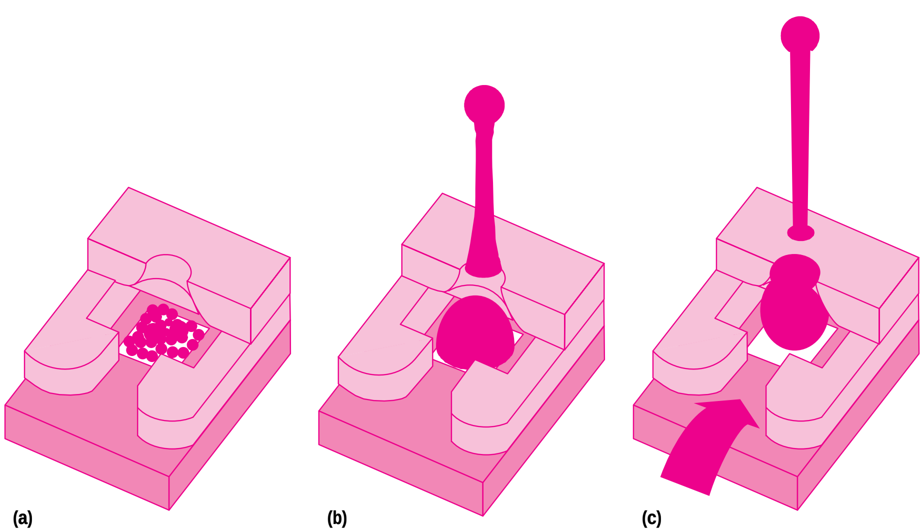

Fig. 3. Inkjet print engine drop ejection process. (a) Nucleation. (b) Bubble growth and drop ejection. (c) Refill.

An Inside View of the Drop Generation Process

The bulk of the print cartridge for the HP DeskJet 1200C printer is a reservoir—a flexible bag—of ink that is connected to the printhead through a passage called the snout. In the printhead there are many small holes, or orifices, through which ink flows to generate the dots on the paper. Unlike most containers that have a set of holes in the bottom, this one will not leak. The ink is held up by a spring in the bag which exerts a force outward on the walls of the bag producing a backpressure that prevents the ink from drooling. The ink would be pulled up into the main reservoir away from the printhead if it were not for opposing capillary forces from the exit orifices, which pull back on the ink, holding it in static equilibrium.

Imagine yourself inside one of the drop generators that exists above each exit orifice. Below you is the hole, which does not drool, thanks to the gentle balance of spring-bag and capillary forces. You are surrounded by a square chamber that has a refill channel cut into one wall, providing access to the reservoir of ink and restricting the flow enough to stabilize the refill process. The ceiling is covered by a flat, square, thin-film resistor, which is connected through an electrical circuit to power circuitry in the printer.

The drop ejection process is shown in Fig. 3 on page 10. It begins suddenly as the ceiling heats up hundreds of degrees Celsius per microsecond. Because the temperature rise is so fast, only a very thin layer of the ink that is in contact with the resistor heats up with it. As that fluid reaches its boiling temperature any small air bubble trapped on the surface will start to grow. However, around the bubble the ink is still heating. When it reaches its superheat temperature limit, the ink can no longer exist in the liquid state because of thermodynamic instability. The ink rapidly vaporizes, creating a pressure wave that acts like a piston to fire the slug of ink in the chamber (with you entrained within it) out of the chamber and through the exit orifice. As the ink slug leaves, air rushes in around it, filling the space that had been occupied by the ink. The air rushes around the ink droplet as the tail breaks off and the ink remaining in the chamber reforms to produce a meniscus, or an air-to-ink interface, which connects by surface tension to the smooth inner walls of the exit orifice.

The meniscus shape is distorted by many factors: the shape of the vaporized ink piston, the state of the fluid's velocity field immediately before vaporization, and the imbalances in the wetting of the exit orifice by the ink. However confused this surface may be, the capillary forces still dominate the force balance, causing the meniscus to climb up the exit orifice, drawing a new charge of ink into the chamber behind it. That charge is pulled against the resistance of the spring bag and the choked refill channel. The inertia of this charge causes the ink to bulge out the exit orifice, which starts to pull back on the overshooting meniscus as soon as it passes the exit plane. Eventually the ink flow is reversed by this force, causing the bulge of ink to return to the drop generation chamber. Over a few cycles this bouncing meniscus damps out and returns to equilibrium. The system is intentionally underdamped to increase the speed with which the ink first crosses the equilibrium plane.

The point at which a new firing cycle is initiated in this refill process has a lot to do with the shape and consistency of the droplets produced (see Fig. 1). If the next firing is well after the meniscus bouncing damps out, the next droplet will be as well-formed as the first. Unfortunately, the repetition frequency that can be achieved in this way is usually too slow to meet the print speed goals. If firing is attempted before the first meniscus equilibrium crossing, then the drops will be fast and spear-shaped, leading to poor print quality. If the next firing occurs near the largest excursion of the refill charge outside of the orifice, the drops will be slow and dumbbell-shaped, again leading to poor print quality. Between these two points well-formed drops can be produced that do produce optimum print quality. This is the earliest point in the refill process that well-formed drops can be produced.

While the new charge is being prepared for the next shot, the last drop travels across the printhead-to-media gap and hits the media. If the drop is well-formed, both the head and the tail of the drop will hit the media in the same spot. On the media a new set of processes take over. The media must first begin to wet, overcoming its resistance to penetration of the ink into it. This happens quickly with HP inks, and the processes of ink penetrating into the media, of ink wicking along fibers on the surface of the media, and of the ink's volatile components evaporating off begin in parallel. The rate at which each of these processes happens relative to the others affects the print quality. More detail on these processes can be obtained from the accompanying article and the article on page NO TAG.

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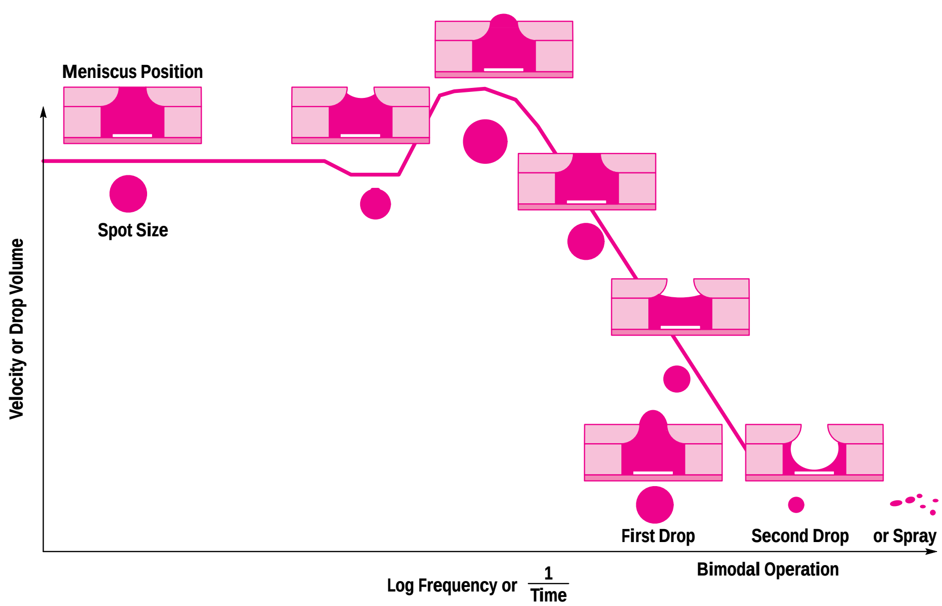

Fig. 1. Meniscus dynamics and drop volume as a function of drop frequency.

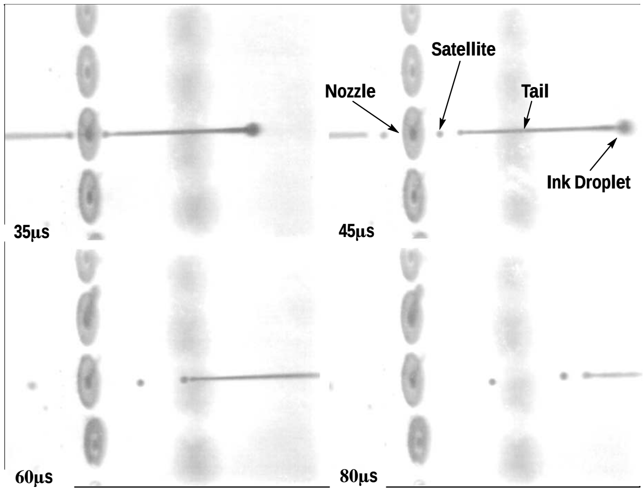

Fig. 4. Tail of ink droplet with satellites at different times after drop ejection.

is to do it and not have the ink rush in with such momentum that it overflows the orifice and spills out onto the top plate. This effect, called puddling, will pull the following drops in the direction of the puddle. This results in the drop landing off-target, and can cause it to break up into spray drops. The dimensions of the pipe refilling the chamber are adjusted to achieve the right balance between refill speed and fluidic damping. Drops can also land off-target if all of the parts of the system (resistor, barrier, and orifice) are not well-aligned.

One characteristic of the pigmented ink used in the DeskJet 1200C black print cartridge is that the tail of the drop tends to stay together much longer than with the dye-based inks used in previous HP inkjet print cartridges. This is an advantage in that it does not break up into random, uncontrollable spray droplets. It is also a disadvantage because anything that disturbs the symmetric nature of the tail may cause it to form one or two large, consistent spray droplets we call satellites (see Fig. 4).

Another fundamental quantity necessary for print cartridge development and tuning is the size of the drop, or the drop volume. There is a design volume, which is defined as the drop volume that a print cartridge design would produce under controlled conditions in a drop volume tester. Testing conditions are kept constant and repeated for all print cartridges so that comparisons can be made. However, the realities of a user plot can vary from that of the laboratory model. For instance, the printhead temperature will vary with the density of drops being fired, and this in turn affects the drop volume. Therefore, the *system drop volume* was conceived as a more meaningful measure of drop size. It correlates with the drop volume expected under actual printer conditions and is determined as follows.

Since the print cartridge is a manufactured product made in large quantities, the randomness of nature ensures that the drop volume will vary by some amount from print cartridge to print cartridge. This variation must be constrained within a certain range for the customer to get consistent results in all environmental conditions, on different media, and using different print modes. A lower drop volume limit is defined by user approval of, among other things, light areas in text, and an upper limit is defined by excessive color bleed on transparency film in high humidity. To determine the system drop volume limits, print cartridges were operated at a number of different setpoints, using all of the printer's print modes (high-quality, normal, fast). A wide selection of media were used including those with low dot gain such as bond papers, glossy paper, and transparency film, and those with high dot gain such as HP CX JetSeries paper. The printing was done in a range of environmental conditions with both text and graphics files. A panel of users picked the minimum and maximum acceptable system drop volumes.

Drop Volume Distribution

Once the acceptable drop volume range has been determined, all the factors that contribute to the production of that drop can be analyzed to ensure that all the print cartridges that are manufactured always produce drop volumes that fall inside the range. The drop volume distribution is composed of print cartridge manufacturing variations, environmental variables, and changes caused by the print cartridge itself.

The manufacturing variations include obvious factors such as the size of the orifice and the size of the resistor, both of which will vary within the specified tolerance limits. Drop volume can also be affected by other, more subtle variations. Among these is the change in drop volume resulting from a change in the frequency response of the print cartridge caused by variations in the size of the refill channel.

Environmental factors encompass everything external to the print cartridge. Printer-supplied energy, ambient temperature, and the temperature inside the printer all can conspire to change the print cartridge's drop volume.

The print cartridge itself adds the largest contributions to the budget. As ink is used, the print cartridge's back pressure will trend upward, which will reduce drop volume. Repeated firings can alter the resistor's surface which in turn can effect the delivered volume. The largest contribution by far is the increase in drop volume as the temperature of the printhead rises during drop firing—an effect called thermal inkjet heating.

A Monte Carlo analysis of all of these factors yields a distribution of expected drop volumes (Fig. 5). The low end of the range was set high enough to fill dark areas completely. Then, when the high end of the range exceeded the allowable limit, each of the factors was examined to find a way to reduce the budget. Tightening manufacturing tolerances produced small budget reductions, but had very large cost consequences. The environment was deemed to be out of

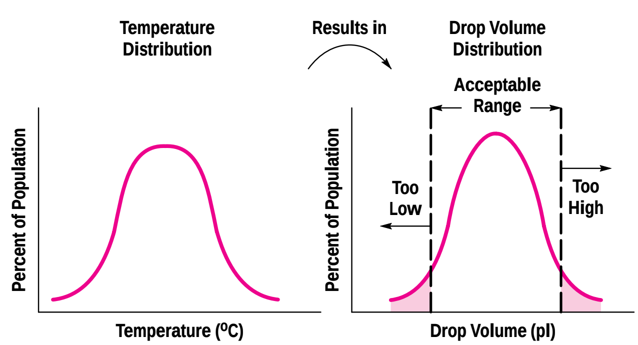

Fig. 5. Printhead temperature is the largest contributor to inkjet drop volume variations.

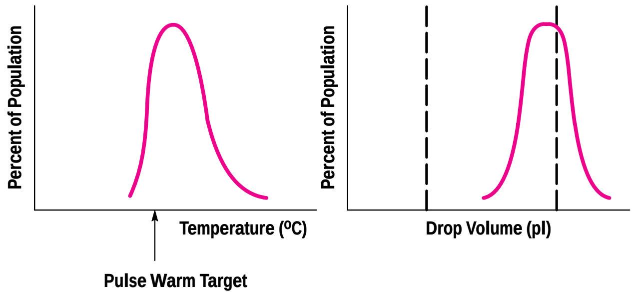

Fig. 6. Prewarming the printhead before printing truncates the temperature distribution and shifts and narrows the drop volume distribution.

the print cartridge's control. However, controlling the printhead temperature through the use of thermal inkjet heating proved feasible.

With all of the built-in heaters in the form of firing resistors, the printhead has plenty of warming capacity. A scheme of having the printer send energy pulses to the print cartridge to warm up the printhead to some initial temperature before printing was devised. The pulses have enough energy to warm the printhead, but not enough to fire a drop of ink. By warming every print cartridge to a given temperature above ambient before printing, the lower portion of the temperature distribution input is effectively truncated, and thus the drop volume distribution is shifted (Fig. 6). The higher the initial temperature to which the printhead is warmed, the smaller is the contribution of the temperature to the drop volume budget. Because the volume distribution is narrowed, the nominal value of the drop volume can be lowered while still keeping the tails of the distribution within the desired limits (Fig. 7).

The drop volume was selected primarily so that text and figures would always be completely closed (with no white space showing) when two drops are printed in 600-by-300-dpi pixel locations. The printer also has a faster printing mode in which the carriage is scanned twice as fast, but the printer only puts down one drop in each 300-dpi pixel location. The ability to warm the print cartridge to differing temperatures before to printing allowed the drop volume to be customized for each print mode, thereby putting down just the right amount of ink to get the job done. By setting a higher warming temperature for the fast mode, a larger drop is produced that more nearly fills in all of the space.

Black Ink Design for Media Independence

Once the print cartridge and printer mechanism have done their job and delivered a well-formed, well-placed drop of ink on the paper, it's up to the ink to set the proper image on the paper. Bares[2] has described many of the physiochemical differences in office papers and some of the ink design issues caused by these differences, such as achieving uniform optical density and dot shape.

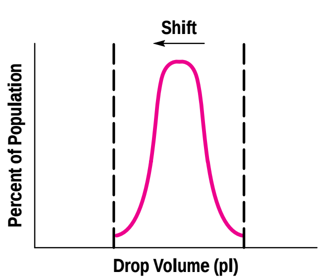

Fig. 7. Lowering the nominal drop volume shifts the narrowed drop volume distribution downward so that it falls within the limits.

The ink is responsible for the printed image's optical density. In the past, poor ink-media interactions have produced print quality that did not match laser quality on many types of commonly available office papers because of low optical density and feathering (wicking along paper fibers). One of the ink development chemists' primary design goals for the DeskJet 1200C was to produce a black ink that gives uniformly good performance over as many office papers as possible. This translates to an ink that maintains optical density and uniform dot size on all paper types and does not feather or wick.

The DeskJet 1200C black ink vehicle is designed to yield excellent text quality. To provide good text edge acuity and high optical density, the ink is constructed so that a drop of ink landing on the substrate medium maintains a hemispherical geometry until the vehicle has been absorbed into the medium. The ink is a pigmented type, which gives better edge acuity than dye-based inks. To further reduce feathering or wicking of the ink along paper fibers, the vehicle formulation was refined until the goal was met.

In general, text print quality is improved with the residence time of the hemispherical drop on the substrate. Although it is tempting to increase drop residence time for improved print quality, any increase necessarily increases the ink drying time and therefore decreases printing throughput. A reasonable compromise between text print quality and drying time was achieved by balancing vehicle components. A combination of several polymers and other solvents is used to improve drop firing reproducibility, increase drop residence time, and decrease ink drying time. An additional solvent further improves print cartridge nozzle crusting characteristics.

The wicking of ink dots is determined in a very short period of time, from less than ten to several hundred milliseconds, during the initial stages of penetration. Even in printers with heaters to improve drying time and cockle, feathering is determined primarily by the ink chemistry and physics during this crucial time period. The tendency of ink to penetrate unevenly along fibers or into capillaries produces misshapen characters. The photographs in Fig. 8 illustrate how well the Deskjet 1200C black ink has been able to improve this.

Pigment Dispersion

Pigment dispersions have been extensively used in the paint and commercial printing industries for the lightfast and waterfast qualities they impart to the final coating. In contrast to the use of dye colorants, which are completely dissolved in the ink vehicle resulting in a true solution, the use of pigments requires the dispersion of solid particles of colorant. It is this solid colorant that gives the resulting coating its light fastness; a sacrificial outer layer of colorant protects the remaining core from deterioration by light and oxidants present in the air surrounding the coating.

The incorporation of solid particles in an inkjet ink poses a tremendous challenge in achieving a dispersion stability sufficient to guarantee that settling or separation of pigment

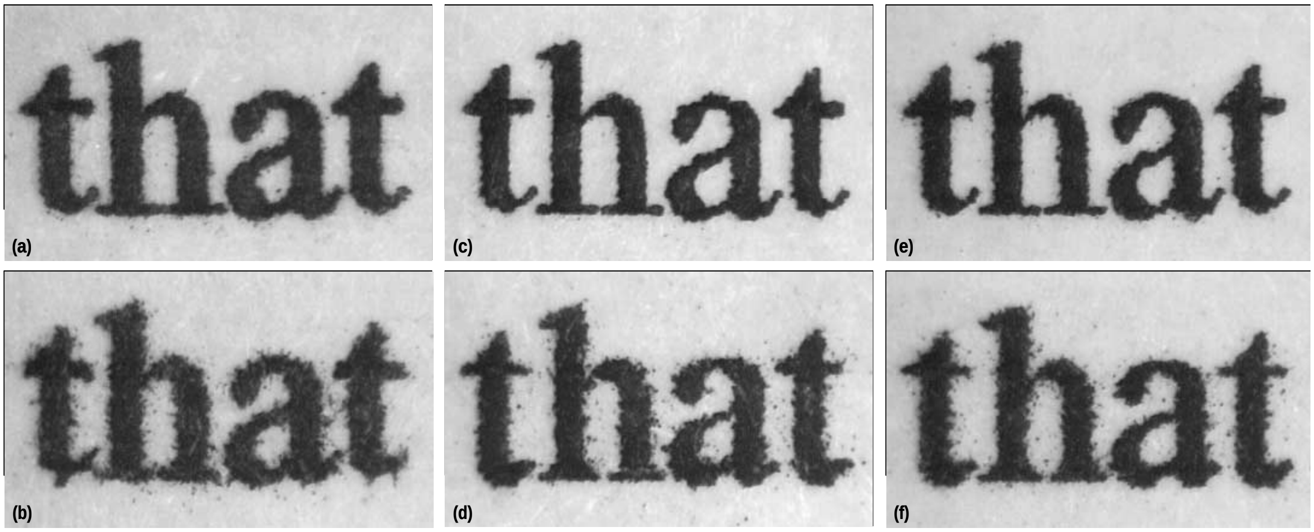

Fig. 8. Photomicrographs showing relative feathering of HP DeskJet 500 and DeskJet 1200C on three papers. (a) DeskJet 1200C on paper A. (b) DeskJet 500 on paper A. (c) DeskJet 1200C on paper B. (d) DeskJet 500 on paper B. (e) DeskJet 1200C on paper C. (f) DeskJet 500 on paper C.

does not occur during a possible print cartridge shelf life of up to two years or upon exposure of the ink to the brutalities of a firing resistor in the interior of the inkjet print cartridge. The stability of the solid colorant particles depends on the ability of the dispersant to adhere to the surface of the pigment, to extend itself into the volume of ink vehicle, and to provide a repulsive environment when the particle is approached by another particle coated with dispersant. Although the exact morphology of a dispersed pigment particle has not been elucidated, the system may be envisioned as a "fuzzy tennis ball," as shown in Fig. 9.

Pigment Selection

Black pigments were initially screened on the basis of the resulting print optical density. In general, "high-jetness" black pigments are all carbon blacks, obtained from the combustion of organic fuels. Three types of processes are used to produce carbon blacks, resulting in two ranges of primary particle sizes. The highest-jetness pigments were chosen for formulation studies.

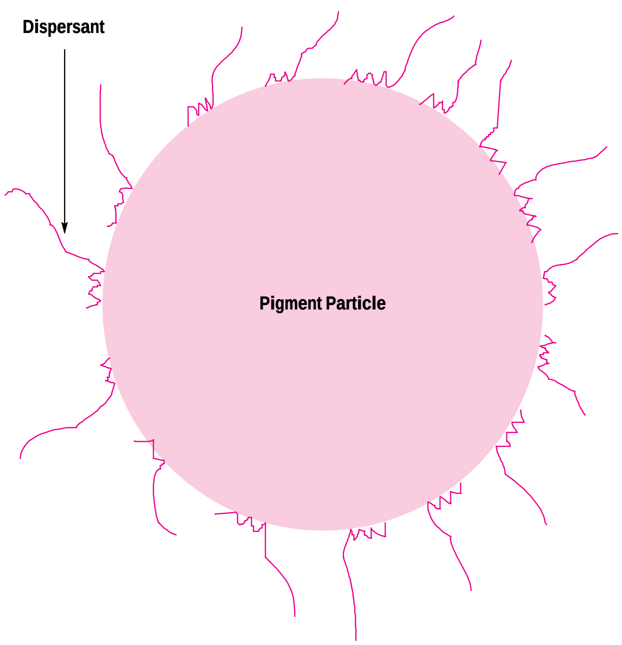

Fig. 9. Dispersed pigment particle.

Once pigment candidates had been identified that yielded high optical density, a screen of surface treatments was pursued. The pigment was selected on the basis of its ability to form a stable dispersion and on its inertness with respect to corrosion of the print cartridge orifice plate, composed of gold-plated nickel. Table I illustrates the uniformity of optical density we have been able to achieve over a range of papers relative to other printer platforms.

Table I
Optical Density Measurements on a Range of Papers

Paper	A	B	C	D	E	F	G	H
HP Deskjet 500	1.1	1.3	1.3	1.3	1.2	1.3	1.1	1.3
HP Deskjet 1200C	1.4	1.4	1.3	1.3	1.3	1.4	1.3	1.3
HP LaserJet III	1.4	1.5	1.4	1.4	1.5	1.4	1.4	1.5

More uniform optical density, tighter dot size control, less feathering, and better edge acuity have combined to make the HP DeskJet 1200C the most paper independent liquid inkjet printer to date. Fig. 10 demonstrates the relative media independence of the HP Deskjet 500, HP Deskjet 1200C, and HP LaserJet IIP printers on a series of papers selected to represent office papers commonly available worldwide.

Laser-Comparable Printing Speed

The speed of any printer is limited by the rate at which the print job is prepared for printing and by the rate at which the print engine can execute the printing operation. The Deskjet 1200C comes with 2M bytes of RAM to speed the download time from the host computer. Its print mode forecaster interprets raster data from either the PCL 5 or the PostScript™ formatter for the print engine in ways that allow the print engine to maximize the throughput while maintaining the high print quality that customers desire.

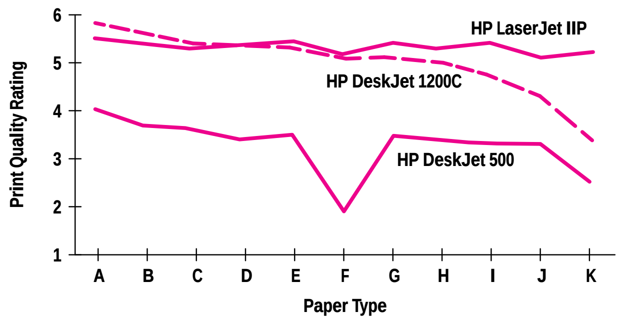

Fig. 10. Print quality of three HP printers for 300-dpi raster text.

The print mode forecaster reads incoming raster data from the language formatter and determines how best to print that data. For example, the forecaster reads ahead enough to decide whether it can print the data in one pass (black only data surrounded by white space) or if the data must be printed in three passes (some color detected or no surrounding white space). In addition, the forecaster detects white space on the page that can be skipped by the print engine. The print engine is notified that these white spaces (on the margins or across the page) can be passed over quickly by sweeping the carriage faster than during printing or by advancing the paper rapidly over the white space. To make these predictions, the forecaster must have enough memory available to store data yet to be printed.

The print engine speed for an inkjet printer is governed by the repetition frequency of each drop generator, the number of drop generators that work in parallel, the rate at which the printer can present the paper to the printhead, and the rate at which ink dries on the paper. Early inkjet printers were mainly limited by the first two factors. It is difficult to increase the stable repetition frequency and still maintain good drop shape, and it is difficult to manufacture large arrays of drop generators working in parallel that all work reliably to produce the optimum print quality. With the DeskJet 1200C, that situation is reversed. The rate at which the media can be moved up to and through the print zone and the rate at which the ink dries on the paper are the limiting factors. Improvements to the paper-moving mechanics reduce the time spent moving the media, and the use of print modes and a heater in the print zone reduce the drying time, increasing the print speed at which high-quality printing can be accomplished.

The production of drops in a thermal inkjet printer involves a complex balance of forces on a very small scale (see "An Inside View of the Drop Generation Process" on page 11). Since surface tension and surface wetting play such dominant roles in the refill process, small variations in these factors can cause chaotic instabilities. The effects of these instabilities can be reduced by controlling the refill speed through fluidic damping and by firing the next vapor bubble piston at a point in the refill process that behaves more consistently than others. The most reliable point of consistency is after a long delay when all the chaotic instabilities have dissipated, but this does not allow the high repetition frequencies desired. The DeskJet 1200C pushes the limits of stability by firing the next drop before the refill from the last has fully damped out. Firing each drop generator before the next charge comes to rest allows a repetition frequency of 8000 Hz. This dynamic point becomes stable only after careful adjustments to the geometry of the fluidic channels that introduce some stability into the chaotic refill process. These channels are constricted in a way that reduces the refill speed and damps the overshoot of the refilling ink front, resulting in a more stable system that is capable of a repetition frequency high enough to remove repetition frequency as a print speed limiting factor.

The effects of this repetition frequency are multiplied by the number of drop generators working in parallel to paint the page. The length of the drop generation array does not come without costs. The more devices the printhead contains in parallel, the higher the probability that a defect can occur in one of them. This risk is reduced by instituting tight control over critical manufacturing processes and by building printhead servicing features into the printer's service station, which help rectify some defects. The printhead size also dictates the length of the print zone in which the printer has to maintain tight control over the media. In the DeskJet 1200C, the media is controlled between a drive roller system and a paper pickup system. The longer the distance between these two, the harder it is to control the media as it is wetted by the drops from the printheads. When the media is first wetted, stresses in the media tend to relax, leading to buckling and cockle. These effects are reduced by the media heating systems and by the control the two media drive rollers exert on the media. The spacing between these two drive rollers allows a printhead array height of one third of an inch, sufficient to print two lines of 12-point text simultaneously in one sweep of the printheads across the page. This helps increase the print speed.

The media handling system of the DeskJet 1200C printer incorporates various mechanical, firmware, and electronic features to increase the printing speed. When the printer receives a print job, the paper is picked by sandwiching it between a platen and rotating rubberized pickwheels. The pickwheels are mounted on a shaft which is driven by a simply mounted stepper motor. The action of the stepper is completely independent of other printer activities. The advantage of this for a multipage document is that the pickwheels can pick a sheet of paper and have it ready and waiting just behind the writing zone while a separate set of rollers ejects the page just printed. A long sheet-feed delay between pages is eliminated. This media handling system can work at full speed or it can be slowed down when the ink density on the page dictates that more drying time (longer time over the heater) is warranted. Customers with low-density output (a page of text) get their pages quickly while those with high-density output (large area fills) still get good print quality without smearing caused by insufficiently dried ink. An additional advantage of moving the paper to just behind the writing zone is that a preheater is located here to precondition the media before it enters the writing zone. The preheater consists of resistive wires embedded in a thin sheet of wear-resistant plastic. The paper is biased against the preheater to provide maximum thermal contact. The effect of the preheater is to dry the paper so that when ink is placed on the paper the heater in the writing zone expends its energy to dry the ink, not the paper. Drying times are cut by 30% by preheating. All this moisture must go somewhere, so a vapor removal system is in place to clear the writing zone of water vapor.

Modifying Office Papers to Improve Inkjet Print Quality

The formulation of paper and the way it is manufactured have an impact on inkjet print quality. Samples of some office papers from three major market regions (North America, Europe, and Asia/Pacific) exhibit variability in black text quality, optical density, color-to-color bleed, color appearance, and mechanical performance. Also observed are changes in the performance of certain paper brands both from sheet to sheet and from ream to ream. This implies that inkjet print quality is not being monitored and controlled during the papermaking process by some manufacturers.

In 1991, Hewlett-Packard created the Office Paper Program to work with the paper industry to improve the inkjet performance of plain paper. Meetings were held with 25 paper manufacturers worldwide to discuss inkjet technology, market growth projections, and print quality issues. A key result of these meetings was a standard-setting document called the Hewlett-Packard Paper Acceptance Criteria for the HP DeskJet 500C Printer.* This document describes minimum print quality specifications for seven key parameters (see Table I) and the corresponding measurement methods. The specifications were set by surveying inkjet printer users in the U.S.A., Europe, and Asia.

The acceptance criteria specifications are being implemented through the Office Paper Program's paper qualification process. After improving inkjet performance (see Fig. 1), paper companies may submit samples for evaluation. These samples must be taken over specified times and at particular paper machine locations as described in the Office Paper Program's paper sampling guidelines. After imaging with black and color test patterns, the paper sample is measured against the criteria for appearance, mechanical performance, and lack of variability. If the paper is acceptable, it is publicized to existing and potential HP printer customers as a multipurpose office paper qualified for use in all plain paper inkjet products.

As of November 1993, four papers have been qualified worldwide.

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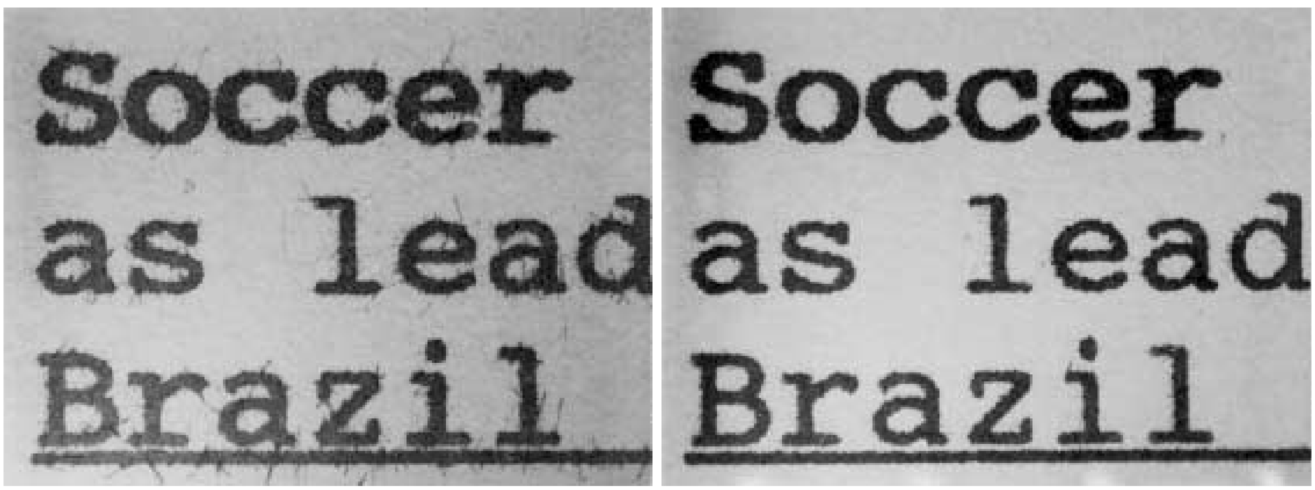

Fig. 1. Samples showing print quality (left) before and (right) after paper improvement.

Other printer features decrease drying time and improve overall print quality. Area fills are more uniform if the heat used to dry them is even over all areas within a printed swath and from swath to swath. To promote this uniformity, the paper is kept in tension during and shortly after printing by the double set of rollers located before and after the writing zone. To further ensure even heating and maximum heat transfer to the paper, a slim piece of sheet metal is pressed against the paper to bias it against the heated writing surface.

While the paper is in the writing zone, the printer performs "smart" printing to increase throughput. The media is quickly advanced over the white space at the top of the page to the first data to be printed. Between sweeps of the print cartridge carriage, the media is advanced to the next data to be printed at the same time as the carriage reverses direction to print the next swath. The length of each sweep is controlled by the forecaster to be only as long as the local margins dictate. When the drop generators need to be fired periodically into a spittoon to keep them working reliably, no time is lost because that action is smoothly integrated into the carriage sweep motion.

All of the techniques described above, which allow four pages per minute in the highest-quality mode, are further exploited in the highest-speed mode by cutting the number of drops hitting the page in half. The high-quality mode prints at 600-by-300-dpi resolution, which allows the application of HP Resolution Enhancement technology rules to enhance the edge quality of the text characters. The fast mode prints at 300-by-300-dpi resolution, which allows printing each swath at twice the speed. However, since the drop volume for the high-quality mode is tuned for that mode, if the same drop volume were used for the fast mode the text would be too light because of more white space between drops. This problem is reduced by dynamically changing the

Table I
Hewlett-Packard Office Paper Program Minimum Print Quality Specifications and Test Methods

Parameter	Specification	Text	Method	Reference
Black				
text	≤ wick #4	2.1.2	visual	figure 1.4
optical density	OD min ≥ 1.2 %D < 8	2.2.1	measurement	
mottling	none allowed	2.2.2.1	visual	figure 1.5
cascading	none allowed	2.2.2.2	visual	figure 1.6
bronzing	none allowed	2.2.2.3	visual	
Color-to-Color Bleed				
black to yellow	until 4/94 < bleed #5	3.1.2	visual	figure 2.3
Color Appearance				TAPPI T524-om-86 & figures
red	score > 0	3.2.4.1	measurement	figure 5.1-5.2
yellow	score > 0	3.2.4.1	measurement	figure 6.1-6.2
green	score > 0	3.2.4.1	measurement	figure 7.1-7.2
cyan	score > 0	3.2.4.1	measurement	figure 8.1-8.2
blue	score > 0	3.2.4.1	measurement	figure 9.1-9.2
magenta	score > 0	3.2.4.1	measurement	figure 10.1-10.2
composite black	OD ≥ 0.75	3.2.2	measurement	
Mechanical Performance				
sheet feed		4.1	operational	
missed feeds*	≤ 2 failures in 1000			
multifeeds*	≤ 2 failures in 1000			
jams*	≤ 1 failure in 1000			
*total combined	≤ 2 failures in 1000			
skew	≤ 0.06 mm/cm	4.2	operational	figure 12
wet cockle	≤ 1 failure in 1000	4.3	operational	figure 12
Black Waterfastness	ΔOD ≤ 0.30	5.1	measurement	figure 13
Black Highlighter Smear	ΔOD ≤ 0.20	5.2	measurement	figure 14
Lightfastness				figure 15
black	ΔE* ≤ 10	5.3	measurement	TAPPI T524-om-86
red	ΔE* ≤ 60	5.3	measurement	TAPPI T524-om-86
green	ΔE* ≤ 50	5.3	measurement	TAPPI T524-om-86
blue	ΔE* ≤ 70	5.3	measurement	TAPPI T524-om-86
cyan	ΔE* ≤ 60	5.3	measurement	TAPPI T524-om-86
yellow	ΔE* ≤ 30	5.3	measurement	TAPPI T524-om-86
magenta	ΔE* ≤ 85	5.3	measurement	TAPPI T524-om-86
composite black	ΔE* ≤ 50	5.3	measurement	TAPPI T524-om-86

Note: All references to text and figures in this table pertain to the Hewlett-Packard Acceptance Criteria for the HP DeskJet 500C Printer.

drop volume between these two print modes. The drop volume is increased for the fast mode by increasing the control temperature used in the printhead temperature control process. The higher the printhead temperature, the larger the drops become. The resulting increase in dot size on the paper provides good print quality at six pages per minute with the same printhead that can do four pages per minute in the highest-quality mode.

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