# Ink Jet Printing with Large Pagewide Arrays: Issues and Challenges

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## Abstract

The scale of the high-speed pagewide printing problem presents technical challenges which are explored for drop-on-demand ink-jet. The solutions developed for desktop serial printers are generally inadequate for pagewide printers, and technology advances in ink, media drying, and printhead servicing, and halftone printing are required to produce an ultra high-speed printer meeting reliability and quality levels achievable on today's desktop. The printer envisioned in this study has no place in the office.

## Introduction

Pagewide ink jet printers capable of more than 100 A4/A3 pages per minute could provide a cost, speed, and quality solution for short-run digital color printing currently unmet by other technologies. Some of the advanced technologies required to build such devices have been demonstrated in the laboratory, and a few pagewide drop-on-demand ink jet products appeared briefly without commercial success more than a decade ago.

While pagewide ink jet technology continues to stir desire among those who would be users of it, lack of solutions in the marketplace today attest to the existence of basic technical issues which present formidable design challenges. These issues primarily involve reliability, power and data requirements, and producing a dry, cockle-free sheet.

## Serial Printers

In a desktop ink-jet printer, a carriage holding printheads for three or four primary colors scans across a sheet of paper printing a swath of pixels, the paper is advanced, and the scan is repeated. This familiar arrangement is shown schematically in Figure 1. This "serial printer" architecture offers a number of attractive features, particularly for implementation in low-cost products:

- Data can be sent a swath at a time, reducing memory and processing requirements in both host and printer compared with processing (and storing) a full page before printing.
- The printer can pause for a slow or multitasking host.
- Partial swath advances allow multiple passes of the printheads over the same pixels. This permits tiling algorithms to interleave dots printed from different orifices on the same scan line. Tiling print modes are so effective in masking paper advance errors and missing dots from non-operating orifices that tiling in some form is used in virtually all serial ink jet printers sold today.
- Multiple passes limit the rate of ink deposition in area-fills and between adjoining pixels to minimize cockle and color bleed.
- Multiple passes can be used in color halftoning technologies to produce colors at different levels of saturation.
- The printheads have relatively few drop generators. This minimizes the size and cost of the printer, pixel processing rates, and power while offering high reliability that each generator will eject a drop on-demand.

The disadvantage of a serial printer is throughput, and this is directly related to the small swath printed with each printhead pass. Even without partial swath advance and tiling, the printheads must scan many times to print a full page. The carriage must accelerate and decelerate at the end of each swath, and the media cannot be advanced until the swath has been printed. The system-level design of a serial printer attempts to maximize the amount of time the printheads are actually scanning and printing over the page. This is done using algorithms to detect and skip over white space, performing I/O while printing, and simutaneous mechanical operations such as media advance and carriage turn-around.

A subtle problem limiting the size of the print swath in a serial printer is the need to keep the paper flat while inking. This is particularly important for water-based inks, because a phenomenon called "wet-cockle" can cause paper to deform out of the plane to bridge the short air gap (typically 1 mm) to the printhead's orifice plate. To control wet cockle, the paper path produces stresses in the sheet to keep it in place. Wrapping the sheet on a drum offers some benefit, but printheads typically have planar orifice plates, and print quality is affected by different flight distances due to drum curvature. With current technologies, paper flatness considerations limit the practical maximum swath height for a scanning printhead to about 1 inch. This limits the number of orifices on the printhead and the possible throughput it can produce.

A simple but fundamental measure of throughput is the maximum area-fill rate

$$A = N \times F / R^2 \qquad (1)$$

where $A$ is the area fill rate (inches$^2$/sec), $N$ the number of printhead orifices, $F$ the drop rate (Hz), and $R$ is the printing resolution (dpi).

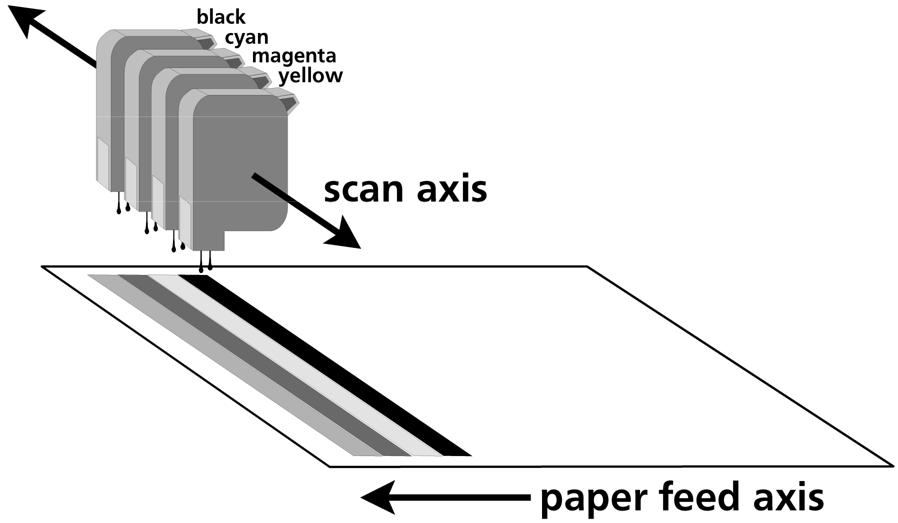


*Figure 1.*

Equation (1) has been called the "tyranny of resolution." It extracts a high price from technology to offer high throughput at high resolution. For example, doubling resolution from 300 to 600dpi reduces throughput by a factor of four. Since customers expect throughput will not be sacrificed for higher resolution, particularly in the A/A4 format, technology advances must deliver a four-fold increase in the product of $N$ and $F$ just to keep even. In general, this means more orifices must be operated with the same or fewer electrical interconnects to the printer and drop generators must operate at higher frequency.

Table 1 shows the area-fill rates for three current HP thermal ink jet printheads (black). What is particularly interesting is how the increase in throughput was obtained comparing the DeskJet 1200C (300dpi) to the DeskJet 850C (600dpi): three times the number of orifices and 50% higher drop rates were required.

**Table 1. Area-fill Throughput**

| | Area-fill Rate (in2/sec) | Resolution (dpi) | Orifices | Frequency (KHz) |
|---|---|---|---|---|
| DeskJet 600C | 4.27 | 300 | 48 | 8 |
| DeskJet 1200C | 9.24 | 300 | 104 | 8 |
| DeskJet 850C | 10 | 600 | 300 | 12 |

The demand for higher operating frequencies pushes drop generator performance to physical limits of the technology. At all frequencies, the drop generator must be refilled and the meniscus settled between drop ejections to assure consistent drop volumes. In thermal ink jet ("TIJ"), a minimum bubble lifetime of about 10 microseconds provides a practical frequency limit of 100KHz. In piezo ink jets, mechanical resonances, inertial loading by drop generator components, and drive power are limiting factors at higher frequencies. Another consideration is heat generation, and this increases for all technologies with increases in orifice density, operating frequency, and more complex demultiplexing circuitry. Higher operating temperatures change the fluid properties of the ink to affect ejected drop volume, refill and settling times in the drop generators, and drop breakoff characteristics.

The scanning printhead must make multiple passes to print a full page, and Equation (1) does not consider factors which determine the actual number of pages printed per minute. These factors include print mode (e.g., "draft," "normal," and "best") and media type, fractional swath advance, bi- or unidirectional printing, print carriage turnaround, service station and heater warm-up cycles, paper pick and feed, data transfer from the host, and image data processing.

For a given printing resolution, higher throughput involves a tradeoff between the size of the swath (number of orifices) and drop frequency. The limiting embodiments are a single, very high frequency drop generator for each color (e.g., continuous ink jet printers) and a printhead as wide as the page.

## Pagewide Printers

A pagewide array of drop generators offers the highest performance from a drop-on-demand ink jet printing technology. To maximize throughput, the array prints along the longest direction of the media, printing entire columns of pixels simultaneously.

Figure 2 shows a schematic representation of a pagewide TIJ printhead. A 12-inch wide, 600dpi device similar to Figure 2 with 7200 drop generators was designed, built, and tested in a research collaboration between HP Laboratories and the HP Ink Jet Business Unit in Corvallis, OR.

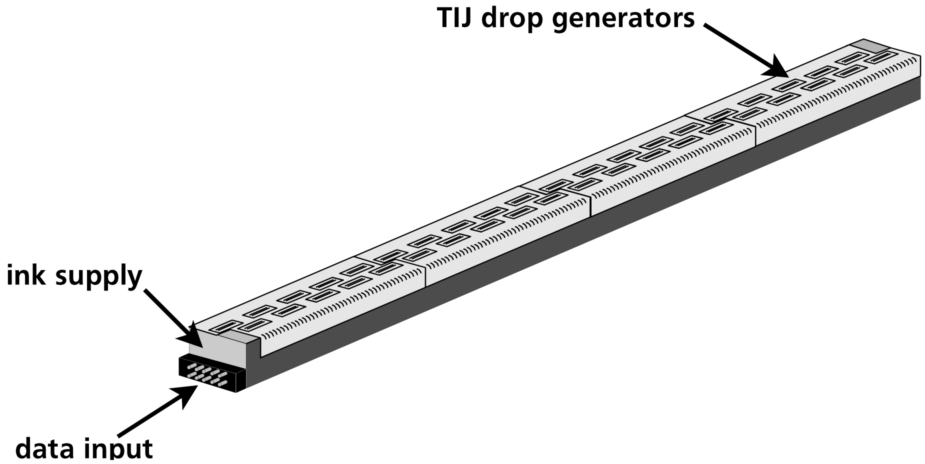


*Figure 2.*

Figure 3 shows a schematic of a four-color pagewide printer based on the printhead of Figure 2. Each color has its own printhead, arranged sequentially so that the recording medium (paper, etc.) is picked, transported under each printhead in a single pass, dried, and stacked.

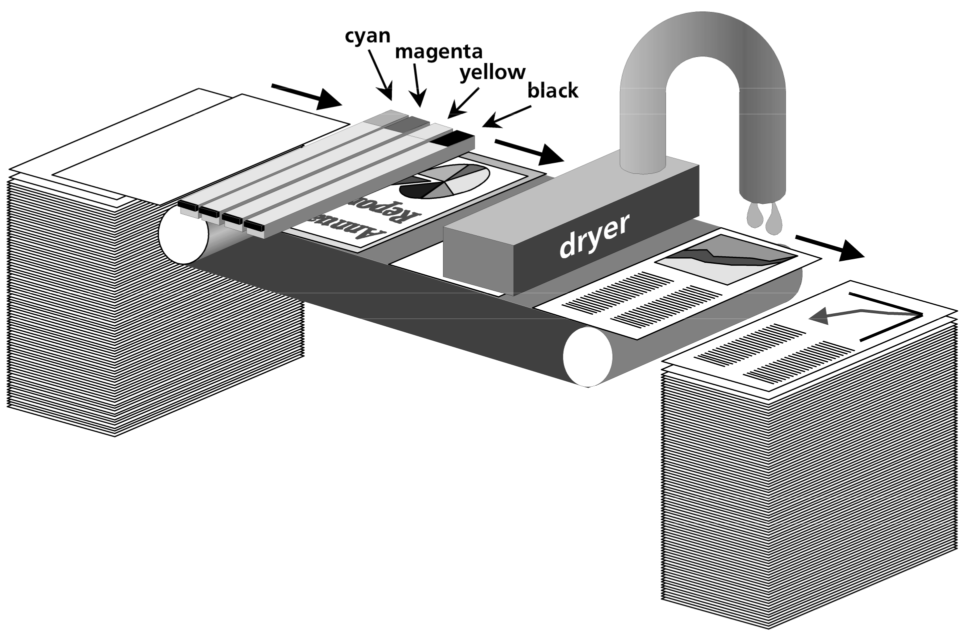


*Figure 3.*

The inputs to the printhead are pixel data, ink, and power. When the number of orifices is larger than about 100, it is impractical from size, cost, and reliability considerations to have a direct electrical interconnection to each drop generator. Active demultiplexing circuitry on the silicon substrate used for the thin-film thermal ink jet heaters achieves a significant reduction in interconnects.[1] For example, the 300 orifices of the DeskJet 850C printhead require only 52 electrical connections. In a printhead with thousands of drop generators, much higher levels of multiplexing or high-speed serial data paths will be required. Ink must be supplied at a well-regulated pressure to produce droplets of constant volume over flow rates from zero to that required to operate all orifices at the maximum frequency. Power must be supplied to the printhead to eject drops and to operate signal-processing circuits. Waste heat must be removed to prevent excessive temperature rise which affects ejected drop volume and dimensional stability of a large printhead.

For a page $W_p$ wide and $H_p$ tall with a print area $W$ by $H$, the number of orifices is

$$N = H \times R \tag{2}$$

The number of ink drops printed per second gives the data transfer rate in bits/second from the controller while the printhead is printing, and this is

$$B = N \times F \tag{3}$$

The average data transfer rate will be lower when the non-printing time between sheets is considered.

The peak volume flow rate for ink delivery for a drop volume of $v_d$ is

$$v_{ink} = B \times v_d \tag{4}$$

The minimum power supplied to the printhead is that required for drop generation. This depends on the technology, for example TIJ or piezo. Additional power is used by the circuitry which decodes multiplexed input signals into drop ejection commands. If individual drops require ejection energy $e_d$, the drop ejection power is

$$P_e = N \times F \times e_d \tag{5}$$

With a sheet-to-sheet separation, $W_{gap}$, as sheets are transported in the printer of Figure 3, the printing throughput of a pagewide printer in pages per second is

$$T = \frac{F/R}{W_p + W_{gap}} \tag{6}$$

Drying the media after printing with liquid inks involves evaporating volatile components from the applied ink. In general, this requires adding sufficient energy to the printed sheet to produce a liquid-to-vapor phase transition of most of the volatile liquids absorbed into the page. In typical office environments, paper contains about 5% - 8% water by weight. Liquid ink ink jet printers typically use inks with high water content, since water is one of the few volatile solvents meeting worldwide environmental and toxicity regulations. Cockle in plain office papers generally occurs when the water content exceeds 20% over a substantial area. A design objective for a media dryer is to reduce water content below 20% in printed regions without removing excessive water from unprinted areas. Even with ink formulations which minimize wet and dry cockle, cockle can occur in the output paper tray in the unprinted areas of a sheet if water vapor diffuses from the underdried printed region of a neighbor.

A phase-change or “solid ink” ink jet does not require a media dryer, since the ink contains little volatile solvent and the ink is immobilized by freezing on the recording media. Some form of finishing, such as a reflow heater or pressure roller, is generally required to produce a smooth, flat inked surface free of “lenslets.” These can refractively scatter light in overhead transparency materials. While the focus of this paper is on printing with water-based liquid inks, the conclusions are applicable to phase-change drop-on-demand pagewide printers with the exception of issues arising from fixing the ink on the recording medium.

Overdrying the sheet causes undesirable changes in paper optical and mechanical properties including browning, shrinkage and embrittlement. Excessive heat may cause color shifts from structural changes in colorant molecules or from precipitation of some ink components at the paper’s surface. With too much energy, sheets could actually be ignited while passing through the dryer.

High-speed serial ink jet printers use a radiant or contact heater in the output paper path. The heater input energy is controlled by the print density of each swath. Even given this localized application of heat and the time available to match heater output to demand, there is a tradeoff between overdrying unprinted space and removing enough water from the printed regions to prevent cockle.

A precise calculation of dryer power involves details of heat transfer, liquid and vapor transport, and the thermal characteristics of the actual recording medium and a specific ink formulation. In order to gain insight into system design issues, a simple analysis will give a useful approximation: assume the ink is 100% water, all the ink is removed from the media by a dryer, and ignore the effects of the temperature rise in the absorbed ink and media during the drying process. From this, the dryer power is

$$P_d = (W \times H \times R^2 \times v_d \times D) \times T \times h_{fg}, \tag{7}$$

where $D$ is the print density and $h_{fg}$ is heat of vaporization of water (J/liter). The term in parentheses is the quantity of ink printed on the page. In case of 100% area-fill by a primary color, $D = 1$. In samples of full-color natural images, CMYK dots were counted and $D$ was found to range between 0.15 - 0.30 for each primary. This makes $D \approx 1$ a practical value to evaluate printing four-color images. The highest logical density, $D = 2$, occurs when the page is printed with 100% area-fill of a secondary color (i.e., red, green, or blue) requiring two drops per pixel. For text documents, $D = 0.04$ - $0.08$ is typical.

For example, consider the following hypothetical design for a pagewide printhead:

- 600dpi;
- A-size paper with 8″ by 10.5″ print area;
- paper feed with 1″ gap between sheets;
- drop generators produce 35pl drops at 12KHz with 3uJ/drop;
- the dryer designed for $D = 1$.

Equations (2) - (7) describe the basic performance characteristics of a pagewide printer. Using the above values, the results are presented in Table 2. Each entry in this table represents a significant engineering challenge to the design of a practical, high-speed device.

**Orifices**

The recording medium passes once under each pagewide printhead. This single-pass constraint eliminates the ability to hide orifice malfunctions and control color bleed using the multi-pass, tiling print modes available to serial printers.

**Table 2. A High-Speed, 600 dpi, A-size Pagewide Printhead**

| Orifices | Bit Rate (bits/sec) | Ink flow (liters/sec) | Power (watts) | Throughput (pages/sec) | Dryer (watts) |
|---|---|---|---|---|---|
| 6300 | 75,600,000 | 0.0027 | 230 | 2.11 (126 ppm) | 4300 |

Pagewide arrays in all technologies, including electrophotographic LED light bars and LCD light valves, are subject to fixed-pattern print quality defects. A single non-operating pixel printer produces a white line across (or down) the page through toned areas. In case groups of pixel printers are affected by systematic factors in pixel generation (i.e., spot size and misdirection), bands of darker or lighter gray tones and visible jags in characters and lines can appear. While these defects can be rendered nearly invisible in multiple-pass printing, there is no simple way to hide these defects in a pagewide printhead.

In single-pass printing, full-density area-fills and boundaries between colors are printed within a fraction of a second. Color bleed reduces edge sharpness and produces undesirable colors at boundaries where two colors meet. Liquid inks for pagewide printers must be formulated to prevent intercolor diffusion, especially at wet boundaries. The ink vehicle should preferentially diffuse into the recording medium, rather than across the surface, so that transport of colorant out of the pixel is minimized. Rapid separation of the colorant from the ink vehicle is required to immobilize the colorant at the point of application. Inks of this type rely upon rapid phase transitions and solubility changes driven by concentration or pH gradients. The formation of bonds between the colorant molecule and cellulose (or constituents of paper coatings) at the paper surface achieves high optical density and waterfastness.

Single-pass printing can print halftone pixels using methods developed for serial printers. In the HP DeskJet 850C series, four levels each of cyan, magenta, and yellow primaries are produced by three passes of a small drop volume printers. This process is called HP's Color Resolution Enhancement technology, or "C-REt." Halftones of each primary are produced by printing one, two, or three drops within the boundary of a single pixel. Three drops produce full saturation. Implementing C-REt in pagewide printers requires three columns of drop generators per color, each producing a small spot. This triples the number of orifices per color, and this introduces issues of reliability and cost. Another method produces variable dot sizes by rapidly ejecting different numbers of small drops from each orifice. This "multidrop" technology requires burst rates an order of magnitude higher than the pixel printing rate to place all droplets within the pixel boundary as the paper moves under the printhead during the process. Control data to the printhead could be encoded as a multi-bit gray-level value for each pixel and decoded into the appropriate number of droplets from a drop generator. This would increase the data transfer rate in Table 2 by a factor of three or four, depending on the number of practical halftone levels.

A service station is provided in ink jet printers to remove ink spray and paper dust from the orifice plate and to recover drop generators which have become clogged or deprimed. In serial printers, the service station is usually located off the paper path at one end of the scan axis where the carriage turns around at the end of a swath. When the printer is idle, the printheads are often capped to minimize loss of volatile ink components and to prevent orifice clogs. A complete service cycle involves wiping the orifice plate and repriming. Repriming can be done by a vacuum pulse, suction, or ejecting droplets into a waste reservoir or porous medium within the printer. In some printers, a means of detecting drop ejection is provided to insure reliable operation. A complete service cycle is often performed automatically at power-on before printing the first page, after printing a specific number of pages or elapsed time, and it can be manually activated using a front-panel pushbutton. The time required is about the same as to print a page. In some scanning printers, wiping the orifice plate can be performed often and with little or no impact on throughput during the turnaround of the carriage over the service station.

Sustained operation is an important part of achieving high throughput in pagewide printers, and runs of hundreds of pages may need to be printed without interruption. Given its large number of orifices compared to a scanning printhead, a pagewide printhead must be very reliable to be practical.

Consider the case where printhead drop generators operate at constant failure rate due to random causes during their useful life. In useful life (and not in "wearout"), it is expected that a service cycle will recover functionality. To explore reliability expectations for a pagewide printhead, start with an assumption based on a 300-orifice scanning printhead: allow only a single detectable and recoverable failure while printing 100 pages. This is a reasonable (but hypothetical) objective for current ink jet technology, since a single service cycle under these circumstances has a negligible effect on document throughput, and many output trays hold 100 sheets or less.

Reliability is the probability of operating a device for a certain interval without failure. If the reliability of an individual drop generator printing $p$ pages is $R(p)$, then for a single failure in $p$ pages for an $N$ orifice printhead,[2] the expectation is

$$N(1-R(p))-1. \tag{8}$$

where the term in parentheses is the failure probability. This gives $R(100) = 0.997$ for $N = 300$. Using $R(100)$ and $N = 6300$ in Equation (8), the number of failures expected while printing 100 pages is 21 for the printhead in Table 2. This result indicates that system-level design changes are needed for pagewide printers to suppress mechanisms producing clogging, paper dust, and depriming. This means drop generator fluidic design must be made more resistant to particles in the ink blocking an orifice or refill inlet and more resistant to trapping or generating bubbles causing deprimes, inks must be more resistant to clogging orifices, and paper handling must suppress dust generation and provide means to remove it. Unless system-level design results in significant increases in drop generator reliability, frequent drop generator testing and servicing will be required.

The failure rate $\lambda$ for individual drop generators is related to reliability by

$$R(p) = \exp(-p\lambda), \tag{9}$$

giving $\lambda$ = 3.385E-05 failures/page for $p$ = 100. Using this value for $\lambda$, and solving for $p$ using Equations (8) and (9), one drop generator failure is expected every 5 pages for $N$ = 6300.

This reliability analysis considers only random failures and ignores systematic effects of sustained operation. Sustained operation is a mix of reliability reducing and enhancing effects: it causes ink spray and paper dust to accumulate on the orifice plate but also helps to clear clogs and gas bubbles from drop generators by moving fresh ink through the printhead.

Whereas a serial printer can move its printheads off the paper path to a service station to monitor drop generator performance and perform a service cycle, this must be done in the paper path between sheet feeds for the pagewide printer. Given the large number of orifices and the possible expectation of a recoverable failure every few pages, frequent functional checks need to be made. Means for drop detection could be included in a cavity under the printhead and below the paper path. During the gap between sheets, this cavity could be exposed and functional tests performed. For the printer of Table 2, an intersheet gap of 1″ allows 50ms for drop detection. At 126 pages per minute, this is time for only 600 drop eject cycles, so multiple orifices must be tested simultaneously to validate the whole array for the next few sheets.

**Bit Rate**

A sustained data rate of 75.6 Mbits/sec is required to operate *each* primary color printer using the design of Table 2. This taxes current raster image processing and data transfer rates from hosts and hard disks. The raster image processor is required to render and output about 30 million 4-color pixels per page. Since today's high-performance disk drives deliver sustained external transfer rates of 40 - 120 Mbits/second,[3] it is likely that the page data for each printhead will be formatted in and transferred from RAM.

Printhead data rate along with the dynamics of media drying indicate that high-speed pagewide printheads are best suited to applications where a page is rendered, transferred, and multiple copies are printed and collated to produce finished documents. This is typical of conventional practice in short-run contact printing processes, where master plates are made by various technologies to produce between 500 - 10,000 copies. The pagewide printhead has an advantage over many short-run press processes because each sheet can have customized fields in each color. The size of these fields is limited only by the bandwidth of real-time rendering and data transfer processes.

**Ink Flow and Ejection Power**

Ink must be delivered at all flow rates without interaction between print density and backpressure. Variations in backpressure affect the rest position of the liquid meniscus in the orifices, and this can cause variations in drop volume.

Printhead temperature must be controlled because variations in viscosity and TIJ vapor bubble energy depend on temperature. Waste heat from drop ejection and control circuitry must be dissipated near the drop generators. Increasing the ink temperature as it passes through the printhead is an effective means of printhead cooling. Assuming all the heat is carried away by the ink during sustained printing, the temperature rise as the ink (i.e., water) passes through the printhead of Table 2 is about 20°C. This is enough to produce a visible modulation of drop volume, so the printhead temperature must be controlled as a function of localized print density to keep the drop generators at nearly constant temperature. When not printing, some locally-controllable means of ohmic heating should be provided as large temperature variations can easily occur across the array.

Maintaining constant temperature across the array is important to managing thermal stresses and to maintain alignment with other printheads. Between printheads in the paper feed and transverse direction, pixel-to-pixel alignment must be maintained to about one quarter-pixel. This requires precision mounting and dimensional stability of mechanical components of the pagewide printer.

**Throughput**

A prime application for the pagewide printhead of Table 2 is in short-run printing. Machines such as this are found in data-processing and document production centers, where fault-free operation for (at least) an 8-hour shift is important to productivity and economical operation.

In continuous operation for an 8-hour shift, without derating throughput for document rendering and printhead service cycles for recoverable failures, the following are extreme values (e.g., $D$ = 2) for a four-color printer operating under conditions in Table 2:

- 290 million drops per orifice (every pixel location printed)
- 60,600 pages printed (a 20 foot stack of 20 lb. paper)
- 130 liters of ink consumed
- 110 liters of water disposed (15% of ink vehicle remains after drying)
- 81 KW-hours of dryer energy

Current disposable technologies, for example the 300 orifice HP DeskJet 850C black print cartridge, are designed to deliver high reliability for its 42ml ink supply and 35pl/drop volume. While the average life is about 4 million drops/orifice, to assure no irrecoverable failures (wearout) before ink exhaustion, the actual drop ejection lifetime must be much higher than the average. A pagewide printhead operating for an 8-hour shift must have drop generators with average life 72 times greater. This requirement will drive development of new material and assembly process technologies to achieve a goal nearly two orders of magnitude higher than required of current, albeit disposable, printheads.

This printer will likely not be found on your desk or in your office because of the quantities of ink and paper needed to support the throughput potential of this device.

### Dryer

In a paper machine, the sheet starts at 99% water at the headbox and requires hundreds of feet in contact with steam-heated cylindrical rollers to emerge dry at about 6% water. One reason for the size of the dryer section (usually requiring about 300 feet of linear floor space) is to limit the drying rate. At the highest logical print density (i.e., $D = 2$), where 2.1 ml of high water-content ink is applied to a sheet of 20 lb. paper (4.54 gms/sheet), the sheet's total water content is raised to over 50% by weight. Removing this water to prevent wet, dry, and stacker cockle at 126 sheets per minute presents challenging problems in compact dryer design for a pagewide printer.

Overdrying unprinted areas must be avoided while bringing printed areas below 20% water content. Drying sheets where half the page contains a dense graphic and the rest is white space (or text) is a problematical condition which limits the rate of energy application to prevent overdrying. In general, the solution is to lower vaporization rates by allowing more time in the dryer. Residence time is space in a high-speed paper path, and each second represents 20 inches of dryer length in the printer of Table 2. The dryer power must be servoed to the print density of the page, and heat capacity of dryer elements may impose a delay to accommodate changes in power level. Pages must be cleared from the dryer while adjusting power levels to prevent under- or overdrying. These factors virtually guarantee a delay of several seconds between printing sheets with different print densities, and this makes printer throughput realizable only for multiple copies of nearly identical pages with complete documents created by collation.

At rated speed and full density ($D = 2$), water vapor must be disposed of at 230 ml per minute. At the end of an 8-hour shift, 110 liters must be vented to atmosphere or condensed into a drain. The dryer power and disposal of waste heat and evaporated water of this printer require the installation of special services.

## Conclusion

Pagewide ink jet printers can achieve very high throughput rates with a large number of drop generators printing an entire column simultaneously. At 600dpi, the printhead for each primary color of an A-size printer has 6300 drop generators. The reliability required to achieve sustained throughput requires advances in system design to eliminate random failures from ink spray, paper dust, clogs, and deprimes. Advances in materials and processes will be required to achieve useful life about two orders of magnitude longer than current disposable printhead technologies. Drying paper printed with high water-content inks poses significant engineering challenges. In operation, this printer requires a physical plant supporting logistics of supplying several hundred liters of ink and six hundred pounds of paper in an 8 hour shift, kilowatts of dryer power, and disposal of hundreds of liters of condensed water vapor.

Pagewide ink jet offers high-speed printing of sheets with the ability to electronically customize the content of each sheet without generating a new physical master. Using existing color halftoning technologies, photographic quality could be achieved in a four-color system at over 120 A-size pages per minute.

In spite of the great technical challenges of the high-performance design proposed in this paper, commercially successful products could be expected within the next decade for a variety of applications, particularly for smaller page formats and lower page throughput.

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