C. D. Elzinga
T. M. Hallmark
R. H. Mattern, Jr.
J. M. Woodward

# Laser Electrophotographic Printing Technology

*This paper describes the development of a non-impact printing technology—electrophotography with laser imaging—and explains its implementation, in both office product and system output devices. The key technical advances made during the development of the two devices are shown.*

## Introduction

Automatic printing devices used with IBM systems, whether word or data processing, have typically employed impact technologies to achieve their characteristic print impressions. As was done in the original invention of movable type, the written alphabetic characters or numerals were broken into their fundamental elements, *i.e.*, letters or single digits, and then combined to form documents of great variety. Although these techniques offered high quality and adequate performance, their limited versatility became increasingly apparent as more complex character sets were required (*e.g.*, Kanji, Farsi) and as formats involving line rules, logos, legends, etc., were found useful. Moreover, as computer and word processing applications expanded, the speed limitations of impact printing technologies began to compromise their overall effectiveness.

In the early 1970s, design requirements for the next family of system output devices strongly suggested that the form and size of any given character should be almost infinitely variable and that print quality, low noise, and high reliability were all important. Consequently, non-impact printing technologies that could break down a character or digit into an array of dots were explored. More specifically, electrophotography with laser exposure appeared to offer good potential for the formation of a high-resolution dot matrix, along with a more quiet and reliable operation. Paramount was the need to print on plain, untreated paper, because both data and word processing applications already used such forms.

In this review, the technology is discussed and five technical challenges are highlighted to identify a number of significant design challenges that were overcome. Two specific machines—a high-speed computer output system printer (the IBM 3800, announced in 1975) and a combination copier and printer (the IBM 6670 Information Distributor, announced in 1979)—are then briefly described to illustrate implementations of this technology.

## Electrophotographic technology

Electrophotography developed as a copier-based reproduction process of the 1960s. The key challenges in extending that technology for an array of printers were to (1) combine the electrophotographic process with a high-quality light exposure station; (2) combine the ability to copy and print, or print with forms overlay in a single process; (3) increase process speeds to accommodate higher print speeds; (4) develop paper handling systems that could be optimized for continuous-forms or cut-sheet paper and merge them with the reproduction process at significantly improved reliability; and (5) implement a microprocessor-based process control system which could manage new demands placed on the electrophotographic process. These included increased process and paper handling speeds, more consistent reproduction

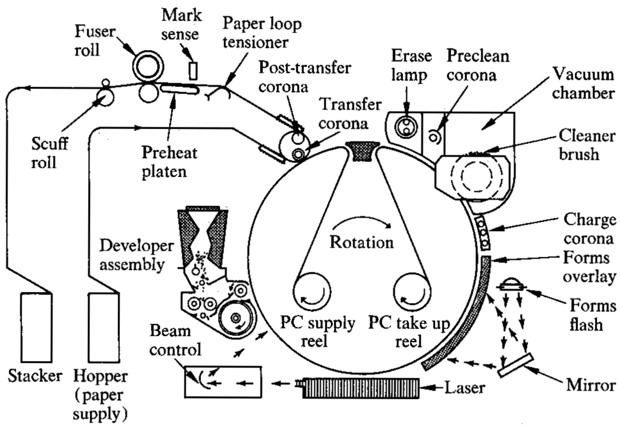



**Figure 1** Configuration of the IBM 3800 electrophotographic printing process.

quality, greater reliability, and asynchronous computer-to-printer operation.

Before each of these challenges is discussed in more detail, the electrophotographic process is reviewed and its application to the requirements of printing is shown.

### Electrophotographic process overview

This process, illustrated in Fig. 1, consists of charging a photoconductor to a negative potential of about 800 V by a grid-controlled charge corona. Images to be printed are provided from a light source and can consist of both variable data (which changes from page to page) and constant data (which does not change and which frequently is the data format itself or a document to be copied). The latent images thus created are developed; *i.e.*, toner is carried to the image by means of coated steel shot in a rotating magnetic brush within the developer assembly. The toned image is transferred electrostatically from the photoconductor to the paper and subsequently fused onto it with heat and pressure. The photoconductor drum continues on to a restoration unit where the surface charges are neutralized and the untransferred toner is swept from the surface. The drum is now ready for another print cycle.

### Light imaging systems

Electrophotographic and laser technologies first appeared in the late 1950s and early 1960s. The IBM 3800 and IBM 6670 Printers advanced the state of the art by introducing the marriage of these developing technologies in the 1970s.

Speed, cost, and font versatility were the key limitations with conventional light sources for non-impact printers. One alternative—xenon flash and font mask—was limited in speed and accessibility to fonts. Another alternative, the cathode ray tube, was limited in speed, cost, and resolution. Light-emitting diode arrays were rejected because of the susceptibility to contamination.

The laser was chosen for its inherent high operating speed and flexibility. It lacked, however, long life and dependable operation. Development associated with the 6670 and 3800 therefore focused on converting the laser from a laboratory device with short life and poor reliability to one that approximated the useful life and reliability of the product itself—an improvement factor of 10. The low-beam divergence, ease of modulation, and resolution of the laser, moreover, opened the door to high-speed, all-points-addressable printing with multiple fonts.

Helium-neon lasers, with power levels of 6 and 40 mW, were compatible with the spectral sensitivities of the photoconductors used in the 6670 and 3800, respectively.

The helium-neon laser used in the 6670 had, moreover, several unique features and requirements. The fundamental problem was to produce long-term power stability, because excessive power reduces character width and insufficient power causes non-uniform background.

Power stability and long life (*e.g.*, 20 000 power-on hours) were the characteristics that separated the 6670 and 3800 lasers from the typical off-the-shelf laser. Factors affecting power stability were mirror alignment, optical cavity design, fill pressure, gas mixture, bore diameter, and material selection. The long life requirement and tight tolerances on beam directional drift dictated the use of hard-sealed mirror bonds without epoxy. Many statistically designed experiments were run in the 6670 development to optimize the effects of design and processing variables on laser performance.

The long optical paths required good pointing stability of the laser, while at the same time the laser had to be isolated from thermally induced torques transmitted through the mounting. This isolation was necessary to make the power output independent of ambient temperature changes. These requirements, however, were in opposition—good pointing stability dictates a rigid mounting, while torque isolation requires a compliant mounting. A solution balancing these effects was developed for the 6670 by utilizing a silicone elastomer placed at three supporting points between the mounting yoke and the laser tube.

In the laser system for the 3800, it was found by means of computer simulation that low helium-diffusion glass could significantly increase the life of the laser. The laser vendor incorporated this glass along with their own developments in mirror coatings, seals, and an enlarged cathode to obtain improved life. The power stability was enhanced by the design of a temperature-controlled enclosure which maintained temperature variations of the laser tube to within ±5° F over an environmental range of 60-85° F.

A unique objective for the laser imaging system in the 6670 was to produce print quality equal to or better than that produced by a fabric-ribbon SELECTRIC® typewriter. In order to produce characters of letter quality, the picture elements (pels) composing a given character had to be placed to an accuracy of approximately one-quarter of the pel dimension (one mil).

Slight irregularities in the surface quality of the multifaceted mirror caused the relationship between beam scanning speed and angular rotation to be inconsistent on a facet-to-facet basis. Hence, if the data stream were clocked to the print head, a given pel of a character would be misplaced relative to the adjacent pel produced by the succeeding scan by an amount greater than the one-quarter pel.

In the 6670 print head, this problem was solved by continuous tracking of a secondary beam, which was also being scanned by the same region of the multifaceted mirror as is the writing beam, as illustrated in Fig. 2. This tracking was accomplished by intercepting this secondary scanned beam with a grating which consisted of alternate transparent and opaque bars. The result was a modulation of beam intensity at a rate corresponding to beam scan position. This modulated scanning beam was then collected on a photodiode using an elliptically shaped mirror [1].

In the 3800, the required relative placement accuracy for adjacent picture elements is two mils. The problem of clocking the picture elements under more relaxed specifications was solved by a unique lower-cost approach using a lens design instead of a grating. The scanner optics used the final spherical lens to provide a linearity correction across the 14-inch scan width, so that the focused spot moved at a constant velocity when scanning across the drum. This permitted the use of a simple detector to signal the start of the scan line as each facet deflected the beam, after which the data for the scan could be clocked at a constant rate by the controller over the entire scan of the facet [2].

## Dual-function image processing

Both the 3800 and 6670 required the implementation of a dual reproduction function. The 3800 merged printing

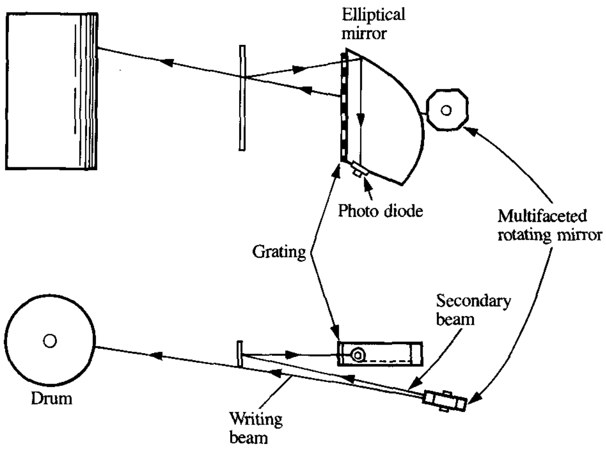



**Figure 2** Beam position tracking system in the IBM 6670.

with full-page forms overlay, while the 6670 provided copying or printing. Each of these combinations produced its own unique technical challenges.

The implementation of superposition (forms and text overlay) in the 3800 required the development of a unique "reversal" electrophotographic process. This process, in contrast to conventional electrophotography, permitted the addition of images, since it exposed the photoreceptor only in those areas where information was to be developed. This reversal process required the development of a carrier and toner system that would develop the images in the light-exposed areas of the photoreceptor. With this process developed, the challenge then became one of combining fixed information with printed information under tight constraints of registration and no image smear. With a customer-changeable negative mask of the form to be imaged, placed 0.06 inch from the photoconductor, illuminated with a xenon flash lamp having a pulse duration of 125 $\mu$s, image smear of less than two mils was achieved, with excellent registration.

The xenon lamp life in a forms flash illumination system presented another challenge. Because of the requirements of high energy and high usage, lamp life initially was only one month. As a result of significant design changes in the optics, the lamp mounting, the triggering, the air flow, and the lamp itself, the lamp life was extended to 60 months.

A consequence of including both copy and print functions in the IBM 6670 was the necessity that the normal non-reversal copier process be retained while the ability to print was added. This requirement demanded that the laser, when printing, expose the non-image area in the

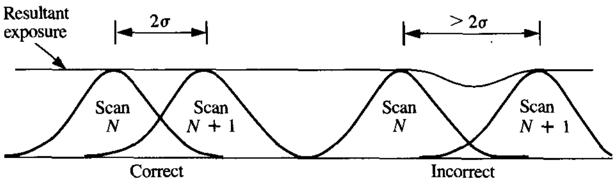



**Figure 3** Configuration of required spacing between adjacent scans of the laser beam in the IBM 6670.

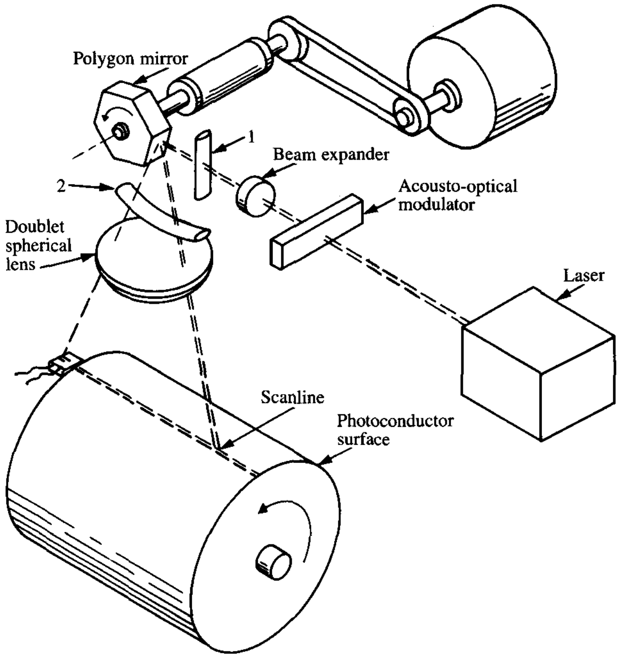



**Figure 4** Optical compensation for rotating mirror declination-angle tolerance.

background with the same uniformity accomplished by the conventional optics of the copier exposure station. In order to provide high-quality printing free of "noise" toner in these background areas, the spacing between adjacent scans of the laser beam, as well as the power density, had to be accurately controlled, as indicated in Fig. 3. Additionally, the optical components had to be free of contaminants such as toner and lubrication vapors.

Highly accurate spacing of adjacent laser scans required that the optical components be mounted so that their vibrations were held to extremely low amplitudes at frequencies near one-half the beam scan rate. For example, the amplitude of vibration of the final mirror in the print head had to be less than $3 \times 10^{-6}$ radians at 1200 Hz. Also, the tolerance on the declination angle of the multi-faceted mirror had to be compensated by optical means. (Declination angle is the variance of each facet's normal from a right angle to the axis of rotation.) This was accomplished by the use of the pair of cylindrical lenses, designated as 1 and 2 in Fig. 4, each placed one focal length from the reflection point of the rotating mirror. This approach relaxed the declination angle tolerance requirement by a factor of 170 [3].

Instabilities in the power density of the writing beam of as much as 25% were compensated for by a closed-loop feedback system in which control of the acousto-optic modulator diffraction efficiency provides the compensation. A power sensor intercepts a portion of the writing beam. Periodically, the output of the sensor is compared to a reference voltage and drift is corrected by readjusting the amplitude of the modulator's carrier frequency [4].

Protection of the optical elements from ambient air contaminants and from lubrication vapors from the rotating mirror's spindle was accomplished by mounting these components in an enclosure purged with clean air. The contamination- and heat-producing components such as the laser, mirror motor, and drive belt were excluded from the enclosure and the purging pressure was created by the motion of the mirror, as shown in Fig. 5 [5].

### High-speed, large-volume process requirements

The third challenge which had to be overcome was to upgrade the electrophotographic process to achieve speeds over three times faster than that of the then-current process. Initial development efforts focused on a wet chemical process to achieve the high-speed, large-volume demands of system output printers. This had a serious disadvantage, however, of being very slow and requiring high-cost, special paper, apart from being difficult for customer personnel to maintain.

With the IBM development of a photoconductor which met the spectral requirements of the laser exposure stations, the way was opened for a high-speed, dry, plain-paper electrophotographic printing process. This new photoconductor had adequate sensitivity at the 632.8-nm wavelength of the HeNe laser. Process speeds of up to 32 inches per second (ips), needed for data processing printing, could be achieved with a 40-mW laser. Parallel improvements also had to be undertaken in the developer, fuser, and cleaning system components of the process.

- *Developer*

The dry electrophotographic process required that toner-coated beads, the carrier, move past the photoconductor and deposit the toner in the electrostatic image areas. At higher process speeds, up to three times those in other electrophotographic devices, the volume of carrier that must be moved past the photoconductor is several tons per hour. The challenge was to design a developer system that would produce high-quality images, while at the same time extending the life of the carrier from $40 \times 10^4$ to $2 \times 10^6$ prints, and yet maintain acceptable photoconductor life, *i.e.*, number of images per panel of photoconductor. Two unique carriers were developed that met the print quality, life, and triboelectric requirements of these products. Both carriers utilized Teflon® [6] coated onto iron beads. A harder Teflon® epoxy coating was developed for the extremely long life required on the IBM 3800 [7].

- *Fuser*

High process speed requirements also established a need for a high-performance, lower-energy fuser that required no consumables. The hot roll fuser was selected because of the energy efficiency of that design. The real challenge was to develop a reliable release system so that paper with melted toner, even on the edge of the paper, would not stick to the hot roll or to a back-up roll contaminated with toner. At that time, hot roll fusers typically used a silicone oil, wicked onto the hot roll, to prevent paper release failures. The oil was not only an expense to the user but might also be deposited on supplies, such as offset masters, where the presence of the oil was not acceptable. Since the hot roll is a relatively expensive maintenance part, a hot roll with long fusing and release life was necessary.

To achieve this requirement, new elastomer materials were developed that could withstand the high tempertures without excessive hardening during the life of the roll. In addition, the release characteristics were maintained such that neither the plastic toner nor the paper stuck to the hot roll.

To extend the life of the hot roll at the speed of the IBM 3800 (32 ips), a multi-zone preheat platen was developed. This platen heated the paper from the side opposite the print and controlled the preheat temperature to 104°C [8].

- *Cleaning system*

Again, because of usage, a new cleaning system had to be developed for the IBM 3800 which had an acceptable brush life while improving the ability to clean fully toned pages. A Dynel® [9] brush was finally developed which achieved a life of two million copies (one month), improving the state of the art by almost two orders of magnitude. Subsequent brush material changes and hardware refinements developed after initial customer shipments further increased brush life to four months.

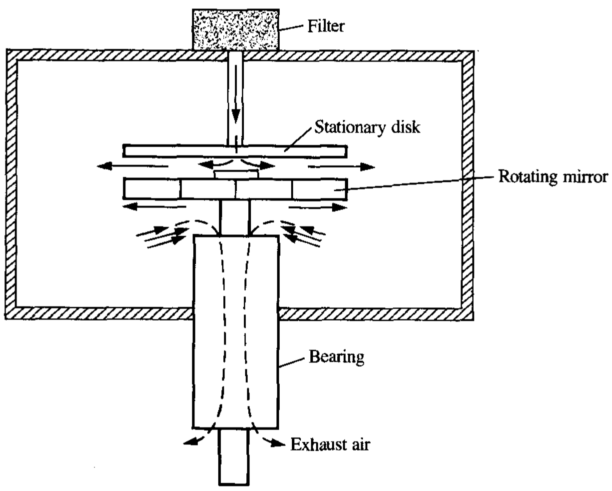



**Figure 5** Enclosure for optical elements for protection against contamination in the ambient air, including lubrication vapors. (From Ref. 5.)

## Paper handling

Application of electrophotographic technology to nonimpact printers required design solutions to a fourth set of problems—automated paper handling mechanisms. Handling continuous paper forms, new to copying technology, necessitated the development of the first narrow-zone transfer station, which in turn permitted the start-stop operation of a continuous-forms paper web. The ability to lift paper away from the drum at transfer and return it quickly in this narrow zone also made it possible to have a gap in the photoconductor surface so that photoconductor coated on Mylar® and stored on rolls inside the drum provided a photoconductor supply of up to one year within the machine.

To accomplish narrow-zone transfer with start-stop capability, a charge of about $4.2 \times 10^{-8}$ coulomb/cm$^2$ was applied to the back side of the paper by the single-wire corona. At the process speed, this wire provided a source for 120 $\mu$A of active current in the 15-mm-wide transfer zone [7].

The paper forms printed with impact devices are of continuously variable width and length. The electrophotographic copiers that served as the technology base for the 3800, however, handled only one or two paper sizes. The 3800 design point was placed between these extremes by handling a range of specific lengths and widths [10].

To accomplish the asynchronous operation of the printer and the computer, three independent closed-loop controls at the transfer, fuser, and burster-trimmer components, which could start and stop within 25 ms with a

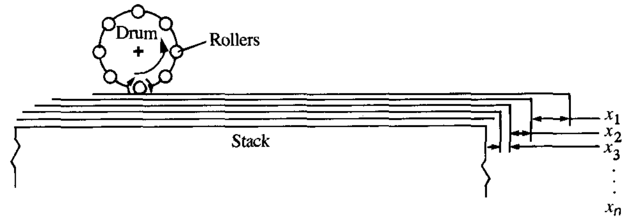



**Figure 6** Action of a rotating drum, having rollers on its periphery, to separate advancing sheets by a distance of $x$.

steady state web velocity of 32 in./s [11], were designed as part of the internal control system of the printer. These servos used high-torque, low-inertia dc motors with shaft angle encoders which utilized a parabolic-shaped input voltage drive *vs* time to give a constant acceleration and deceleration force. The paper path is indicated in Fig. 1. This gave the smooth paper motion necessary to prevent toner particles from separating from the paper prior to fusing and yielded a registration accuracy to within ±0.010 in. [8].

Paper path sensors detected problems as early as possible to minimize paper damage, an important aspect for high-speed web movement. The paper line could then be stopped and started within 0.50 in. if a severe error (such as a failure to release at the fuser roll) was detected. Other sensors detected the presence and position of the web, web movement, servo motor overloads, or improper motion at the stacker or burster/trimmer.

Since the IBM 6670, the combination word processor and information distributor, had to perform in a general-purpose office environment, it had to handle a wide variety of cut-sheet papers. The two commonly accepted means of "picking" a single sheet from a stack were not acceptable. Vacuum pickers were sensitive to paper porosity; separator-restraint devices were sensitive to the coefficient of friction of the paper. The device selected was relatively insensitive to both of these parameters.

Previous IBM inventions by Walter Buslick and Ronald Hunt were used as a starting point to design a new paper picking and separating means.

According to Hunt's invention, the rolling action of wheels on a stack of paper caused the sheets to advance forward. The top sheet traveled a greater distance than the second, the second a greater distance than the third, and so on. To accomplish this action, Hunt described a drum having a plurality of rollers around the drum periphery as shown in Fig. 6.

This technique eliminated most of the disadvantages of previous methods and thus enhanced significantly the handling characteristics of cut-sheet paper in the IBM 6670.

## Microprocessor control

The last technical hurdle that had to be addressed was a comprehensive control over the printing process. Sustained print quality and reliability necessitated the development of a sophisticated microprocessor-based process control system to monitor and control system characteristics such as print contrast, paper handling, and host interaction.

• *Print contrast*

Prior to the 3800 Printer, a common experience with electrophotographic devices was an unpredictable change of print reflectance—sometimes copies were too dark and at other times too light. To provide long-term runs with consistent reflectance, without operator intervention, a special control mark was placed at the margin of a page by the laser. After development and transfer to the paper, the print contrast of the mark was measured and servo-controlled using a light-emitting diode and a sensor. Toner was fed into the developer mix to maintain a nearly constant reflectance in the printed images of between 6 and 10 percent.

• *Host interaction*

Complex control requirements have had to be engineered, given the asynchronous nature of the print operation. The printing process in the 3800 runs with constant velocity at 32 in./s while the computer channel provides data up to 250 kilobytes per second [12]. In addition, it was necessary to place the laser-generated data in close registration (within ±0.015 in.) on either preprinted continuous forms of various lengths and widths or forms overlay images previously exposed on the photoconductor drum.

To make the printer highly reliable, extensive error checking and automatic recovery or page-abort capabilities were included. Single-bit error correction and double-bit error detection in the Writeable Control Store (WCS), byte parity checking, and microinstruction retry in the microprocessor and storage areas were incorporated into the design.

Customer requirements dictated that three print pitches—10, 12, and 15 characters per inch—be intermixed on the same page. This had not been possible on impact printers. The control assembly architecture permitted the customer-designed fonts to be loaded from the host computer. Format control also provided, for the first time, the ability to customize copies of a page with routing information or the withholding of print from desired portions of the page depending on the copy number. This function, on impact printers, required the use of over-printing or of spot carbons. The control assembly was designed with microprogrammed control logic and a microprocessor which used multilevel priority-interrupt-driven logic [12].

As a consequence of these design elements and related technologies, the 3800 printing subsystem provided high-quality, large-volume output from a data processing system with font and format flexibility well matched to current and future business and scientific applications.

## Product development summary: IBM 3800 and IBM 6670

The IBM 3800 printer subsystem, the first electrophotographic laser printer in the industry, was announced on April 15, 1975. Its characteristics included the ability to print at 10 020–20 040 lines per minute depending on the line density (6 to 12 lines per inch) at a process speed of 32.0 in./s. The characters were composed of laser-exposed elements, 144 per inch vertically by 180 per inch horizontally. It incorporated an optical mask, called a forms overlay, for printing constant data and formatting. The paper was margin-punched with continuous-web fan-fold in a range of sizes from 3-1/2 in. × 6-1/2 in. to 11 in. × 14-7/8 in. The output could be either refolded or burst and trimmed to sheet form. The expected print volumes were typically two to three million ft/month.

The IBM 6670 Information Distributor was announced on February 14, 1979. Some of the features of the IBM 6670 are high speed, letter quality, laser printing (up to 36 pages per minute), text processing, communications, convenience copying, and electronically stored fonts that can be intermixed on a page. Documents can be printed or copied on one or two sides of various sizes and types of cut-sheet paper. These are fed from either of two supply drawers. The print speed is up to 2376 lines per minute at a process speed of 10 ips. Letter quality print was achieved with a resolution of 240 × 240 pels per inch.

The key technical advances which were implemented on these two devices were: (1) a narrow transfer zone and asynchronous paper path with a fan-fold web (used only on the 3800); (2) dry-release fusers; (3) a laser print head with a high-speed, multifaceted mirror, linearity correcting optics, and relaxed declination-angle tolerance; (4) electrophotographic materials development enabling reliability and longer life; and (5) microprocessor control with font and page format flexibility.

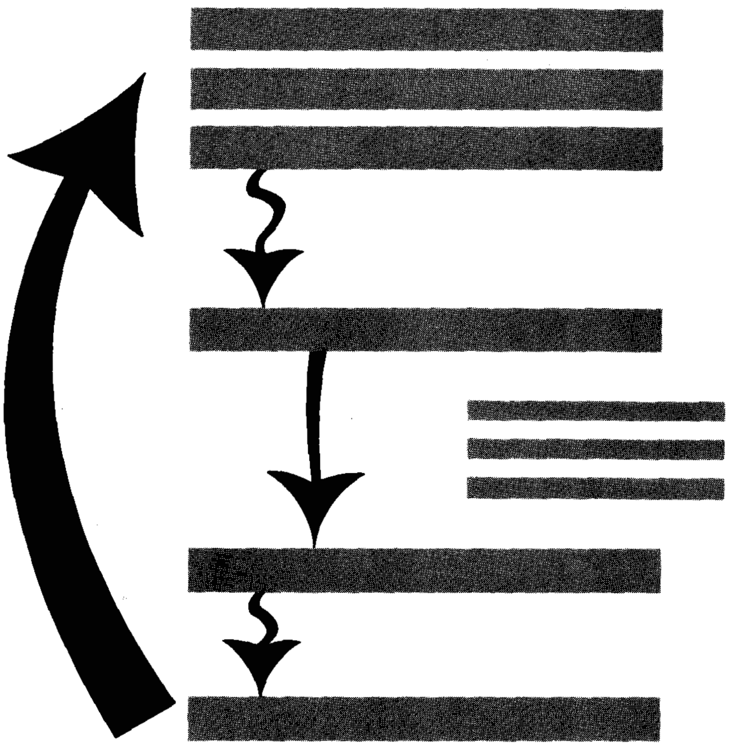
## References and notes


1. A. J. Dattilo and D. W. Zegafuse, Jr., "Scanning Light Synchronization System," U.S. Patent 3,835,249, 1975.
2. J. M. Fleischer, M. R. Latta, and M. E. Rabedeau, "Laser-Optical System of the IBM 3800 Printer," *IBM J. Res. Develop.* **21,** 479 (1977).
3. J. M. Fleischer, "Light Scanning and Printing System," U.S. Patent 3,750,189, 1973.
4. N. R. Davie and J. C. Lambiotte, "Feedback Control for Laser Discharge System," U.S. Patent 4,144,539, 1979.
5. J. C. Lambiotte and R. H. Yates, "Clean Rotating Mirror System," *IBM Tech. Disclosure Bull.* **18,** 1709 (1975).
6. Teflon® and Mylar® are registered trademarks of E. I. du Pont de Nemours and Co., Inc., Wilmington, DE.
7. U. Vahtra and R. F. Wolter, "Electrophotographic Process in a High Speed Printer," *IBM J. Res. Develop.* **22,** 34 (1978).
8. K. D. Brooms, "Design of the Fusing System for an Electrophotographic Laser Printer," *IBM J. Res. Develop.* **22,** 26 (1978).
9. Dynel® is a registered trademark of Union Carbide Corp., New York, NY.
10. R. G. Svendsen, "Paper Path of an On-Line Computer-Output Printer," *IBM J. Res. Develop.* **22,** 13 (1978).
11. T. J. Cameron and M. H. Dost, "Paper Servo Design for a High Speed Printer Using Simulation," *IBM J. Res. Develop.* **22,** 19 (1978).
12. G. I. Findley, D. P. Leabo, and A. C. Slutman, "Control of the IBM 3800 Printing Subsystem," *IBM J. Res. Develop.* **22,** 2 (1978).


*Received May 29, 1980; revised March 3, 1981*

*C. D. Elzinga is located at the IBM General Products Division facility, 9000 South Rita Road, Tucson, Arizona 85744. T. M. Hallmark and J. M. Woodward are located at the IBM Information Systems Division facility, P.O. Box 1900, Boulder, Colorado 80302. R. H. Mattern, Jr., is located at the IBM General Products Division headquarters, 5600 Cottle Road, San Jose, California 95193.*

# IBM Scientific Contributions



*Four level laser*

The *Journal* acknowledges the contributions of V. Y. Merritt to the acquisition, review, and editing of the papers in this section.

*Editor*