HEWLETT·PACKARD JOURNAL

HEWLETT-PACKARD JOURNAL

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At any given moment, all over the world, printers of various kinds attached to computers large and small are spitting out reports, paychecks, address labels, letters, invoices, processed data—nearly anything that can be printed. Much of the run-of-the-mill computer output is produced by high-speed line printers (they print a line at a time) on the z-fold computer paper familiar to many of us—11×15-inch sheets, plain on one side, alternating half-inch blue and white stripes on the other. Much of that paper is quickly thrown away, as people cut off part of it or photocopy it to get standard-size sheets of paper that can be handled and filed more easily. Sometimes the data is completely retyped, either to put it into a more convenient format or because line-printer type quality is somewhat variable.

The subject of this month's issue is a product that can save a lot of this wasted paper and effort. The Hewlett-Packard Model 2680 Laser Printing System can act just like a conventional line printer, but it produces printed copy faster, with higher quality, on convenient regular-size (8 1/2×11-inch) sheets of paper. It works with the HP 3000, HP's powerful business data processing computer family. The 2680 prints up to 45 regular-size pages per minute, regardless of what's on them. Although it's designed to be cost-effective as a line printer replacement, the 2680 is much more versatile than any line printer. It can print characters in various sizes and orientations, and it can print symbols, forms, letterheads, even signatures. Special programs written for the HP 3000 help the user design the output that the printer will print. Among commercial laser printers, the 2680 is in the middle of the range in cost and at the high end in versatility.

The articles in this month's issue describe the laser printing system and its architecture, the special software for the HP 3000, and several aspects of the design of the 2680A Laser Printer, including the electrophotographic process and the data control system that formats the computer-originated data for the laser. Next month we'll cover the 2680A Laser Printer optics assembly and the machine control system, which controls the printing process and the operator interface. This month's cover photo of the optics assembly is actually two photographs superimposed, one of the assembly taken with the room lights on, and the other of the laser beam, taken with the lights off.

-R.P. Dolan

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Laser Printing System Provides Flexible, High-Quality, Cost-Effective Computer Output

Used with the HP 3000 family of distributed data processing systems, this combination of powerful, interactive software and innovative, state-of-the-art hardware produces excellent print quality on notebook-size paper at 45 pages per minute.

by James A. Hall

HEWLETT-PACKARD's 2680 Laser Printing System introduces a new era of output printing flexibility, quality, and speed to HP 3000 Computer Systems. It combines the 2680A Laser Page Printer (Fig. 1) with powerful interactive output design software and is fully integrated with the HP 3000 family of on-line distributed data processing and data base management systems.

The 2680A Laser Page Printer uses laser-scanned electrophotographic technology to print 45 pages per minute on plain, letter-size paper (8½×11-in or A4). The laser scanning system can place high-quality images anywhere on the page. Character sets and electronic forms (up to 32 of each) may be used to organize page formats and highlight key

information. Fonts as small as 22 characters per inch can be used to place more information on each page, saving paper and space (Fig. 2). Large, bold characters up to 1.4 inches high provide eye-catching headings and labels. Information can be rotated so the output can be read like a book. The 2680A monitors and self-corrects its internal process to maintain excellent print quality. A display panel tells the operator when to perform preventive maintenance. Self-diagnostics and modular design simplify repair.

Two software packages simplify the design of printed output (see article, page 10). The Interactive Design System (IDS/3000) is used for the design of characters, symbols, and forms. Easy-to-use, menu-driven software interacts with a

Fig. 1. *Model 2680A Laser Page Printer provides printed output for the HP 3000 Computer System. Powerful interactive software for the HP 3000 simplifies the design of the printer's output.*
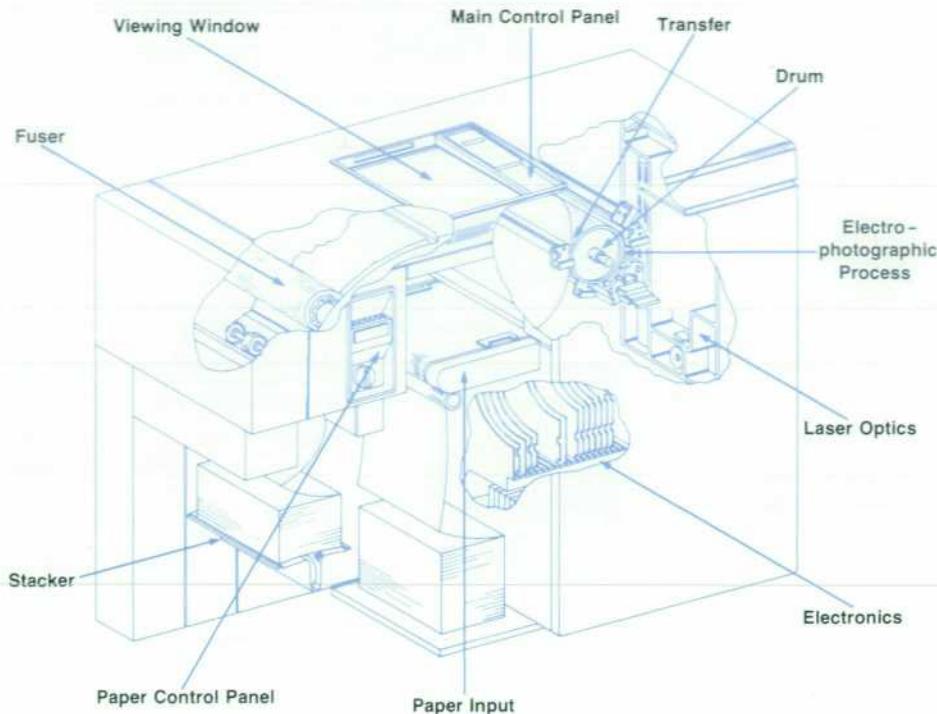
Fig. 2. *Three examples of standard-size pages printed by the 2680 Laser Printing System. The system prints up to 45 pages per minute.*

graphics terminal to create any desired image. A digitizer can be used to facilitate creation of images such as special characters, logos, or symbols.

Interactive forms design includes the definition and modification of forms ranging from simple memos to elaborate invoices. Using multicopy capabilities in the 2680A,

one form may be repeated up to eight times during printing with parts of the form changed on each subsequent copy. Different headings or copy distribution information can be printed on each copy, or confidential information can be blocked out on specific copies. With these capabilities, expensive preprinted multipart forms can be replaced by electronically defined forms.

The Interactive Formatting System (IFS/3000) is used to tailor printed output to each user's needs. Character fonts, logos, symbols, and forms designed with IDS/3000 can be selected for use in a printing application. Any of the more than 40 character sets supplied with the formatting software can be selected, and users can specify exactly how each page is to be formatted.

Defining the Product

Over the last ten years, there has been a major shift away from centralized, batch-oriented data processing to distributed, on-line, interactive computer systems. As access to and control of computers have moved out to end users, users have asked for more effective ways to access, view, and distribute information. This has affected the requirements for computer output printing in several important ways. For example, better print quality is needed to satisfy the expanding variety of printed output, which includes letters, memos, charts, graphics, forms, and tabular information. Output is preferred on standard 8½×11-in or A4 paper because users don't want the inconvenience of handling, storing, or photocopying large computer printouts. Multiple character sets are needed to highlight information and meet the needs of a worldwide market.

Preprinted forms are expensive and require inventory and storage, and handling them reduces operator productivity. Electronic forms, which can be called from memory as needed and automatically merged with data, can eliminate most of these problems and give the user the added flexibility of making changes rapidly.

The computer information explosion has resulted in an ever increasing print volume, so extra speed and volume printing features are needed. As the cost of printing and distributing computer output continues to grow, minimizing paper size, squeezing more information on each sheet of paper, reducing operator interaction, minimizing postprocessing (e.g., reduction copying), and streamlining distribution become highly desirable attributes of a computer output printer.

Of the presently available printer technologies, laser-scanned electrophotography best matches these needs and was chosen for the 2680A. The basic strengths of this technology include very high resolution, a very high-contrast image, dot matrix print flexibility, use of plain paper, high speed, and low acoustic noise.

Laser Page Printer Overview

A drawing of the 2680A Laser Page Printer is shown in Fig. 3. A continuous web of fan-fold paper enters the printer from a splicing table. The splicing table allows a new box of paper to be spliced to the end of the previous box of paper, giving an alternative to rethreading the new box of paper through the printer. Paper next passes to the transfer station, where the printed image is transferred from the

Fig. 3. *Inside the 2680A Laser Printer.*

photoconductor drum to the paper. The printed image can be viewed by the operator at the viewing window. The paper then passes through the fuser system, where the printed output is permanently fixed to the paper. Finally, the paper is folded and stacked by the stacker. Operation of the paper system (threading, splicing, stacking, etc.) is controlled by the paper control panel. The overall print process and printer diagnostic routines are controlled by the main control panel.

The electrophotographic process used in the 2680A is described on page 6. While most copiers and laser printers use a drum coated with a single-layer, exposed photoconductor, the 2680A uses a two-layer photoconductor that includes a transparent dielectric layer. The use of this additional layer requires some extra processing steps in printing, but it provides some significant advantages over conventional photoconductor systems. The polyester dielectric is more resistant than most photoconductors to scratching from paper abrasion, development, and cleaning. This gives the photoconductor a relatively long lifetime while maintaining small size. The resistance of the polyester to abrasion allows the use of a conductive carrier in the developer system. This permits better development of large solid areas with a smaller, single-roll developer assembly. The polyester layer is also compatible with blade cleaning, which eliminates the need for complex rotating brush systems. The cadmium sulphide photoconductor is very sensitive to illumination at the wavelength of a conventional HeNe (helium-neon) laser. This permits a relatively high speed of operation with a low-power, relatively inexpensive, very reliable laser.

Some photoconductive materials are somewhat hazardous. The dielectric layer prevents any abrasive action between the paper and the photoconductor and the possible deposition of minute quantities of photoconductor material

on the paper.

Many of the traditional problems of electrophotography have been circumvented in the 2680A by innovative design. For example, the electrophotographic process is sensitive to variations in environmental conditions. Changes in atmospheric pressure or relative humidity can change the efficiency with which the corona produces ions and hence the electrostatic potentials on the drum. This in turn can degrade print quality. In the 2680A, this problem is eliminated by a microprocessor-controlled closed-loop system which automatically maintains the proper drum potentials. Sensitivity of the developed image density to changes in toner and environmental conditions is minimized by a second microprocessor-controlled closed-loop system, which automatically adjusts the toner mixture to maintain the desired image density.

Fuser rolls can pick up toner, inks, contaminants, etc.
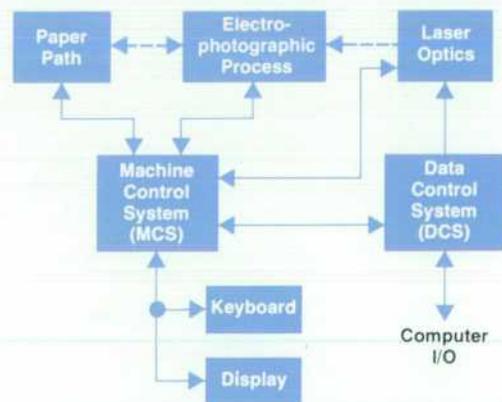
Fig. 4. *Block diagram of the 2680A Laser Printer. Two microprocessor systems monitor and control printing.*

Six Steps to a Printed Page

by Robert R. Hay

The electrophotographic process by which the 2680 Laser Printing System creates images on paper consists of six steps. First, a pattern of laser on/off signals corresponding to the information to be printed on the page is generated by the 2680 digital electronics in response to commands from the HP 3000 Computer System. Second, the laser beam causes an electrostatic image consisting of charged and uncharged areas to be formed on the surface of a cylindrical drum. In the third stage a toner (ink) consisting of small, black, electrically charged particles is brought near the drum surface, and the toner particles adhere by electrostatic attraction to the charged areas of the drum image. Next, the paper is brought near the drum and a charge is applied to the back of the paper to attract the toner particles away from the drum and onto the paper. The fifth step is to fix the toner permanently to the paper by heating, and the last step is to restore the drum to its original condition.

Generating the Laser Pattern

A simplified drawing of the laser scan system is shown in Fig. 1. The laser beam is reflected from the surface of a rotating 18-sided mirror. This scans the beam along the axis of the photoconductive drum (X direction). Rotation of the drum moves the scan along the surface of the photoconductor in the Y direction. The result is a raster scan of the drum surface.

The acoustooptic modulator, in response to a digital signal, deflects the beam either into the optical path to the drum or away from it, in effect turning the beam on and off. By appropriately timing when the beam is turned on, the character or image to be printed can be projected onto the drum as the laser beam scans its surface. The operation of the optical system will be discussed in detail in next month's issue. Digital signal formation is described in the article on page 30.

Forming an Electrostatic Image from the Laser Pattern

The drum used in the 2680A Laser Printer is a photoconductive sandwich applied to an aluminum cylinder. The sandwich consists of an aluminum layer on which there is a cadmium sulfide photoconductive layer, as shown in Fig. 2. Outside the CdS is an insulating polyester layer.
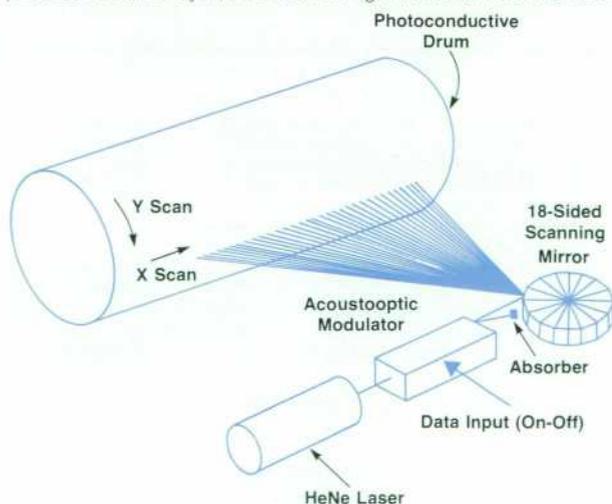
Fig. 3 shows how the drum is used in the laser printer. The elements used for forming the electrostatic image are the positive charging corona, the ac simultaneous discharging corona, the laser beam, and the overall illumination stage.

At the charging corona (station A), positive ions are produced, charging the surface of the drum. After passing this corona the potential of the drum surface is about 1300 volts.

At station B, a negatively biased simultaneous ac corona discharger tends to drive the drum surface to zero volts. At the same point, the modulated laser beam impinges on the drum. When the laser beam is on, the CdS region struck by the beam is made conductive, and the voltage throughout the sandwich is zero. In areas where the laser beam is off, the voltage inside the sandwich is several hundred volts negative even though the surface potential is zero.

By applying an overall illumination (station C) this internal voltage difference is converted to a surface voltage. The laser-exposed areas remain at zero volts, while those areas not exposed to the laser change to approximately +500 volts. A more detailed explanation of this process can be found in the article on page 16.

Following the image formation process, the potentials of both laser exposed and nonexposed areas are measured with a noncontacting electrostatic voltmeter and compared with target values. The machine control processor (to be covered in next month's issue) adjusts the appropriate parameters to keep the potentials at the target levels.

Development of the Imaged Areas

The surface of the drum now enters the development section with either an exposed area (approximately zero volts) or a nonexposed area (approximately +500 volts). The developer station contains a mixture of small black plastic particles known as
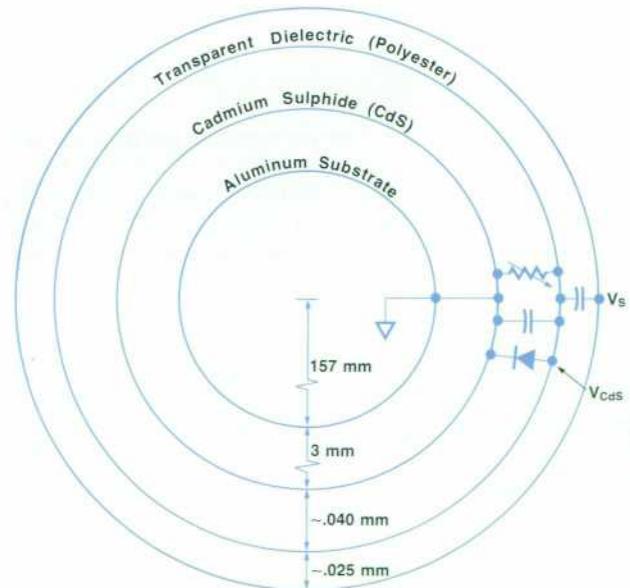

Fig. 1. *Simplified drawing of the laser raster-scan system of the HP 2680A Laser Printer.*

Fig. 2. *The laser printer's drum is a photoconductive sandwich applied to an aluminum cylinder.*
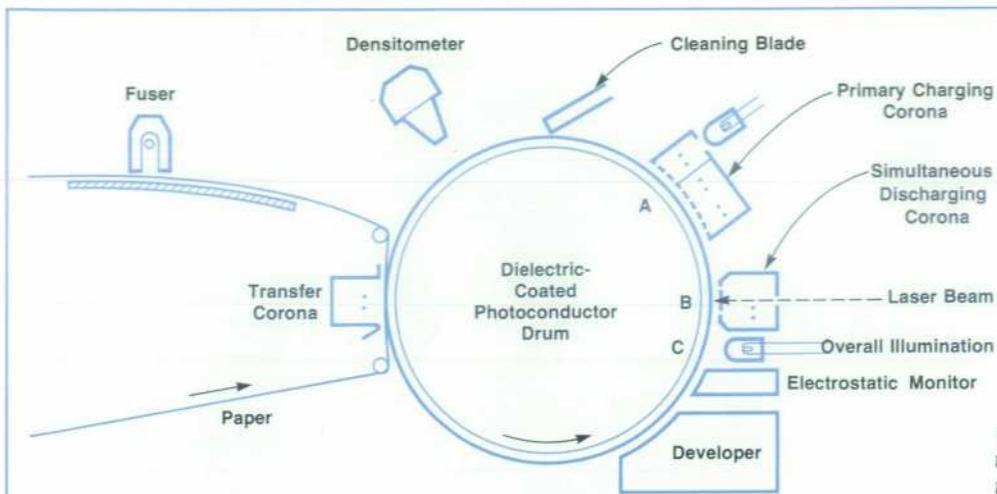
Fig. 3. *Elements of the electrophotographic process used in the 2680A Laser Printer.*

toner along with larger iron-based particles known as carrier. This toner is transported to the drum on a magnetic brush which generates a toner cloud at the drum surface. The toner is charged in such a way that it is attracted to the portions of the drum near zero volts and is not attracted to the portions of the drum surface with a high positive potential. There is now a visible image on the surface of the drum, with toner in the areas that were exposed by the laser beam.

Control of the development parameters is accomplished by measuring the developed density (blackness) of a pattern printed on an area of the drum that does not contact the paper in the transfer process. This developed density is measured by the reflective densitometer shown in Fig. 3. The measured density is compared with the target density by the machine control processor, which then adjusts the appropriate development parameters to maintain the proper density. More details of the development and control process appear in the article on page 20.

Transfer of the Image to Paper

The transfer process is simply a way of transferring the toner from the drum to the paper. In the 2680A, the positively charged toner is attracted to the paper by applying a negative charge to the paper. This is done by a negative corona behind the paper, as explained more fully in the article on page 20.

Fixing the Toner to the Paper

After transfer the toner appears on the paper surface as small particles. To hold the toner in place permanently, it is necessary to melt it into the paper. The toner used in the 2680A is a carefully chosen thermoplastic that has a well controlled melting point. The 2680A uses a noncontacting radiant fusing system along with a preheating area to assure reliable and effective fusing. This pro-

cess is described in more detail in the article on page 24.

Cleaning the Toner off the Drum

Following transfer the small amount of toner that remains on the drum must be removed. The 2680A contains a blade made of soft plastic that scrapes loose the toner that has adhered to the drum. A vacuum system removes the toner that piles up in front of the blade. The toner-laden air that is removed from the cleaning station passes through a cyclonic separator that deposits most of the waste toner in a disposable container. The remainder of the material is collected in a filter bag. The drum is then ready to begin the next cycle.

Robert R. Hay
Bob Hay was born in Pittsburgh, Pennsylvania, and received the BSEE (1967) and MSEE (1968) degrees from Carnegie-Mellon University. A member of the IEEE, he has been with HP since 1968 and has directed projects related to RF signal generators and part of the 2680A. He is now a project manager for development of future printing technology. During his early years at HP, Bob studied for an MBA degree at the University of Santa Clara and received it in 1972. He is named co-inventor on three patents concerned with electrophotography, an RF tracking generator, and a railroad track circuit. Bob lives in Boise, Idaho, is married, and has two children. He enjoys backpacking, woodworking, cross-country skiing, and bicycling.

from the paper and "print" these back on the paper, reducing print quality. A noncontacting fuser system was designed to eliminate this problem.

The electrophotographic process is complex and parameters are interrelated. For example, poor print quality can arise from several different areas in the process. In the copier industry, specialized repair personnel learn to troubleshoot successfully by keen observation, intuition, and trial and error. Comprehensive measurement and diagnostic systems in the 2680A greatly simplify troubleshooting and repair even for service personnel unfamiliar with the technology.

A block diagram of the 2680A is shown in Fig. 4. Operation of the printer is controlled by two microprocessor systems. The machine control system (MCS), which will be described in next month's issue, controls the basic printing process. For example, it controls paper movement through the printer, controls the electrophotographic process, accepts operator inputs via the keyboards, and displays operator messages. The data control system (DCS) communicates with the host computer and converts ASCII data into the correct form to modulate the laser as it scans the photoconductive drum (see article, page 30). The MCS and DCS communicate to synchronize overall printer operation,

pass necessary information from the host computer to the MCS (e.g., page size) and pass necessary information from the MCS to the host computer (e.g., printer status). Printer diagnostics are controlled and results communicated by the MCS.

James A. Hall

Jim Hall joined HP in 1972 with several years of experience designing microwave communication systems. At HP he has worked on the design of the 83003 educational TV receiver, managed the 8660C Synthesizer and 2680A Laser Printer projects, and was the R&D manager for the Boise Division. Jim currently manages the impact printer R&D section. He is an inventor on seven patents related to microwave communications and is a member of the IEEE. This article is his third contribution to the HP Journal. Jim was born in Halifax, Virginia, and holds a BSEE degree (1959) from North Carolina State University and an MS degree in physics (1971) from Lynchburg College, Virginia. He is married, has two children, lives in Boise, Idaho, and is active in amateur radio.

Laser Printing System Architecture

by James T. Langley

DESIGN OF THE HP 2680 Laser Printing System began with the question of what kind of printer it should be and what features it should have. Some time later, having decided that it would be a page printer, and having developed an idea of the capabilities we wanted it to have, such as electronic forms and many character fonts on a page, we faced the question of how to achieve these capabilities. The technique of generating a complete dot-per-bit image of the page and then dumping it out was not economically feasible. 32,400 dots to the square inch and the requirement of buffering four standard pages to keep the drum turning at speed requires about 1.5 megabytes of memory. And besides, why store all the white space? Another approach considered was to do the character generation by creating a high-speed vector generator. This requires that characters be represented as vector lists when processed. This approach yields simple character scaling and rotation and the lines in forms fall out nicely. However, there are two major drawbacks. To represent very high-quality characters on a 180-dot-per-inch grid, many vectors are reduced to single points, negating the storage space benefit of vector lists over bit maps. Second, forms require large shaded-area fills to compensate for the lack of color, and vectors don't work well here, tending to reduce to many single points, ballooning the storage and processing requirements.

The Cell Printer

The approach we decided upon was the idea of a cell printer. If one can define a cell to be of arbitrary rectangular size and contain any bit pattern, and if these cells can be placed anywhere on the page to the resolution of the printer's grid, then a very capable page formatter results. By defining wide short cells or tall skinny ones, horizontal and vertical lines of arbitrary size can be printed. By putting an image of a character into a cell and then carefully controlling the placement of the cell, proportional spacing, kerning, and line justification can all be achieved. Electronic forms composed of cells and data composed of cells can be easily merged and overlapped and printed on the same page.

However, the cell approach also has drawbacks. Diagonal lines require a lot of storage space. The problem of graphics, generating the contents of a big elaborate cell, is not addressed by the printer. Something else in the system must create the image within the cell. The printer will merely place it where specified on the page. Thus the concept of the printing system evolved: powerful applications software to create cells of varying content such as characters, forms, logos, graphics, signatures, and musical notes, combined with high-speed cell manipulation and placement on the page by the printer.

System Architecture

Fig. 1 shows the architecture of the 2680 Laser Printing system. The key elements are the functional partitioning into subsystems and the communication between subsystems. The major functional tasks, as shown in Fig. 1, are applications software for building the proper data structures, the spooling system for linking the user to the printer,
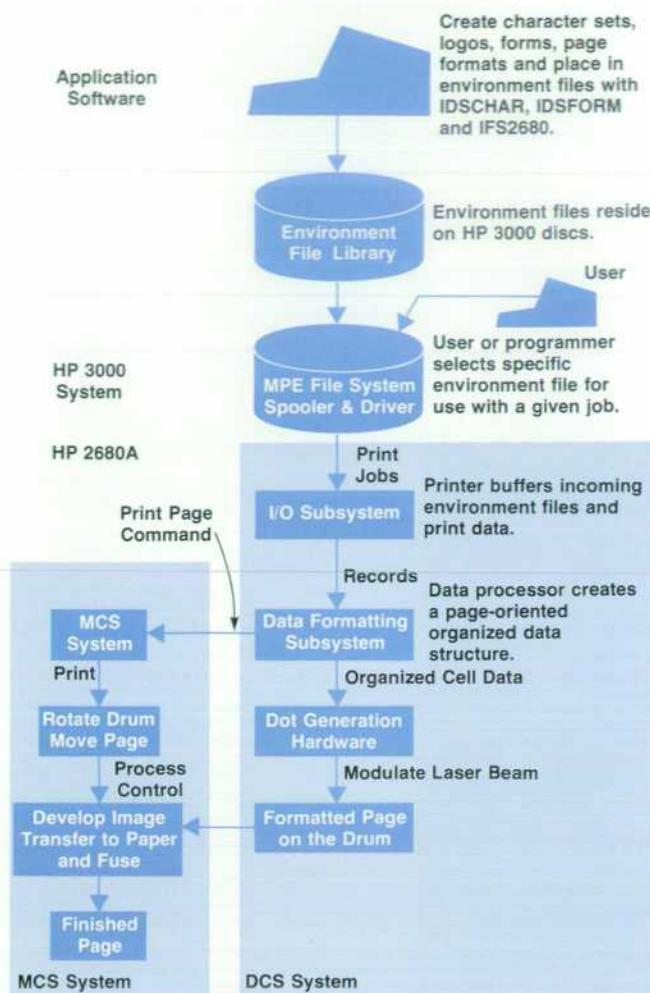
Figure 1 (diagram labels)

Application Software

Create character sets, logos, forms, page formats and place in environment files with IDSCHAR, IDSFORM and IFS2680.

Environment File Library

Environment files reside on HP 3000 discs.

User

HP 3000 System

MPE File System Spooler & Driver

User or programmer selects specific environment file for use with a given job.

HP 2680A

Print Jobs

Print Page Command

I/O Subsystem

Printer buffers incoming environment files and print data.

Records

MCS System

Print

Data Formatting Subsystem

Data processor creates a page-oriented organized data structure.

Organized Cell Data

Rotate Drum Move Page

Dot Generation Hardware

Process Control

Modulate Laser Beam

Develop Image Transfer to Paper and Fuse

Formatted Page on the Drum

Finished Page

MCS System

DCS System

Fig. 1. *Architecture of the HP 2680 Laser Printing System.*

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the firmware data formatting system which manipulates cells, and finally the hardware which prints cells on the page. The corresponding data elements that provide communication between levels are the environment file, the spool file, and the cell triplet. Two electronic subsystems within the 2680A Laser Page Printer control its operation. The data control system (DCS) formats cells for the laser printer, and the machine control system (MCS) monitors and controls the printing process. This functional partitioning and communication scheme results in a very flexible, high-performance page printer.

Designing a High-Speed Cell Formatter

A description of the DCS is in the article on page 30. Basically, the cell formatting system is partitioned into a firmware-executed part and a hardware-implemented part. The hardware is given a description of each cell and its location on the page, and generates the proper dot representation of each scan line for controlling the laser beam. This character generation scheme is used to image everything on the finished page.

The next major DCS level up from the dot generation hardware is the data formatting subsystem. While the dot generation logic must run at bit-stream speeds and there-fore is implemented in hardware, the data formatting system runs at character speeds, which peak around 15,000 characters per second. This subsystem is implemented with bit-slice components built into a custom processor. This system is responsible for managing memory: storing character sets, forms, and page formats. It also emulates a conventional line printer. When presented with a line of characters the data processor reduces it to several lower-level commands for the cell processing hardware.

Data Structures

Only five data structures are required to control the 2680A. These data structures are character sets, forms, logical pages, vertical forms controls (VFCs) and the multicopy forms overlay table. These five structures are generated at a high level using applications software and then sent to the printer before sending the data to be printed. These data structures are used by the printer to configure itself and to format the print data properly.

The most frequently used data structures are the character sets, which consist of three tables. The first table is a 16-word block containing the number of characters in the character set, the size of the characters, intercharacter spacing, and similar data. The second table consists of the dot-per-bit picture of each character. The last table is only required for proportionally spaced character sets. It contains the intercharacter spacing information for each character in the set. The printer can support 32 different character sets simultaneously.

The electronic forms are essentially reduced to character cells when they reach the printer. They have two components. First, a data structure specifying every cell in the form is received. Three words describe the location on the page, specify the size of the cell, and point to the dot-per-bit representation of the cell. All of the dot-per-bit images of the cells compose the second half of the forms data structure.

The third data structure is the logical page table. This table is 32 entries long and describes rectangular areas on the printed page. When the page eject command is executed the logical page table is scanned. If the end of the table is encountered, the printer advances to the next sheet of paper. Otherwise the printer moves the pen to the next logical page on the current sheet of paper. Each logical page can have one or two forms associated with it. These forms will be automatically located to overlay the logical page at a specified origin. A vertical forms control (VFC) can also be associated with a logical page. Data is checked so that characters cannot exceed the limits of the logical page. Unprinted characters are counted and reported in the error trailer.

The fourth data structure, the multicopy forms table, is implemented primarily to emulate multipart carbon forms. The table instructs the printer to repeat the same page of data up to eight times with any two forms overlaid on each printing. Thus, for example, the first copy can have a base part plus a shipping form overlaid, then the data will be reprinted with the base part and a receiving form.

The fifth data structure is the VFC table. It provides backwards compatibility with line printers. The VFC is 16 channels wide and allows slewing to predetermined locations on the page.

HP 3000 System Enhancements

In parallel with defining the data structures necessary to drive the printer, there was an effort to create the data structures and automatically send them to the printer at the start of each job. This involves the HP 3000 spooling and file system. Spooling is the process of placing line printer output on the disc and then transmitting it to the printer. The reason for this process is that printers and similar output devices are very slow. Spooling allows all programs needing a printer to run whether or not a printer is ready; later the printers can run on into the night catching up. Spooling thus enhances overall system throughput. Control information for controlling line printers was already embedded in HP 3000 spool files, and was simply extended to contain additional control information for the 2680A. The HP 3000 spooler was modified to send character sets, forms, and other data structures to the printer before sending the spooled print data. The unifying concept for this is termed an environment file.

An environment file contains all the character sets, forms, and page formatting information needed for a specific job. At the spooling level, the content of the environment file is irrelevant. The spooler only needs to know which environment file to fetch and place into the spool file before the data to be printed is placed into the spool file. By substituting an environment file containing a pica character set for the environment file containing an elite character set a job can be printed in pica instead of elite type. In the same manner, by switching electronic forms in the environment file the job can be printed with a new or modified form. The HP 3000 spooler was extended to select a specific environment file and use it whenever opening a spool file destined for the 2680A. The user tells the spooler which environment file to use by a single new parameter in the user-specified file equation or via a new FOPEN parameter for program access to a print file.

Close coupling between the HP 3000 spooling process and the 2680A yields several other benefits. The most important is very high performance. With regular printers the spooler reads the data from the spool file and sends it to the driver program. The driver is responsible for looking at the data and properly manuipulating the control lines on the printer's hardware interface to get the printer to do what-

ever it is supposed to do. Typical commands include "go to the next page", "print this record", or "skip to VFC channel number 5." On the HP 3000 this process can consume 10 to 20 percent of the CPU's bandwidth with printers running at up to 1200 lines per minute. The HP 2680A runs at about 3000 lpm but consumes less than two percent of the HP 3000's CPU. This tremendous performance increase is the result of the printer's taking the spool file data from the spooling system without the driver's ever looking at the data. Outspooling to the 2680A is simply reading the spool file from the disc and sending it to the printer without modifications.

Applications Software

Referring again to Fig. 1, the last and highest level of the printing system is the creation of the contents of the environment file. The next article describes this software. Basically, the software is a set of tools allowing easy creation, modification and manipulation of the five entities that constitute an environment file: character sets, forms, VFCs, the logical page table, and the multicopy forms overlay table.

James T. Langley
Jim Langley received his BSME degree from the University of California at Berkeley in 1972 and his MS degree in mechanical engineering and computer science from Stanford University in 1975. With HP since 1972, he contributed to the 2680A Laser Printer as a system and firmware designer, mechanical design project manager, and system integration project manager, and has presented four technical conference papers on aspects of the 2680A design. Now a section manager with HP's Boise Division, he estimates he made over 100 round trips between Boise, Idaho and Cupertino, California during the 2680A project. Jim was born in Berkeley and now lives in Eagle, Idaho. He is married and enjoys outdoor activities, including shooting, hunting, and backpacking.

Interactive Software for Intelligent Printers

by Kathleen A. Fitzgerald

THE DEVELOPMENT OF THE HP 2680A Laser Printer, an electronic page printer with unprecedented flexibility and intelligence, prompted the development of a new concept of how the HP 3000 Computer System supports output devices. To make its flexibility and intelligence fully available, the 2680A requires not only the normal MPE* driver and spooler support, but also high-level tools that enable a user to take advantage of special features of the printer, such as downloadable character fonts, electronic forms, logical pages, and electronic vertical forms controls. In addition, application

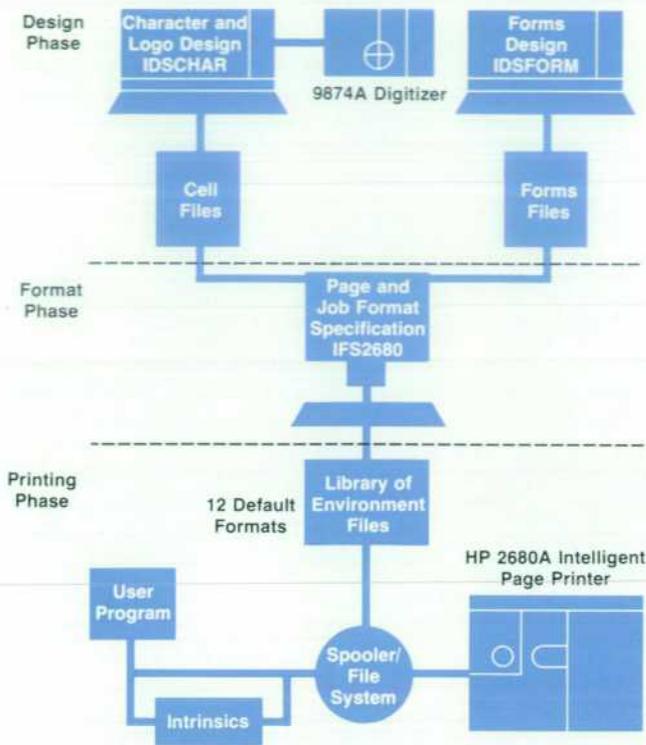*MPE=Multiprogramming Executive, the HP 3000 Computer operating system.

Fig. 1. *The 2680 Laser Printing System consists of a 2680A Laser Page Printer and two software packages for the HP 3000 Computer System, IDS/3000 and IFS/3000.*

programmers need easy ways to use these features in both new and existing programs.

This needed high-level support of the 2680A is provided by two specially developed software products: IDS/3000 (Interactive Design System) and IFS/3000 (Interactive Formatting System). In addition to supporting the 2680A, this software package provides a foundation for HP 3000 support of other intelligent output devices.

Three objectives governed the design of the printer support package. The first was compatibility: our customers have many existing application programs and require a fast, simple, and inexpensive conversion process. The second objective was ease of use: we felt that this was the primary contribution we could make over our competitors' products. Extensibility of each component's design was the third objective: we anticipate that HP will develop new intelligent output devices and identify new applications for this software.

Printer Support Package Overview

Fig. 1 diagrams the HP 2680 Laser Printing System. The primary components of the printer support package are shown, along with the communications links between them. Note also how the support software relates to user programs, the MPE file system, and the laser printer.

IDS/3000, the Interactive Design System, consists of two programs, IDSCHAR and IDSFORM. These programs are used during the design phase of the output production process. IFS/3000, the Interactive Formatting System, consists of a program named IFS2680, a set of user-callable intrinsics (routines), 21 HP-supplied environment files,

and 27 HP-supplied character font files. These font files actually include 46 different character fonts. IFS/3000 is used during the formatting phase of the output production process. IFS2680 and the HP-supplied environment files are the only parts of the system that are designed specifically for the 2680A. The rest of the system is device-independent.

IDSCHAR

IDSCHAR, an interactive, menu-driven program, enables the user to design character fonts and logos. This is done by creating and modifying individual characters. A character, represented internally by a bit per dot, is a dot pattern in a fixed-size grid, like the character shown in Fig. 2. This pattern describes an alphabetic character, a numeral, a special symbol, a company logo, or business artwork. A character font is a complete set of characters, one for each of the ASCII character codes. A special type of character font, called a logo, consists of exactly one character. To allow for scaling, all sizes of a given character font are contained in one character font file. Similarly, a logo file contains multiple sizes of a given logo.

Although many character font files are provided by Hewlett-Packard, users may add to or modify these fonts, create their own specialty character fonts, and design business artwork, such as company logos.

IDSCHAR's key contribution is that it simulates the characteristics of the device for which a font is being designed. For example, in Figs. 2a and 2b two different output devices are being simulated. This capability has proved valuable for producing high-quality character fonts for low-resolution raster devices such as the 2680A. The program uses the graphics capabilities of HP's graphics terminals (2647A and 2648A) for this simulation.

The character font designer must make many subjective decisions during the design process. Research shows that artists are best qualified to make those decisions. Thus, an additional contribution of IDSCHAR is its user interface: it was designed specifically for an industrial designer. This user interface is discussed in more detail below.

How do IDSCHAR and its output fit into the 2680 Laser Printing System? To print on the 2680A Laser Printer with an IDSCHAR-designed character font, a user selects that character font during the formatting phase, using IFS2680.
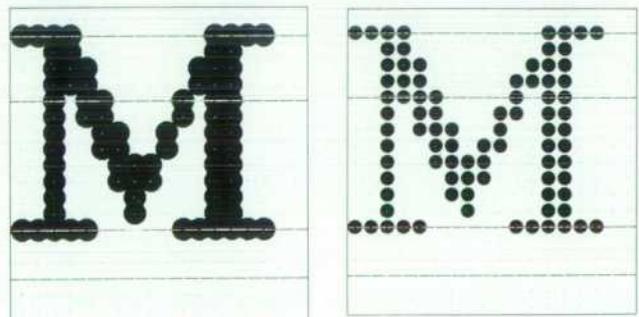

Fig. 2. *Using IDCHAR, the user can design character fonts and logos. Characters are represented as a dot pattern in a fixed grid. Different output devices can be simulated, as shown by these two examples.*
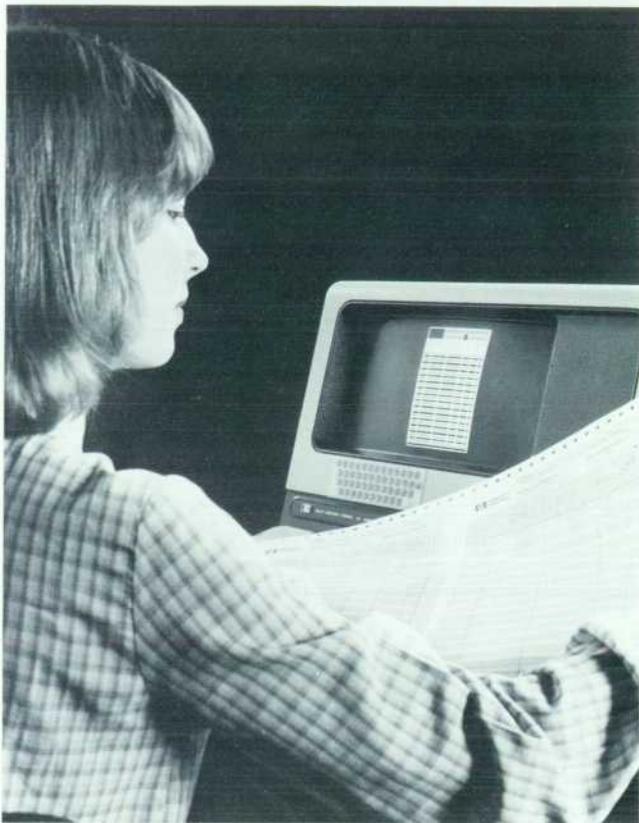
Fig. 3. IDSFORM uses HP graphics terminals to show the user the actual appearance of the form being designed.

IDSFORM

IDSFORM, an interactive, menu-driven program like IDSCHAR, enables a user to design and modify forms. A form, the fixed, static, nondata portion of a document, can range in complexity from a simple letterhead to an elaborate customer invoice. Forms can contain both characters and simple graphics. Some kinds of graphics created by IDSFORM are lines, boxes, and shaded areas. One or more forms can be grouped together in a forms file; these forms can be related or unrelated.

IDSFORM uses HP's graphics terminals to represent to the user the actual appearance of the form that is being designed (Fig. 3). A subsystem that works this way is using a technique known as "what you see is what you get."

Two methods of filling in forms are supported by IDSFORM. Print-and-space is the conventional method, already used in applications where output is directed to a line printer. Symbolic access, a method particular to the printer support package, eliminates the programmer's need to count lines and spaces and to change the application program when the form is changed. If the forms designer gives a name to each data field on a form, the applications programmer can invoke a special intrinsic to cause data to be written to that named field, leaving the computation of the exact position to the support software. These techniques are discussed in more detail in the section below on compatibility.

To use a form in a document to be printed on the 2680A, a user selects that form during the formatting phase, using IFS2680.

IFS2680

IFS2680, also an interactive, menu-driven program, enables a user to control the format of documents to be printed by the 2680A. With IFS2680, a user combines desired character fonts and forms with device-specific printing information. This information includes physical page definition, logical page definition, and vertical forms control specification. All of the user's formatting instructions are compiled into an environment file. Thus, an environment file contains device-specific instructions for printing a document or an application job. Typically, one environment file represents one application.

IFS2680 provides for automatic rotation and scaling, when possible, of forms and character fonts. Because forms definition is independent of the ultimate printing device and the desired print orientation, it may be necessary for IFS2680 to rotate or scale a form to map it to the 2680A's logical page. Character font scaling for text in forms is accomplished by selecting the appropriate size from the previously specified character font file. Although character fonts can be designed for specific orientations, IFS2680 automatically rotates character fonts if a specific orientation is needed but has not been defined.

IFS/3000 includes a set of the most commonly used environments. Using HP-supplied environments, output can resemble a pica typewriter, an elite typewriter, a regular line printer, or a Times Roman document. 2:1 and 4:1 reductions of these environments are also available.

Intrinsics

IFS/3000 includes a set of user-callable intrinsics to allow application programs to control the format of their output dynamically. Users can select character fonts, forms, and logical pages, acquire information such as the state of the printer, the length of a given string, or the text of an error message, and direct data to a particular field on a form.

```
                SAVE CELL

 ------------------------------------------------

 [A]      Character
            -OR-
 [    ]   Character code number
 [1  ]   Version number
 [1  ]   Ranking (1 is best, 999 is worst)
 [0  ]   Orientation (0,90,180,270 degrees)

 [S]     Destination
          H - Temporary hold
          S - Stored in file

          File name
 [CHARFILE                                    ]
 [       ] Point size
            -OR-
          Cell size
 [ 25]   Height
 [ 20]   Width
```

Fig. 4. In this IDS/3000 menu, users enter information on the left side and read information from the right side. When the user presses the **TAB** key the cursor moves in a smooth vertical path through the menu. "Character," the most frequently used field, is at the top.

Compatibility

The most important design consideration for the printer support package was compatibility. It is crucial that existing application programs be able to use the 2680A with as little conversion effort as possible. This conversion process actually takes place in two steps, with a third step provided for new applications.

Suppose an application program already exists whose output is printed on a conventional line printer. That application can be converted immediately to use the 2680A as a line printer replacement. Conversion on this first level is simple: no programming is involved, but the full feature set of the 2680A is not used.

To redirect an application's output to the 2680A the programmer simply adds a file equation to the stream job for that application. A file equation is a tool provided by MPE to use files (in this case, the output file) in a manner other than what has been specified in the application program. Among the parameters that can be specified in the file equation are the output device (DEV) and the environment file to be used to format the output of the application program (ENV). In this case, the user can take advantage of the HP-supplied environment file (LP.ENV2680A.SYS), which makes the 2680A output look like that of a regular line printer. An example of a file equation is:

```
:FILE FormalFileDesignator;DEV=PP;ENV=LP.ENV2680A.SYS
```

where FormalFileDesignator is the formal file name used by the application program in the FOPEN command of its output file and PP stands for page printer.

A level-two conversion effort is required by an existing application program that prints its output on a preprinted form. Conversion on this level is a bit more complicated than that on the first level. In the pre-2680A world, the preprinted form is on special paper that gets mounted by an operator before the application's output is printed. To make the conversion, no programming is required. Instead, the application programmer (or some other individual) must use IDSFORM to design an electronic form that looks exactly like the existing preprinted form. Then, the programmer creates an environment file, using IFS2680, that contains that form. The name of that environment file is used in place of the HP-supplied environment file specified in the level-one conversion, like this:

```
:FILE FormalFileDesignator;DEV=PP;ENV=YourEnvironmentFile
```

FormalFileDesignator is as above and YourEnvironmentFile is the name of the environment file containing the needed form. Since the form is stored and downloaded to the printer electronically, no operator intervention is required at print time. Note that it may have been necessary to use IDSCHAR to design a company logo to be included as part of the form. At this conversion level, no additional programming is required, yet many of the 2680A's features can be exploited.

Historically, application programmers cause data to be placed in specific locations on the printed page by using print-and-space techniques: the programmer needs to specify the exact row and column location of each data item

on the page. Application programs that can be converted on levels one and two use this technique.

The third level of conversion actually involves a brand new technique for positioning data on the printed page. This technique is known as symbolic access and can be used for new application programs. To make this possible, first the IDSFORM user gives a name to each field on the form; a field is defined as an area on a form where data can be placed. Then, instead of using the print and space method, the application programmer invokes the printer support package intrinsics to cause data to be written to a named field. The intrinsics calculate the exact location of each data item, relieving the application programmer of that chore. An additional benefit of the symbolic access method is low overhead when modifying forms: if a field needs to be moved to a different location on a form, as long as the name of the field isn't changed, the application program doesn't need to be modified. This third level of conversion allows programmers to take advantage of the full feature set of the 2680A.

Ease of Use

Another prime consideration in the design of the printer support package was ease of use: the system should be usable by people with little or no computer background. Several specific features of the system are results of this design criterion.

Instead of using a command-driven or design-language type of interface, the printer support programs use interactive, CRT-oriented, menu-driven interfaces. This type of interface makes the system available to all nontechnical users and is especially friendly for novices. To avoid penalizing the sophisticated user, IDSCHAR also provides an expert mode, consisting of two-letter commands. Moreover, since the interface is interactive, IDSCHAR and IDSFORM are able to use graphics simulation to provide "what you see is what you get" feedback.

The system was designed around the "principle of least astonishment," which states that good software minimizes the user's astonishment at what actually happens when the user invokes a function. Following this principle, useful defaults are provided throughout the system. These defaults serve to minimize the efforts and expertise required of the novice user and to increase the productivity of the expert user. Second, menus are partially filled in by the system; often, if it doesn't know some information, it makes a reasonable guess or uses a default. Third, HP supplies the

```
IDSCHAR MAIN MENU                          COPYRIGHT HEWLETT-PACKARD CO.
X.01.06                                    MENUS X.01.06          1980

[nn] Selection

  CR  - Create

  M   - Modify/Add

  DO  - Document

  D   - Delete

  E   - Exit

  File name
[charfile]
```

Fig. 5. *A general principle of IDS/3000 menu design is that each word should convey important information.*

most commonly required character fonts and environments as part of the system.

Menu Design

Although the printer support software was designed with ease of use as a goal, initial feedback from test sites indicated that the design team had not achieved that goal as well as anticipated. Fortunately, the artists and designers using the system made some valuable suggestions. Working with the design team, they established several general principles and assisted in designing the menus according to those principles.

The first principle stresses the importance of laying out the menus with consistent focal points, as shown in Fig. 4. This minimizes user confusion and fatigue and speeds up the learning process. Second, certain conventions that dictate where various types of information should be placed within a menu have become the rule. Fig. 4, for instance, shows a menu with fields in which users can enter information on the left side of the menu and read textual information from the right side. This placement of information results in "alleys" which are easier to work with than scattered blanks. This layout also solves a third problem. By pressing the **TAB** key a user can move the cursor directly to the beginning of the next field. The cursor moves in a smooth, vertical path through the menu instead of jumping unexpectedly in the horizontal direction. Undesirable cursor hopping can cause user frustration and a waste of valuable time.

Fourth, it is always desirable to reduce the number of actions a user has to perform to accomplish a task, in this case to design a character or form. To speed the process, the new interface contains sensible defaults and a logical arrangement of entry blanks. In the first menus that were developed, entries were scattered; the most frequently used entries were not near the top. Fig. 4 shows a menu designed to reflect actual frequency of use. "Character," the most frequently used field, is the first one on the menu. Fig. 4 also demonstrates a convention in information placement: variable information that cannot be changed by the user is located in unhighlighted fields on the left side of the menu.

Finally, it is important to ensure that all the words in a menu convey important information: short, succinct menus save both user reading time and system response time. Fig. 5 gives an example of this principle.

Systems Tailored to the User

Each subsystem's interface is oriented specifically to its primary user. Since IDSCHAR's audience typically consists of artists and industrial designers, the program uses terminology and concepts already familiar to them.

IDSFORM's users are both application programmers and industrial designers. Many features of the program provide a link between these two groups of users. For example, often forms must be designed according to the constraints of the application program. In a print-and-space form, data can only be printed at discrete line and character locations. Therefore, IDSFORM optionally displays a grid indicating those discrete locations, allowing the form designer to align graphics more easily with printed data.

IFS2680's users are almost exclusively application programmers. The menus tend to be more complex than would

be tolerated by a nontechnical user, but use terminology appropriate to its technical target audience.

Extensibility

The third major design consideration, extensibility, concerns the internals of the printer support package. Since this is the first software package of its type, very little information was available during its design about who the actual users of the system would be and how they would use it. The development team anticipated that by studying the first customers and modifying the software appropriately, they would be able to achieve more fully the original ease-of-use goal. Thus, it was important that the internal structure of the software lend itself to easy modifications.

Furthermore, although the 2680A is currently the only intelligent printer manufactured by HP, there may some day be other devices that need to be supported by the printer support software. Hence, it was also important that the system be designed to ease the process of making extensions to the product.

To facilitate extending the software to support new devices, IDSCHAR and IDSFORM are designed so that they can be used without modification to create character fonts, logos, and forms for any new intelligent printer that HP might decide to build. IDSCHAR achieves its device independence by allowing the user to specify the characteristics of the target output device and actually simulating those characteristics during the design process. Once the font has been designed, however, it should always be used with the device for which it was created (or a device that has identical characteristics). Business forms created using IDSFORM are not tied to a particular target device, since a form's simple graphics (boxes, lines, shading) can be converted to a format understandable by any dot matrix printer.

Of course, to use either of these device-independent packages with a particular printer, the character fonts, logos, and forms need to be converted into a format understandable by the target printer. In the case of the 2680A, this missing piece of software is the IFS2680 program. It is anticipated that an IFS program will be written for many intelligent printing devices that HP will build in the future.

Since the development team was exploring somewhat

Fig. 6. *A special program used in the development project underlines key words, such as if-then-else in this example, to make them easy for development programmers to see when debugging code.*

uncharted territory with this system, we decided to develop a prototype version of IDSCHAR. This program was used by HP's Corporate Industrial Design group to design character fonts for the 2680A. The prototype development did, in fact, prove to be extremely worthwhile.

Because the Industrial Design group was involved at such an early stage, their valuable feedback was easy to incorporate; the design was still in a very flexible state. The development engineers were able to assure that IDSCHAR uses terminology appropriate to the artist. In addition, by making most of the design mistakes with the prototype program and throwing that program away, they were able to develop well structured code in the final version of IDSCHAR that didn't suffer the ravages of experimentation.

Coding Standards

To make the code more readable and sharable, the development team agreed on a set of coding conventions. First, all compiled code, before being printed, is filtered through a program that underlines reserved words. The result is that compiler keywords are very easy to identify—especially those that are misspelled—and constructs, when indented properly, seem to jump off the printed page. Notice how this works for the if-then-else construct in the code shown in Fig. 6.

Second, all procedure names and macros* are typed in uppercase letters, with liberal use of ' to make them more readable. Macros, except for those used for debugging (discussed in the next section) have an initial lowercase d. Some procedures in the sample code in Fig. 6 are:

COMPUTE'CELL'PLACEMENT, COMPUTE'CELL'BOUNDS, and FLOOR.

Third, variables and constants are a mixture of uppercase

and lowercase. Some examples shown in Fig. 6 are: CurrentCell, SpaceOnLeft, and CC'XBottomLeft. CC'XBottomLeft demonstrates another convention used. It is part of the record rCurrentCell, and the beginning of its name is derived from the initials of the record of which it is a part.

Finally, an intitial lowercase letter is used to distinguish certain classes of names: g indicates a global variable; c, an equated constant; r, a record structure; d, a macro (the keyword for a macro is "define"); and l, the length of a record. For example, in Fig. 6, rCurrentCell is a record structure and cLeftMostPointOnScreen is an equated constant.

Debugging Package

To make it easier to modify the code, the development team used parameterized macros to build a debugging package into the software. The package consists of several macros which fall into three major categories: procedure tracing, assertion testing, and variable information.

CURRENT'PROCEDURE'IS, in Fig. 6, is an example of a procedure-tracing macro. It causes the name of the current procedure to be displayed. The two ASSERTs in Fig. 7 are examples of assertion testing. Failure of assertions causes the program to abort; the ASSERT macro is used only when the conditions that cause the assertion failure imply that disaster has already taken place. Variable information about the current state of the program is displayed by the DEBUG'MSGs shown in Fig. 8. Notice that for the debugging macros the team chose to apply the capitalization conventions for procedures.

Each macro takes at least two parameters: region and level. During design, the development engineer breaks the program up into regions, or strings that describe functional areas, with each region roughly equivalent to one source module (less than 1000 lines of code). The level is a numerical value that describes the level of detail that this

*A macro is a compound command that stands for a sequence of commands and is invoked by a single name. Macros may also be called macrocommands, macroinstructions, or defines.

Fig. 7. *The project's debugging package is based on parameterized macros. ASSERTs are macros that test assertions. Failure of an assertion causes the program to abort.*

Fig. 8. *Variable information about the current state of the program is displayed by DEBUG'MSG macros. Such information is useful to HP programmers debugging the software.*

particular debug message shows, 1 being least detailed and 7 being most detailed. Other possible parameters include strings to be printed literally and variables whose values are to be printed.

In Fig. 7, the first DEBUG'MSG specifies the region Main, while the level is 2. In Fig. 8, the region used in the first DEBUG'MSG is NEWCGF and the level is 4. Fig. 8 shows several DEBUG'MSGs which also include a string to be printed, along with a variable whose value is to be plugged into the string.

To use the debug package, the HP programmer enables all of the regions to be debugged by setting appropriate JCWs (job control words). Second, the programmer specifies, via a file equation, the logical device number of the terminal to which the debug message should be directed. The final step is to run the program, specifying a run parameter that indicates the desired debug message and trace levels.

Use of this debugging package had a significant effect on the productivity of the original printer support package development team. Engineers who work on the product in the future will undoubtedly also benefit.

Kathleen A. Fitzgerald
Kathy Fitzgerald is a project manager with HP's Information Networks Division and was responsible for IDSCHAR, a component of the 2680 Laser Printing System software. A native of Utica, New York, she received her BS degree in computer science and mathematics from the University of Scranton in 1978. She joined HP in 1979 after fourteen months as a scientific programmer with an aerospace company. She's a member of the ACM and a resident of Menlo Park, California. Her interests include books "by the dozen", movies ("all of them"), dancing, weight lifting, skiing, and river rafting.

Electrostatic Image Formation in a Laser Printer

by Erwin H. Schwiebert and Paul R. Spencer

IN ELECTROPHOTOGRAPHY, the image on the paper is created in several stages, as explained in the box on page 6. This article covers the second step, that of producing the electrical image on the drum, including initializing the drum electrically.

The heart of the process is the photoconductor drum, the structure of which is shown in Fig. 1. The aluminum substrate is coated with a layer of cadmium sulfide about 40 micrometres thick. On top of this is a layer of polyester about 25 micrometres thick. The cadmium sulfide layer is photoconductive. Its electrical resistance is high in the dark and becomes several orders of magnitude lower in the presence of light. The polyester layer is a high-quality electrical insulator. Electrical charges are applied to the drum by corona discharge devices which consist of one or more fine wires held at a potential high enough to ionize the air nearby.

To describe the imaging process, it is convenient to use a simplified ideal electrical circuit model as shown in Fig. 2. Some of the departures from this ideal will be mentioned below. The CdS layer is represented as a capacitor in parallel with a resistance that varies with the amount of light shining on it (C_p and R_p). The dielectric polyester layer is represented as a capacitor only, since it is a very good insulator (C_i). The corona will be described later but it can be modeled as a Thevenin-equivalent voltage source with a
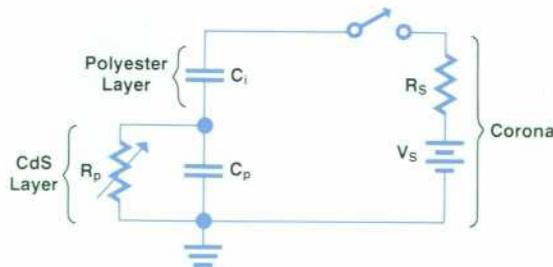

Fig. 1. *Photoconductor drum construction.*

Fig. 2. *Idealized electrical circuit model of the photoconductor drum and the charging corona.*

fairly high internal resistance (V_S and R_S).

The electrical image is formed in three stages as shown in Fig. 3.* This figure shows the voltages of the drum surface and the CdS-insulator interface as functions of time. Fig. 3b is for a drum area not exposed to the laser, and Fig. 3c is for an area that is exposed to the laser. Shown in Figs. 3a and 3d are snapshots of side views of the drum illustrating the charges at each of the interfaces between drum layers for each of the process stages.

First, a layer of positive charge is applied to the drum at the time labeled "charging." Light is also applied to make the CdS layer conductive. Because the layer is conductive the voltage across it stays small. The voltage across the insulating layer increases to 1300V. The charge pattern in the drum after the charging step is shown at A in Fig. 3a and 3d. The negative charges are image charges attracted from the substrate and through the conducting CdS layer by the positive charge applied to the surface. Referring to Fig. 2, this process is equivalent to closing the switch for a time, while the variable resistance is kept small.

Second, the drum is scanned by a laser beam which is modulated to make the dots that will form the characters to be printed. At the same time, a corona discharge device with a negatively biased ac voltage applied to the corona wire provides a mixture of positive and negative ions to make the air conductive. This drives the drum surface potential to zero in both the exposed and nonexposed areas.

*In Fig. 3, the effects designated A, B, and C correspond to stations A, B, and C in Fig. 3 on page 7.
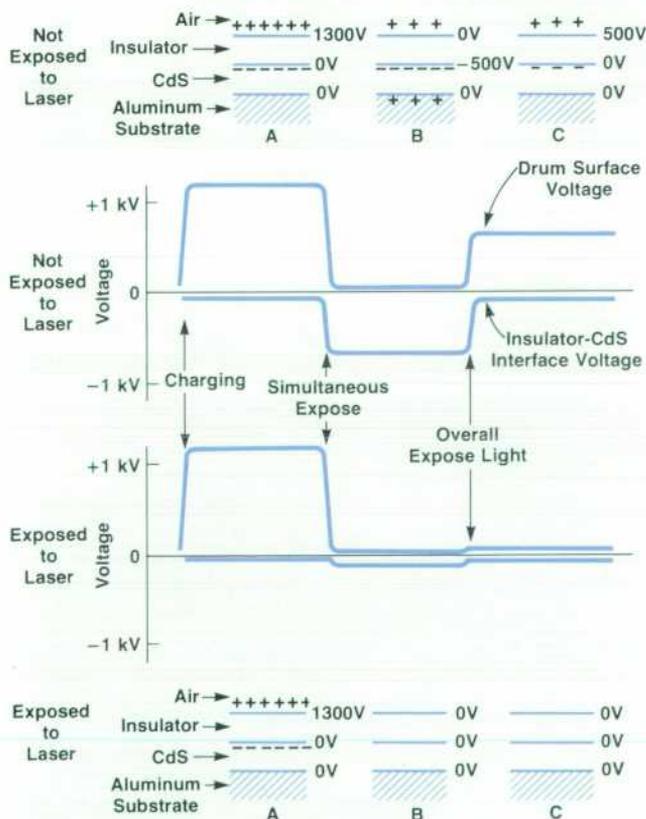
(For the present discussion the effect of the negative bias can be ignored.) For areas exposed to the laser the CdS remains conducting and the voltage across the CdS is also zero (B in Fig. 3c). Where the drum is not exposed to the laser the CdS-insulator interface voltage is driven negative (B in Fig. 3b). This is because a net negative charge is delivered to the surface of the drum resulting in the charge configuration shown at B in Fig. 3a. Considering this process in terms of Fig. 2, the voltage source must be replaced by a resistance (with the switch closed). For the laser-exposed case the variable resistance is small but for the nonexposed case it is very large.

Third, in the overall-expose step, the drum is flooded with light which makes the CdS conductive. After this step, the potential of the surface in laser-exposed areas is approximately zero and in nonexposed areas it is about 500 volts, as shown at C in Figs. 3b and 3c. Again referring to the capacitor model in Fig. 2, this is equivalent to making the variable resistance small. The electrostatic image formation is complete after this step. The means for using these voltages to produce a visible image on the drum is explained in another article (page 20).

Corona Design

The corona devices are the elements that produce the charges used to make the electrostatic image as explained above. There are three corona devices, the primary corona device, the simultaneous corona device, and the transfer corona device.

The elements of the simultaneous corona device, for example, are shown in Fig. 4. If the corona wire is at a high enough voltage, air molecules near the wire are ionized. This happens when the electric field (or voltage gradient) near the corona wire is greater than the threshold electric field for air breakdown. Some of these ions migrate to the photoconductor surface and increase or decrease the surface charge depending on the ion and drum surface polarities. The endblocks are made of insulating material and support the corona wire or wires and the connector to the corona power supply. The housing is a frame to hold the endblocks and help direct the ion current to the photoconductor, and to support a wire grid if it is needed. A grid may be used to control the spatial distribution of ion current, or to allow control of the ion current by photoconductor voltage if the grid is biased to some voltage.

Corona Wires

The primary requirement for a corona wire is that it produce ions by means of a corona discharge at a reasonable voltage. The electric field outside a wire held at a high voltage is inversely proportional to the radius. To achieve the required field at a reasonable voltage the corona wire diameter must be less than approximately 90 micrometres (0.0035 in). The wire material must be chosen to resist the harsh environment (ozone, ultraviolet light and various nitrogen-oxygen compounds are produced in the corona discharge), and to resist breakage caused by the stresses of stringing, handling and cleaning. For this reason and because of relatively low cost, 76-micrometre-diameter uncoated tungsten was chosen. Smaller-diameter wires had a significantly higher breakage rate.
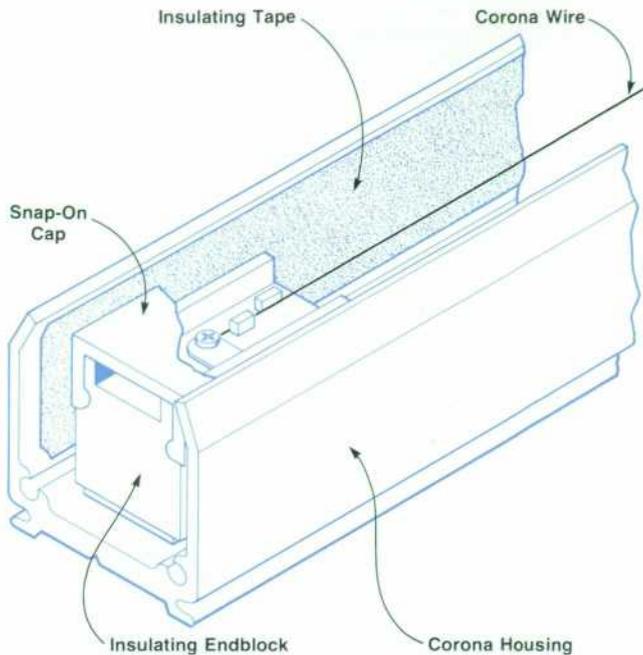

Fig. 3. *Formation of the electrical image on the photoconductor drum.*

Fig. 4. *There are three corona devices in the laser printer. This one, the simultaneous corona device, illustrates the elements of a corona device and the insulating endblock.*

Wire vibration is a potential problem for the simultaneous corona device, which is driven with a 400-Hz ac voltage which can be as great as 17 kV p-p. The wire is attracted to any conductors with a different potential, so that wire vibration at twice the frequency of the ac waveform can be induced. This occurs either when the wire is too loose or when the tension puts the natural vibration frequency of the wire near 800 Hz. Thus the wire tension for this corona must be held within a tolerance band of about 20%.

During operation, the surface of the corona wire degrades because dust and some of the chemicals synthesized by the discharge are deposited on the wire. It must therefore be cleaned periodically with a brush or with a swab and alcohol.

Insulating Blocks

The corona wire must be supported by the insulating endblocks in such a way that there is no high-voltage breakdown during operation even after a long period of operation. Breakdown can be avoided by choosing a material with good insulating properties and designing the surface topography so that there is not a short, straight path from a high voltage to ground. In addition, the voltages present are high enough that it is important to avoid edges or points with a small radius to prevent unwanted corona discharge from conductors at high voltage or from grounded conductors adjacent to high-voltage areas. A sketch of an endblock that satisfies these requirements is shown in Fig. 4. The body is molded from Mycalex™, which is a combination of glass and mica. This material is inert and does not burn. The snap-on cap is extruded from a fluorocarbon plastic which is an excellent insulator and is also chemically inert.

The corona wires can be strung easily (with cap removed)

because the surface on which the wire rests extends the whole length of the block. The wire can be positioned and pulled to the correct tension from either end of the corona assembly before a handle is installed.

One endblock provides a detachable connection to the power supply so that the corona device can be removed from the machine for cleaning or inspection.

Corona Housing

The corona housing is a U-shaped piece of aluminum made by extrusion. It slides into a track mounted in the printer. This track is accurately aligned during machine assembly so that the wires are parallel and at the proper distance from the drum surface. This means that the coronas can be accurately positioned and yet are easily removable for cleaning, inspection, or replacement.

The primary corona device and the simultaneous corona device both have a thin insulating coating on part of the inside of the housing. This increases ion current to the drum for the same corona wire current.

Primary Corona Device

In the printing process some areas of the photoconductor drum are treated differently from others. For example, some are written with the laser while others are not. This means that the potential of the photoconductor just before it enters the primary charging corona may be as low as -180 volts or as high as $+100$ volts. So that previously written data does not appear as ghosts in subsequent pages, the photoconductor charge must be uniform and at a standard value before data is written with the laser. One way often used in electrophotographic technology to accomplish this is to erase the photoconductor evenly to the desired value. We have chosen instead to charge it directly to the desired potential with a single corona device. This eliminates a high-voltage ac power supply and the associated control circuits and has resulted in longer photoconductor lifetime because of improved suppression of ghosts.

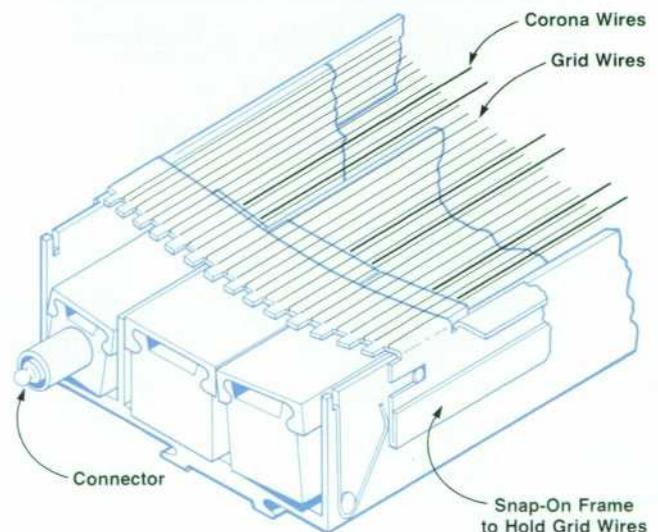A screened corona device is used for this purpose. A diagram of such a device is shown in Fig. 5. This type of

Fig. 5. *Primary corona device.*

corona charging device has a wire screen, or grid, held at a potential near the desired photoconductor charging potential so that the potential of the photoconductor controls the charging rate. As the drum potential reaches the desired value for any position on the drum, the charging current decreases. Thus different areas of the photoconductor drum are charged differently depending on the starting potential, so that all areas reach nearly the same potential after charging. To help provide more constant final drum potential, the drum is illuminated by an electroluminescent strip between the transfer and cleaning stations and by incandescent bulbs behind the first section of the primary charging corona.

Corona Grids

As explained above, the primary corona device has a wire grid to allow the drum potential to control the charging rate. The grid design is based on a compromise between available charging rate and precision of control of the final drum potential. As the number of wires per centimetre increases, the control of the drum potential improves but the charging rate decreases because of the greater fraction of ions intercepted by the grid wires. The distance between the grid wires was chosen to achieve the best potential control (closest wire spacing) possible at a reasonable corona wire supply current. Grid wire diameter was chosen to be small enough to allow conveniently low stringing force. The material is stainless steel to avoid corrosion.

The simultaneous corona device also has a grid between the corona wire and the drum surface. Its purpose is to help direct the ion flow to the drum at the proper location relative to the laser beam so that the maximum contrast between dark and light potential is achieved. The wire size in this case is the same as the corona wire, 76 μm, and the wire positions were chosen empirically.

Electrostatic Potential Control System

To achieve consistent image development it is necessary to maintain the laser-exposed (light) and unexposed (dark) potentials at the proper values for each image and machine. In a practical machine the drum potentials depend on a large number of factors; several of these vary with time or ambient conditions or depend on the specific component used to assemble the printer. For example, neither the primary charging process nor the simultaneous-expose process go to completion and there is a negative dc bias superimposed on the ac voltage for the simultaneous corona. This means that both the light potential and the dark potential are functions of the currents for both the primary and the simultaneous coronas. (Light potential is dependent on laser beam intensity as well.) The fraction of corona wire current that reaches the drum in the form of ions depends in turn on wire surface contamination, relative humidity, and other factors. Other examples of factors that can vary are photoconductor and polyester layer capacitance and photoconductor sensitivity.

Long-term variations of light and dark potentials of the drum are avoided by measuring the drum potentials with an electrostatic voltmeter and adjusting the primary charging corona and simultaneous corona power supply settings until the drum potentials are within a few volts of the desired values. We have chosen to make corona settings control corona supply current. This is because the relationship between corona supply current and drum voltage is much more linear than the relationship between supply voltage and drum voltage. The supplies are controllable constant-current supplies which provide good short-term control of corona operation.

The electrostatic voltmeter used to measure the drum potentials is described in another article in this issue (page 26). The photoconductor drum has a seam which is slightly diagonal (not quite parallel to the drum's axis). The triangular drum areas near the seam cannot be used for printing and therefore are available for process control. On alternate revolutions this area is exposed or not exposed to the laser, giving light and dark potentials, respectively. A voltage reading is made once each revolution for the the process control patch near the drum seam. When both light and dark potentials have been measured (every other drum revolution), corrections to the corona settings are made if the

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Paul Spencer received his BS degree in physics in 1963 from Washington State University. He was awarded a master's degree and a PhD in physics by the University of Illinois in 1969, and spent a year doing postdoctoral research in solid-state physics at Stuttgart University in Germany. Since joining HP in 1979 he has worked on a variety of tasks in the process area for the 2680A Laser Printer. His previous experience was in electrophotography, sensor development and ink-jet printing. He is a member of the American Physical Society and is the inventor or a co-inventor for three patents in electrophotography and ink-jet printing. He is co-author of a paper on nuclear magnetic resonance and a review of toner adhesion. Paul is married to a chemistry professor and has a son and a daughter. He is an avid soccer player, enjoys camping, hiking, photography, and mechanical and electronic design and fabrication in his home shop.

Erwin H. Schwiebert

Erwin Schwiebert was born in Boise, Idaho, received the BS degree in mathematics and physics from the College of Idaho in 1963, and went to Ghana with the Peace corps to teach high school mathematics and physics. Returning home, he received his MS degree in physics from Oregon State University in 1968 and for the next five years he did space simulation test engineering. In 1975 he received his MEE degree from the University of Idaho and joined HP's Boise Division 2680A Laser Printer design team. Last year he was named manufacturing engineering section manager for the 2680A. He's a member of the IEEE, lives in Eagle, Idaho, is married to an HP engineer, and has two daughters. Erwin has built his last two houses and is working on an active solar system for his current one. He also enjoys music and camping.

potentials are different from the light and dark potential targets. Both settings are corrected at the same time using the equations given below.

$$\Delta P = \frac{\partial P}{\partial D}\Delta D + \frac{\partial P}{\partial L}\Delta L$$

$$\Delta S = \frac{\partial S}{\partial D}\Delta D + \frac{\partial S}{\partial L}\Delta L$$

ΔD and ΔL are the desired changes for the dark and light potentials, respectively. ΔP and ΔS are the changes that should be made to the primary and simultaneous corona current settings to achieve these dark and light potential changes. The partial derivatives are the variations required for a primary or simultaneous corona current setting to obtain a change in light or dark drum potential. Actually,

these coefficients are chosen to be smaller than the experimentally measured values of the partial derivatives to ensure that the control loop is stable.

Once the new settings have been determined, these values, the three previous corona settings, and the drum potentials are evaluated for error or fault conditions. Depending on the seriousness of a fault, a warning message may be displayed or the printer may be stopped and a failure message displayed. If no error or fault conditions are found, and if the corona settings have not changed by more than one count from the previous values, it is assumed that the corona settings have reached a stable state within the operating range of the corona supplies.

This is a type 1 or integrating control system. It does not require a high gain to maintain operating values close to a desired point. This is important for the 2680A because it provides very good immunity to noise.

Laser Printer Image Development System

by Thomas Camis

THE 2680A LASER PAGE PRINTER uses a dual-component, conductive, reversal developer mixture designed for compatibility with a negative-to-positive development system sometimes called discharged-area development. In this system the electrostatic lines of force terminate in the laser-exposed character regions and are used to drive toner into this area. The dual-component mixture consists of electrostatically charged dry toner particles attached to oppositely charged iron carrier beads. The toner particles are a low-melting-point thermoplastic polymer material with small amounts of carbon black and a special additive dispersed within the polymer to give it color, hardness, and the proper (positive) triboelectrification properties. Triboelectrification or "tribo" charging of dissimilar, nonconducting materials may be thought of as a combination of frictional charging plus rubbing-assisted contact charging. The basic charging mechanism is an exchange of electrons from the material having the lowest work function potential to one having a higher value. The work function is usually measured in electron-volts (eV), and may be thought of as the energy required for an electron to just free itself from the material with no kinetic energy remaining.

In the 2680A the small toner particles are mixed with larger dissimiliar carrier particles. The result is a positive tribo charging of the toner and a negative charging of the carrier. The substantial positive charge on the toner makes it compatible with the negative (reversed) latent image on the 2680A's photoconductive drum. The carrier particles

are electrically conductive, ferromagnetic oxidized beads that serve two purposes: they provide a means for transporting the toner in the magnetic brush system, and they serve to charge the toner to a proper polarity by triboelectrification.

Mixture Design Objectives

A number of design objectives were proposed for the 2680A developer mixture to satisfy requirements for quality, reliability, and safety. Among these are excellent print quality, compatibility with the electrophotographic process, long mixture life, radiant fuser compatibility, high toner yield, nontoxic/noncarcinogenic materials, and environmental compatibility.

Overall print quality is of major importance. Required are uniform large solid-area densities near 1.0 density units with low background (nonimaged area) toner deposition. High-resolution images are also desirable. The maximum allowable printed dot size is 0.20 mm from a nominal latent-image dot size of 0.13 mm.

The developer mixture ingredients must work harmoniously within the electrophotographic process, which uses a polyethylenetelephthalate (Mylar™) overcoated photoconductive drum. The drum cleaner system is a vacuum assisted polyurethane blade arrangement.

A developer mixture lifetime goal of more than 150,000 rotations (200,000 pages) was established for the 1.2-kg mixture charge. A high toner yield is also desirable, with the goal being at least 15,000 pages from each kilogram of

toner assuming a nominal coverage of about 7-10%. The toner must have a low melting point and be compatible with a radiant fusing system in which the maximum temperature is 160°C.

Health and safety considerations are also prerequisites for the toner materials. Toner and carrier formulations must comply with all EPA standards, and must not contain any ingredients that may be considered carcinogenic or constitute a hazardous waste.

Developer materials must be compatible with the photoreceptor and blade cleaner assembly. Carrier and toner materials and properties must be chosen so they do not abrade the wear layer or damage the cleaning blade during development, transfer, and cleaning sequences.

Both developer and toner material must function properly within the environmental operating specifications of 15°C to 35°C at relative humidities of 10% to 70%.

Mixture Design Approach

Hewlett-Packard's major contribution in the development of the toner/carrier mixture was in specifying the optimum carrier and toner parameters through theoretical analysis and extended machine testing. A portion of the development effort went into optimization of the toner parameters to achieve a long-lived developer mixture using a low-melting-point toner. One of the important constraints imposed upon the toner was that the charge per unit mass (q/m) should be sufficiently low to prevent what is called a "tribo-limited" development system. Preventing this condition requires that the counterdevelopment potential generated by the toner on the photoconductive drum be substantially less than the applied development potential. Tribo-limited development is undesirable because it ultimately causes print quality degradation and limited mixture lifetime because of higher than normal toner concentrations. The following expression was used to determine a maximum limit for the toner triboelectric charge per unit mass assuming more than a monolayer of toner.

$$T_{max} < \frac{V_B}{\left\{\left(\frac{m}{A}\right)\frac{L_m}{\epsilon_o k_m} + \left(\frac{m}{A}\right)^2 \frac{1}{2\epsilon_o \rho k_t P}\right\}}$$

Where toner parameters are defined as:

ρ = Toner density (grams/cubic centimetre)
V_B = Developer bias (volts)
T_{max} = Maximum toner triboelectric charge per unit mass (coulombs/gram)
ϵ_o = Permittivity of free space (farads/centimetre)
m/A = Developed toner mass per unit area required to achieve specified output density (grams per square centimetre)
L_m = Thickness of Mylar overcoating on photoconductive drum (centimetres)
k_t = Dielectric constant of toner
P = Packing factor
k_m = Dielectric constant of Mylar overcoating.

There are a number of important tradeoffs when selecting the proper toner triboelectric charge q/m. For example, if q/m is too high the operating toner concentration will ulti-
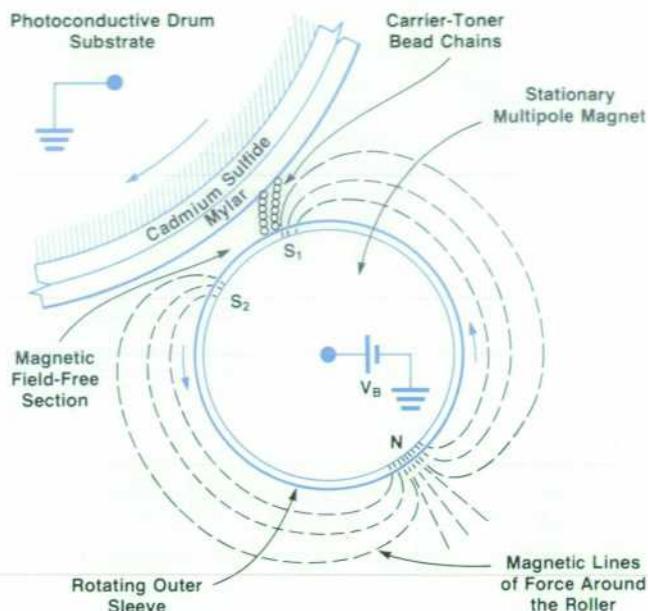

Fig. 1. *Toner developing unit configuration.*

mately increase, causing more unwanted background toner deposition. A high-q/m toner is also more difficult to detach from the photoconductive drum, making cleaning and transfer more difficult. Very high-q/m toners also tend to remain on the carrier surface for longer periods of time; to some extent this responsible for a rapid increase in the filming of the carrier commonly known as impaction.

A very different condition such as low toner q/m will result in the toner's being scattered into the nonimage or background regions of the print area causing poor print quality. Loss in edge acuity of characters and solid areas is characteristic of low-charged toner, which should be avoided. In principle, the toner charge per unit mass is chosen somewhere between a minimum value that may cause toner scattering and a high value that causes higher toner concentrations and a more rapid impaction of the carrier substrate, which leads to failure. Characteristics of the toner development curve as a function of q/m and toner concentration are discussed in a later section.

The toner particle size distribution for the 2680A was determined experimentally by evaluating toner size effects upon the following: image quality, useful carrier lifetime, toner transfer efficiency, toner flow properties, machine dirt and contamination, and compatibility with the cleaner assembly and photoconductive drum. Toner particles that are relatively large are more easily developed and transferred because of the large detachment forces that can be applied to them. This result is not inconsistent with adhesion theory, since the forces acting to detach a given toner mass increase faster than the adhesion component. The tradeoff in performance for larger particles is that they inherently provide less optical covering power and produce lower-resolution images. Large particles are also less effective in providing the residual lubricating layer of toner that is essential in a blade cleaning system.

It follows that very small toner particles are typically more difficult to develop, transfer and clean from the photoconductive drum. Smaller toner particles also create

contamination problems in the machine area. An additional concern and an important consideration when optimizing the toner size distribution is the rate at which the toner films or impacts the carrier surface. Very small toner particles have a tendency to cause rapid filming of the carrier surface because of selective retention within the developer assembly. The small particles are subjected to long-term mechanical forces which eventually permanently affix them to the carrier surface. Poor print quality results, characterized by loss of character edge acuity and high background toner deposition. The toner shape is also an important parameter to consider since rough-surface toners exhibit lower nonelectrostatic, Van der Waals adhesion forces. A careful choice of toner surface properties, therefore, can enhance development, transfer, and cleaning.

The melting properties of the 2680A toner are specified to be compatible with the radiant fusing system, in which the maximum fixing temperature reaches about 160°C. Carrier lifetime is also a consideration when choosing the melting point of the toner since very soft resinous powders tend to film the carrier more readily.

The carrier size, shape, electrical conductivity, surface finish and magnetic properties are all chosen and optimized to achieve the best print quality and long mixture lifetimes. Preserving the electrical conductivity of the particles in the bulk of the mixture was one of the more important parameters and is highly dependent upon the surface characteristics, shape and size.

Toner Development Unit Configuration

The toner developing unit, Fig. 1, consists of a stationary multipole magnet within a biased rotating outer sleeve. The magnetically responsive carrier beads surrounding the roller assembly are metered at the N pole using a doctor blade, then carried onto the sleeve and through the development zone using the strong applied magnetic fields.

In the development zone, the multipole arrangement provides a field-free region where a toner cloud is generated between two soft brushes S1 and S2. Toner cloud development complements the major development mechanism which is the biased electrode effect created by the conductive bead layer. Developer mixture remaining on the roller surface after development drops off the roller in the low magnetic field section (S2-N) and is recycled by a feedscrew system.

Toner Development Model

The toner development model, Fig. 2, shows the cross sectional view of the layered structure and the biased magnetic roller system. A general model is shown including a fictitious air gap that is used to calculate the E-field (electric field) acting on free toner particles. In practice, the dielectric thickness of the mixture layer combined with the Mylar™ insulator (overcoating) is much greater than that of the toner layer, air gap and photosensitive layer. The photoconductive drum can also be considered at near zero potential in the imaged areas that are to be developed. In addition, all induced charge densities resulting from the toner charge and developer bias are not shown but have been accounted for.

The adhesion forces acting between the toner and carrier are assumed to be primarily electrostatic with the nonelectrostatic contributions very small by comparison. The initial condition for toner development, then, is when the detachment force

$$F_D = qE$$

is greater than the force of adhesion given by

$$F_A = \frac{q^2}{16\pi\epsilon_0 r_t^2}$$

It can be shown that a typical adhesion force for the 2680A toner-carrier mixture is on the order of 0.8 millidynes, which requires an electrostatic detachment E-field of approximately 4.5 kV/cm. An equation for the development E-field as a function of the toner development parameters is given below.

$$E = \frac{V_B - V_P - \left(\dfrac{T}{\epsilon_0}\right)\left\{\left(\dfrac{m}{A}\right)\dfrac{L_m}{k_m} + \left(\dfrac{m}{A}\right)^2\dfrac{1}{2\rho k_t P}\right\}}{\left\{\dfrac{L_m}{k_m} + \dfrac{L_B}{k_B} + \dfrac{L_t}{k_t} + L_a\right\}}$$

In the above equations,

V_B = Magnetic roller bias (volts)
V_P = Photoconductive drum potential (volts)
L_m = Mylar thickness (cm)
k_m = Dielectric constant of Mylar
L_B = Thickness of developer mass (cm)
k_B = Dielectric constant of bead layer
L_t = Toner layer thickness (cm)
k_t = Dielectric constant of toner
L_a = Fictitious air layer thickness (cm)
E_o = Initial (no-toner) development field (volts/cm)
E = Net development field (volts/cm)
T = Triboelectric charge (coulombs/gram)
ϵ_o = Permittivity of free space (farads/cm)
m/A = Developed mass per unit area (g/cm²)
ρ = Toner density (g/cm³)
P = Packing factor
q = Toner charge (coulombs)
r_t = Toner radius (cm)

In the 2680A the initial E_o-field (before multiple toner layer deposition) is estimated to be in excess of 100 kV/cm, dropping to an E-field of about 60 kV/cm when development of toner is complete. Changes in the development field over long periods of running time are caused primarily by changes in the dielectric thickness (L_B/k_B) of the developer mass between the roller and the photoconductive drum.

Toner Development Curves

The performance of the toner development system, which includes machine development parameters, is shown in Fig. 3. The toner development curve shows the solid area output print density as a function of the net applied development potential. The print darkness control
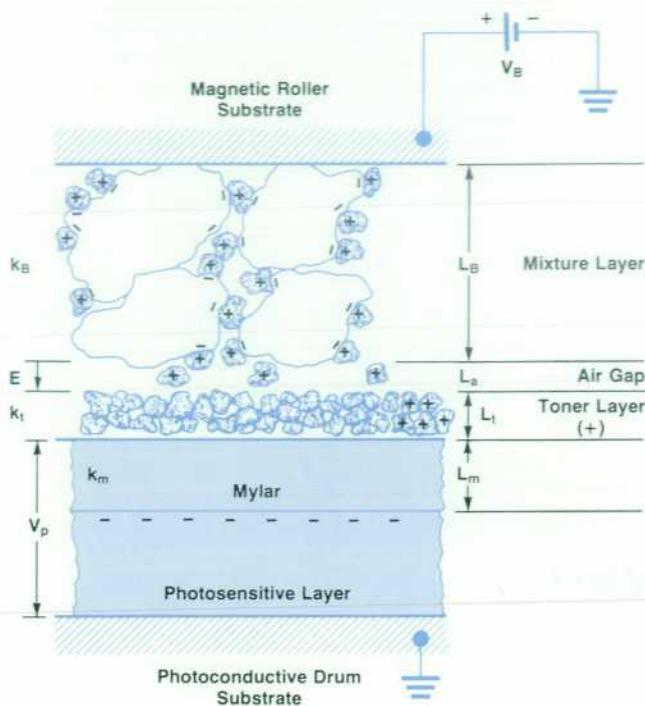
Fig. 2. *Toner development model.*

Fig. 3. *Toner development curve.*

described in the article on page 26 automatically adjusts the toner-to-carrier ratio to achieve the desired output image density setpoint. In practice, as the developer mixture ages because of the gradual impaction or filming of the carrier, several events take place that ultimately degrade the overall print quality.

The gradual accumulation of toner mass on the carrier through electrostatic and mechanical forces will cause a corresponding decrease in the electrical conductivity of the mixture bulk as well as a loss in toner charge. The lower the conductivity of the bead mass, the lower the development E-field. The response from the printer diagnostics will be to increase the toner-to-carrier ratio, which will maintain the output density but will also increase the amount of unwanted background toner. Therefore, the typical print-quality failure mode is not loss in density but unwanted background toner and loss in edge acuity because of low-charge toner.

Printer development parameters and mixture parameters have been optimized to impede the rate of impaction, which is typically responsible for the degradation in print quality. Fig. 3 also shows the potential range or carry-out region where the negatively charged carrier beads can be detached from the biased magnetic roller surface and developed onto the drum. This undesirable condition is avoided in the printer by fixing bias and drum potentials within acceptable limits.

In addition to physical parameters of the toner and carrier mixture, there are other machine influences that can rapidly degrade the print quality. Photoconductive drum potentials are very important to mixture performance, as shown by Fig. 3. The maximum operating range indicated is the allowable range over which bead carry-out and unwanted backgrou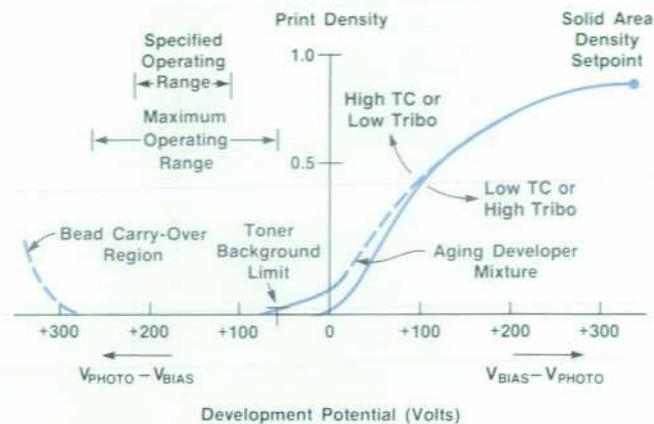nd toner deposition can be avoided under fresh-mixture conditions. However, as the mixture ages a higher drum potential is required to prevent toner deposition in nonimage areas. Therefore, photoconductive drum potentials must not be allowed to fluctuate beyond this 100V boundary during the entire 150,000-rotation lifetime specified for drums and mixtures. Typically 40V of noise is allowed for initial end-to-end and circumferential potential variations, leaving an additional 60V for the remaining lifetime. There are also user-dependent parameters such as high percentage of toner coverage and certain environmental conditions (e.g., high relative humidity) that can adversely effect mixture lifetime and print quality.

Toner Transfer

The toner transfer system in the 2680A is a corona system. A nearly constant negative charge density is applied to the paper while it is in intimate contact with the photoconductive drum containing the developed toner images. The transfer mechanism is designed to retract during the time when the seam area of the drum is passing under the corona, preserving essential process control markings that are used

Thomas Camis
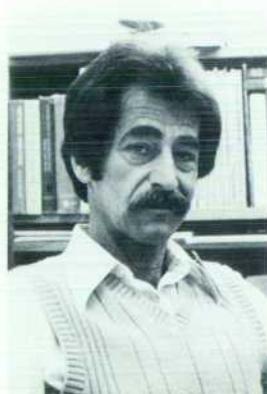
Tom Camis has been an electrophotographer and project leader in the 2680A Laser Printer process control group and is currently a member of the Boise Division technical staff. He joined HP in 1977 with nine years' experience as an electrophotographer. A member of the Society of Photographic Engineers and Scientists, he is named as an inventor on one patent and seven pending patents in the field of electrophotography. Tom received his BS degree in engineering physics in 1969 from Weber State College in Ogden, Utah, and has served two tours of duty in the U.S. Army. A competitive masters division long-distance runner, he has run in five marathons and holds several masters division records in half-marathon hill runs. He also enjoys home computers, family hikes, and off-road motorcycle riding. He's married, has three children, and lives in Boise, Idaho.

to control photoconductive drum potentials and printed image density. The corona-generated electrostatic transfer fields are sufficiently high to transfer over 80% of the toner from the photoconductive drum to the paper under normal computer-room environmental conditions. The voltage applied to the corona is approximately -5 kV, delivering a current density at the drum of approximately 1.5 μA per centimetre of drum length. The efficient transfer of toner is directly related to the ratio of detachment and adhesion forces. The detachment force depends upon the applied electrostatic fields and the adhesion forces result from toner charge properties and nonelectrostatic influences. It can be

shown that transfer efficiencies are highly dependent upon the amount of deposited toner as well as the physical size and charge characteristics. Larger quantities or multilayers of toner are more easily removed from the drum because of the lower toner-to-drum adhesion. Toner size and charge characteristics were chosen to allow an optimum transfer efficiency. Discharging of the paper following the transfer step is accomplished with a passive, conductive, electrically grounded brush arrangement. Discharging of the paper prevents unwanted paper charge and disruptive toner fields which may cause image degradation.

Laser Printer Fusing System

by Roger D. Archibald

DURING THE ELECTROPHOTOGRAPHIC printing process, an image or print is created on a photoconductor drum. This image is made of small (3-7 μm) black toner particles. The toner image is then transferred to a receptor sheet (paper) by contact and electrostatic forces. This toner image is now held on the receptor sheet by low surface and electrostatic forces. The printed image in this condition can be easily smeared by touching or rubbing it. Additional processing must be done to have a permanent image. The additional process is called fusing or fixing.

The toner used in this type of nonimpact printing technology is a thermoplastic resinous powder. When heated, the toner undergoes a change in viscosity, going from a solid powder to a sticky semiliquid substance. Toner particles in this condition will flow together and adhere to the paper, forming a permanent image.

The most common receptor sheet used in nonimpact printing is white bond paper. The 2680 Laser Printing System uses continuous fanfold, single-ply bond paper with left and right margins punched for tractor feed. Uniform heating of this paper is very important to avoid changes in physical dimensions. Paper generally contains about 7% water trapped in the cellulose fibers. Because the fusing temperature of the toner is above 100°C, the trapped water is boiled out. The paper may also have other inks preprinted
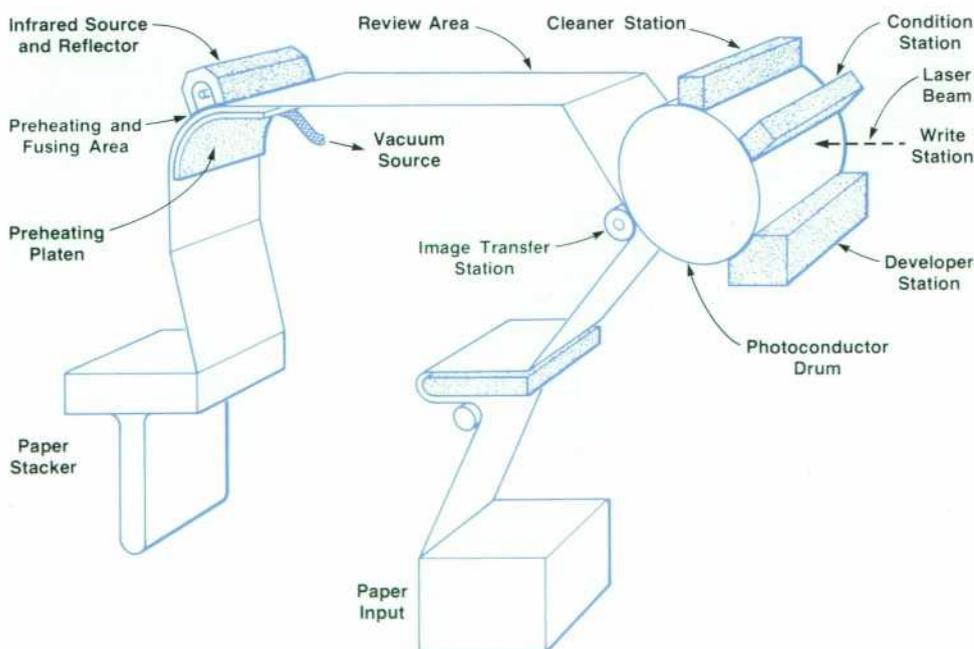

Fig. 1. *To fuse the toner to the paper in the 2680A Laser Printer, the paper and toner are first heated by conduction and then the toner is selectively heated by radiation.*

on it (e.g., a form).

Previously used fusing techniques for heat-softenable toner include radiant heating, which tends to burn the paper if not carefully controlled, and passing the paper and toner between a pair of heated rollers. The latter method suffers from the tendency of the softened toner to stick to one of the rollers and create an offset image or ghost image on the next sheet of paper. Attempts to eliminate this problem by lubricating the roller have been less than perfectly effective.

New Fusing Method

The fusing process in the 2680A Laser Printer uses two methods of heat transfer. The paper and toner are first heated using conduction and then the toner is selectively heated by radiation to complete the fusing. The conductive heating is accomplished by a preheater system and the selective heating of the toner by an infrared fusing system (Fig. 1).

The preheater system consists of a heating plate, a vacuum source, and controlling electronics. As the web of paper with the toned image enters the fusing system it carries with it a boundary layer of air. This layer is trapped between the paper and the preheater and tends to restrict heat transfer between the preheater and the paper. Therefore, it is removed by a series of holes at the leading edge of the preheater. A low vacuum (0.25 metres of water) created on the back side of the preheater removes the trapped boundary layer of air through the series of holes. Heat transfer is enhanced by the removal of this boundary layer. As the paper rises in temperature, the water and other chemicals used in the papermaking process begin to vaporize, creating another insulating layer between the paper and the preheater. This layer is also removed by a series of vacuum holes positioned across the preheater surface. As the paper moves across the preheater its temperature is elevated from room temperature to 125°C. Approximately 2000 watts (113 BTU/min) is transferred to the paper to accomplish this.

The preheater is constructed of a 0.8-mm-thick aluminum plate with a foil-etched silicone rubber heater vulcanized to the back side. The foil heater has a power density designed to compensate for the heat transfer that occurs as the paper travels across the preheater and the heat lost through the edge of the heater where the plate is held. The maximum power density is 3.5 watts/cm². The top surface, which the paper contacts, is coated using an anodized Teflon™-impregnated process, creating a long-wearing, low-friction surface. This is important for paper transport and for preventing stray toner from sticking when heated.

The 2680A can print on paper ranging in width from 165 to 320 mm. To accommodate this range the preheater has four switchable sections. The input tractors sense the width of the paper at the input and the unneeded heater sections are turned off after the preheater reaches operating temperature. Some of the vacuum holes in the preheater surface are uncovered when narrower paper is used. The vacuum holes are sized as restricting orifices, so approximately the same air flow is achieved whether the hole is covered or not. By sizing the holes for choked flow the vacuum level can remain constant regardless of the paper width.

The final step in the fusing process is accomplished by radiant heat transfer. Paper has a spectral response as shown in Fig. 2. It absorbs more energy at longer wavelengths than at shorter wavelengths. To take advantage of this, a quartz halogen lamp was chosen as the infrared source. The lamp has an approximate color temperature of 3100K. At this temperature the lamp emits maximum radiant flux at a wavelength of 0.93 μm, as shown in Fig. 2. The paper is somewhat reflective at this wavelength, while the toner appears as a perfect absorber at all wavelengths. Because of these characteristics the toner can be selectively heated to its melting point (fusing point) without a significant amount of energy going to the paper. This minimizes the total energy required to fuse the toner to the paper.

Because the printer is an on-line device, the fusing system must be able to stop and start rapidly. Therefore, the elements of the fusing system have short time constants. The preheater, the slowest to warm up, requires only 30 seconds to reach its operating temperature.
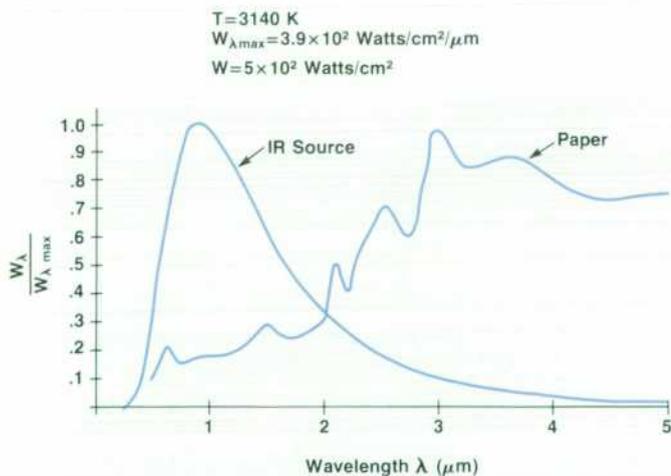
T = 3140 K
$W_{\lambda max}$ = 3.9 × 10² Watts/cm²/μm
W = 5 × 10² Watts/cm²

Fig. 2. *Spectrum of infrared source and paper spectral response. The paper is somewhat reflective at the IR wavelength, while the toner is a near-perfect absorber at all wavelengths.*
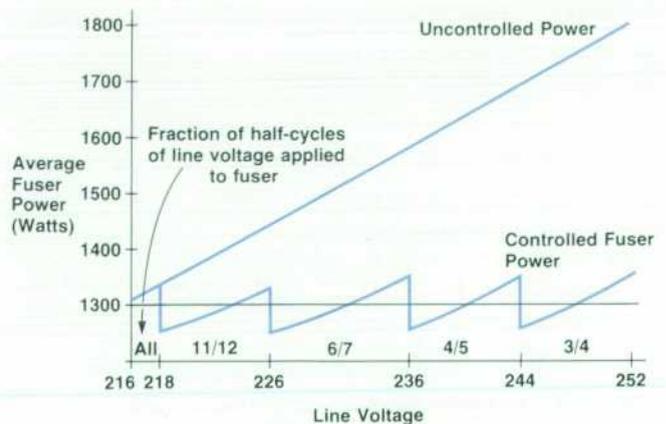

Fig. 3. *Input voltage to the fusing system is regulated by clipping half-cycles of the line voltage if the rms line voltage rises above 216V.*

Fusing System Electronics

The controlling electronics for the fusing system can be divided into two areas: 1) control of input line voltage and 2) temperature control of the preheater. The fusing system has been designed to operate at 216 volts rms. This is the lowest voltage at which the 2680A will operate.

The line voltage to the fusing system is monitored by the machine control system (MCS). To maintain nearly constant fuser power, half cycles of the ac line voltage are clipped. For example, at a line voltage of 250 volts one out of every four half cycles is clipped out of the ac input voltage. As the line voltage changes, the fraction of clipped half cycles changes, as shown in Fig. 3.

The temperature of the preheater surface is measured by small thermocouples attached to the back side of the preheater plate. The silicone rubber foil heater is divided into three sections which are controlled separately. A thermocouple in the center of each section provides a feedback signal to a proportional controller. The thermocouple signal is also used by the microprocessor to monitor the operation of the preheater. If for some reason a failure occurs and the temperature of the preheater exceeds a preset temperature, the line voltage is removed from the fusing system. If a paper jam occurs, the fusing system is shut down immediately.

Roger D. Archibald
With HP since 1975, Roger Archibald was part of the 2680A project team and now is a project manager for non-impact printers. He was born in Blackfoot, Idaho and attended Brigham Young University, earning the BS (1974) and MS (1975) degrees in mechanical engineering. Roger also holds an MBA degree from Boise State University, awarded in 1979. He is a registered professional engineer in the State of Idaho. Roger is married and has two small children. Besides holding various positions in his church and the Boy Scouts of America, his outside interests include tennis, snow and water skiing, woodworking, and tinkering around his home in Boise, Idaho.

Monitoring the Laser Printing Process

by Ronald A. Juve and David K. Donald

ELECTROPHOTOGRAPHIC SYSTEMS are very sensitive to environmental variations and corona device contamination. If the important print parameters are not monitored, print quality may be poor. The measurement systems within the 2680A Laser Printer monitor the potentials of the photoconductive drum, the developed image density, and the toner/carrier mixture level in the developer housing. This information enables the process control system to maintain good print quality for hundreds of thousands of pages by overcoming the problems created by variations in assemblies, humidity, and atmospheric pressure. The system is also capable of warning the operator of marginal operating conditions or stopping the printer in case of failure.

Electrostatic Monitor

Drum potentials monitored and controlled by the microprocessor system are measured by an electrostatic volt-
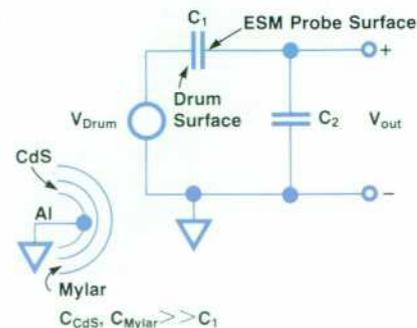

Fig. 1. *Electrostatic monitor (ESM) equivalent circuit. The ESM is a noncontacting electrostatic voltmeter used to measure drum potentials.*

meter. This noncontacting voltmeter measures drum potentials from −130V to 630V in a diagnostic area of the drum and scales them between 0 and 5V for analog-to-digital conversion. If the measured drum potentials are not equal to the target values, the power supplies for the voltage generating devices (corona assemblies) are adjusted to correct the error. This closed-loop control reduces operator intervention to cleaning the corona devices to maintain a good electrostatic image. No other operator adjustments are necessary.

The detection of the drum potential begins with a capacitive divider. In Fig. 1, C1 represents the capacitance from the electrostatic monitor (ESM) probe to the drum and C2 represents the ESM input capacitance. Very simply derived,

$$V_{out} = \frac{C1}{C1+C2}.$$

One disadvantage of this is that the gain depends on C1, which is determined by the size and position of the ESM probe relative to the drum. To overcome this calibration problem, an ac signal source is used to inject a reference signal for a gain control loop. As shown in Fig. 2a, this configuration has the ESM probe referenced to ground and the drum potential referenced to the ac signal source. The output by superposition then equals:

$$V_{out} = (V_{dc}+V_{ac})\frac{C1}{C1+C2}.$$

As expected, the gain is the same for the drum potential and the ac signal. However, having the system ground at this position means isolating the normally grounded aluminum layer of the drum and creating a sliding contact to the drum for the ac signal. Both of these are undesirable. The 2680A system is implemented with the ground on the other side of the ac signal source as shown in Fig. 2b. This means the drum is used as it was originally designed and the ESM circuitry is referenced to the ac signal. For this configuration,

$$V_{out1} = V_{dc}\frac{C1}{C1+C2} - V_{ac}\frac{C2}{C1+C2}.$$

Since the ESM circuitry is referenced to and uses the
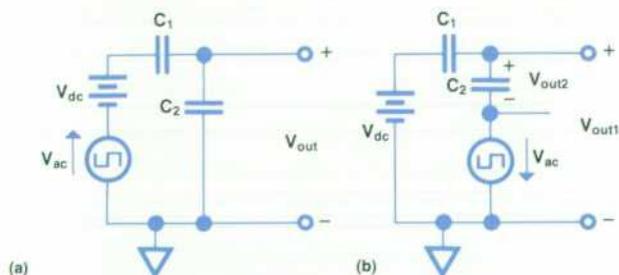

Fig. 2. An ac signal is used as a reference signal for a gain control loop to remove ESM gain dependence on the size and position of the ESM probe. Of two possible configurations, the 2680A Laser Printer uses (b).
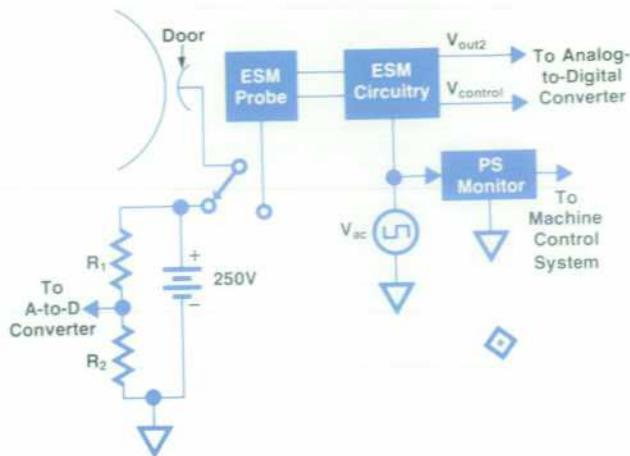

Fig. 3. ESM block diagram. Initial conditions are zeroed with the door between the probe and the drum. For measurements, the door is rotated out of the way.

voltage across C2, V_{out2} is more useful.

$$V_{out2} = V_{out1}+V_{ac} = (V_{dc}+V_{ac})\frac{C1}{C1+C2}.$$

The initial conditions of C1 and C2 are controlled by a removable door and by a reed switch across C2 inside the ESM probe (Fig. 3). The initial conditions are zeroed with the door between the probe and drum and the reed switch across C2 closed. To make a measurement, the reed switch is opened and then the door is rotated out of the way. The change in voltage that occurs at the node between C1 and C2 represents the drum potential. This voltage is buffered by a
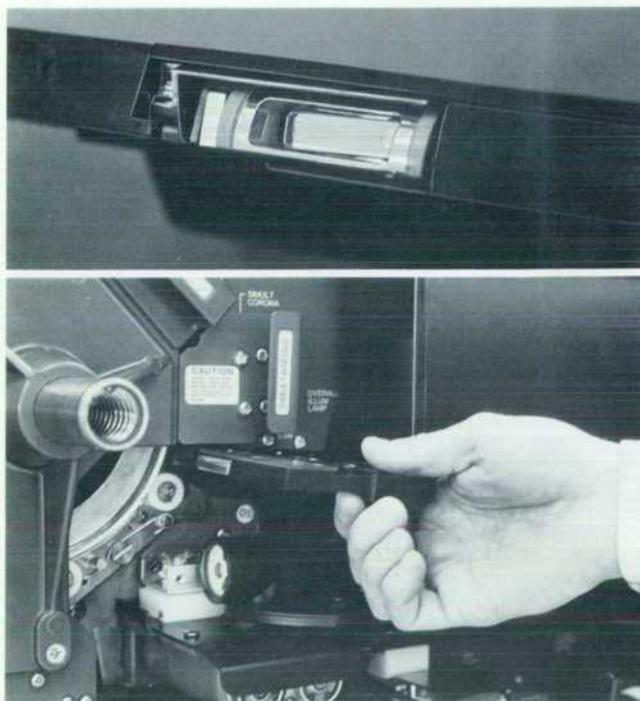

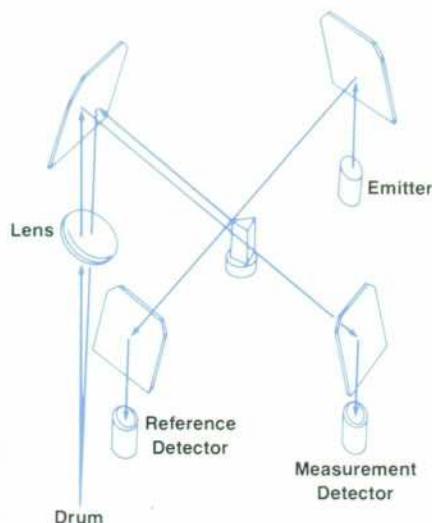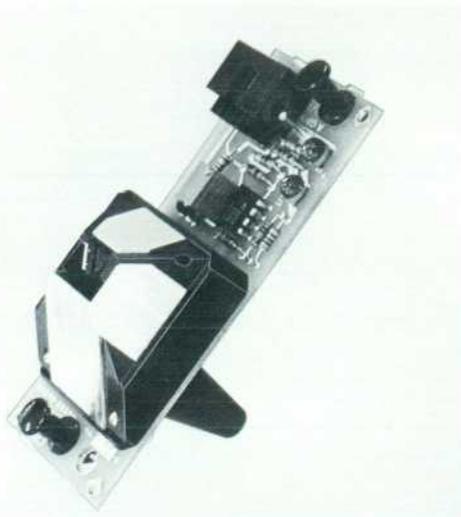**Fig. 4.** ESM probe assembly and mounting location.

Fig. 5. Density monitor (DSM) measures developed image density by reflecting infrared light from a process mark on the drum.

MOSFET whose source voltage is in turn buffered by another transistor. The impedance conversion that occurs through these stages is from about 10^{12} ohms to less than 20 ohms. A low output impedance was necessary to drive the 0.75-metre output signal path from the probe position near the drum to the remaining ESM circuitry in the cardcage.

The ESM circuitry is coupled both in frequency and amplitude to the ac signal source. Should this ac source change frequency or amplitude, the ESM's operation is not disturbed and the assembly continues to make accurate drum potential measurements. Several diagnostic routines monitor the ESM circuitry to catch the problems before print quality suffers. The amplitude of the ac reference power supply V_{ac} is monitored on a regular basis. The check made is for positive and negative supply voltages of at least 50 percent of the expected amplitude. Before each job starts printing, a gain diagnostic is executed. During the diagnostic the ESM prepares to make a measurement, but at the time when the door should open, the normally grounded door is temporarily switched to a known potential and measured. The potential is known from a measurement of the output of a resistive divider across the source of the potential, and the ESM's output should agree very closely with this value.

During printing, when measurements are taken every rotation of the drum, a control signal from the ESM is monitored; this signal represents how much gain is being adjusted. The requirement is that the ESM gain during a measurement settle at something less than the maximum gain. Normally the gain settles at about half the maximum.

Fig. 4 shows the ESM probe assembly and mounting arrangement near the drum. Also shown are the probe surface and the door rotated to the measurement position.

Density Monitor

The second important process parameter monitored in the 2680A is developed image density. The monitor measures the amount of toner developed in the interdocument zone, a diagnostic area of the drum. This represents the amount of toner in the user's area of the drum. If the density is below the target value, the system adds toner to the developer assembly. From time to time the operator is required to add a new bag of toner to the toner dispensing

hopper. The operator is warned of a low toner supply with the message TONER HOPPER LOW. The density monitor is a closed-loop system controlled by the machine control system (MCS).

Like the electrostatic monitor, the densitometer (DSM) has a sensing assembly near the drum. The sensing assembly, shown in Fig. 5, overcame a difficult optics problem—undisturbed operation in a dirty environment. Toner particles are very small, typically 13 micrometres in diameter, and have a bad habit of depositing where they're not wanted. Our first densitometers, which were mounted close to the drum, were contaminated after 2,000 to 5,000 pages. The present system has a lens and a protective cone, and contamination of the densitometer has been eliminated.

The density measurement is made by shining a pulsed infrared (IR) light onto the drum and measuring the amount of light reflected from a test pattern, or process mark. Toner particles absorb IR and a clean drum surface reflects IR. Therefore, the more toner there is on the drum, the less reflected IR is measured. The assembly near the drum holds the IR emitter, which is strobed at 2.4 kHz, two IR detectors, and the optics housing. The optical path is shown in Fig. 5.

To check image density, the system prints the process mark in the interdocument area on each drum revolution. The process mark is a group of three 4.5-mm-wide bars separated by spaces, accommodating the user's need for both conventional print and extended black areas. The signal reflected from the process mark is averaged over three measurements, each measured value being the darkest of ten strobed glimpses at the drum (to eliminate timing errors). A running average of 19 three-measurement averages smooths the signal for comparison with the target value.

Once every 20 rotations, a solid black area is printed. Once every 500 rotations a clean drum measurement is made to check the optics. These values and the printing conditions for each rotation are stored in nonvolatile memory for use in relative reflectance computations and to help the customer engineer diagnose failures.

Fig. 6 shows the DSM circuit. Detector D1 measures the intensity of the IR emitter in a direct path completely within the optics head. This measured reference signal is used to control the current to the IR emitter. IR emitters degrade
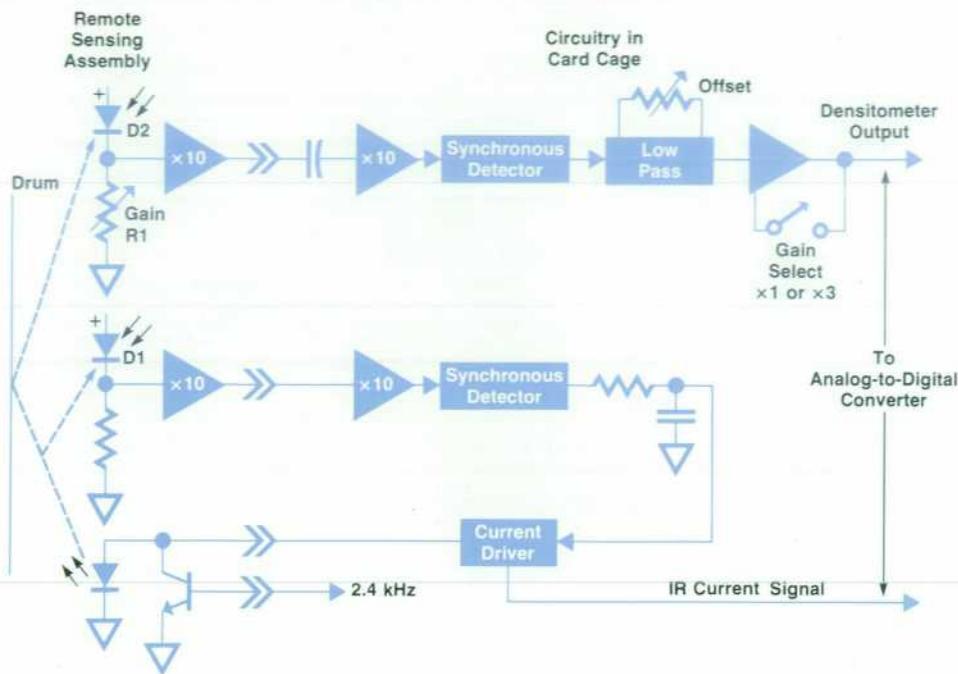
Fig. 6. *DSM circuit.*

with time; for the same drive current, the light output drops. This would directly affect the density measurement, but with closed-loop control of the drive current, the light output remains calibrated after the gain is set by R1 in Fig. 6. A signal from the current driver is used to determine if the current is within an acceptable range.

The measurement signal path is also shown in Fig. 6. The output of detector D2 is amplified, demodulated, filtered, and amplified again. With the normal ×1 gain, a clean drum measurement is nearly full-scale for the analog-to-digital converter. However, when looking at a black toner-covered area, more resolution is needed, so the final amplifier's gain is switched to three times the normal value.

Developer Volume Sensor

The third process parameter measured in the 2680A is the level of the image developing mixture. This mixture normally consists of 95% iron particles called carrier and 5%
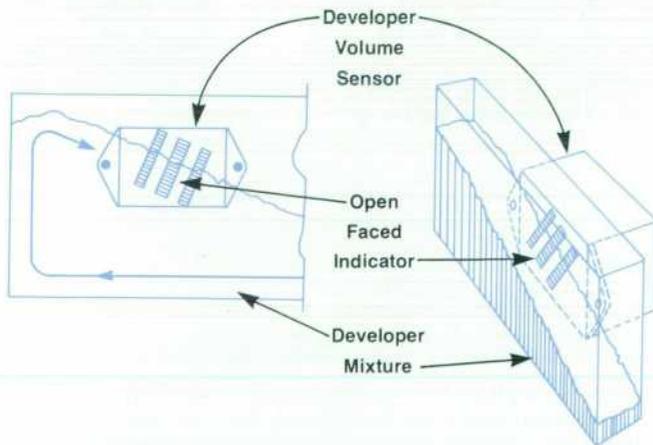
toner particles. The developer assembly holds the mixture and is located next to the drum. A magnet and rotating roller in the developer assembly move the carrier and toner past the drum surface.

While toner is the major consumable component of the developer mixture, small amounts of carrier are also con-
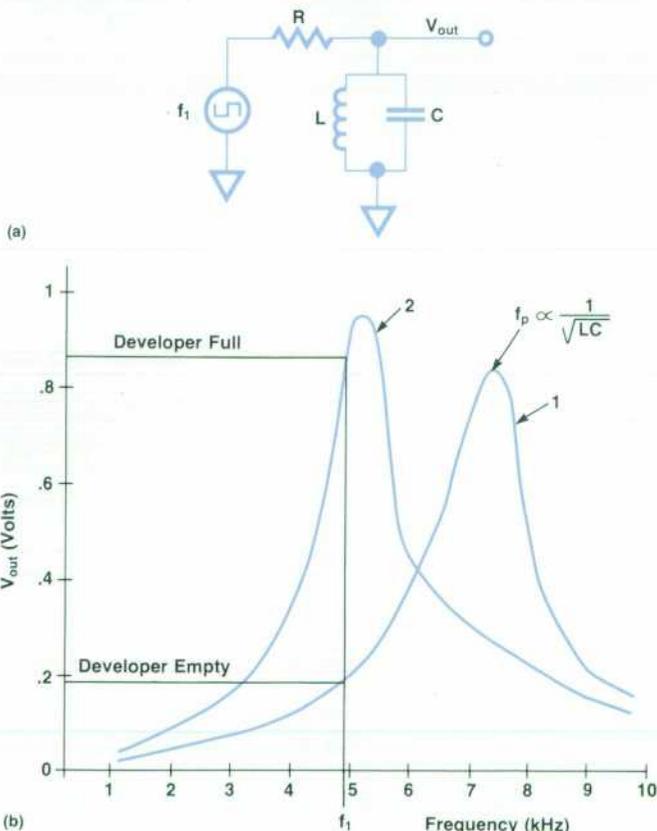

Fig. 7. *Developer volume sensor (DVS) measures the level of the image developing mixture.*

Fig. 8. *DVS circuit and frequency response.*

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Dave Donald received a BA degree in physics from the College of Wooster and BS and MS degrees in electrical engineering from Massachusetts Institute of Technology, all in 1958. He then spend a number of years researching electric fields in, at, and on surfaces. This work related to photocopying machines, adhesion of dust to surfaces, and static electricity. When not "up to his elbows in dust," he contributed to a dozen publications in these areas, electroluminescence, and Schottky barriers. He is named as a co-inventor on two patents on electroluminescent devices and a pending patent on printing technology. Dave joined HP laboratories in 1975. He has done research on printing methods and worked on the 2680A Laser Printer project. He's a member of APS, IEEE, SPSE, and Sigma Xi. Born in Chicago, Dave now lives in Palo Alto, California. "In an earlier life" he raced small sailboats and iceboats, but now prefers the more relaxed pace of hiking.

Ronald A. Juve
Ron Juve received the BSEE degree in 1976 from Washington State University and then joined HP to work on various electrical aspects of the 2680A Laser Printer. He is now a support engineer for the 2680A. Ron has continued his studies while at HP, earning the MSEE degree from Stanford University in 1981. He is named inventor on an electrostatic voltmeter patent. He is single and hails from Clarkston, Washington. Ron's interests include backpacking, skiing, playing guitar, and working on his home in Boise, Idaho.

sumed. If the mixture falls below a minimum level there will not be enough to fill the gap between the drum and the developer roller, and proper development of the image will not occur. To monitor the mixture level, a developer volume sensor (DVS) is attached to the back of the developer assembly. Print quality is constant over a wide range of developer volume, and the DVS assures that the volume remains within this range. The DVS output has three significant values. At CARRIER LOW the operator is notified to add carrier. At DEVELOPER FULL the addition of toner is stopped, and at DEVELOPER OVERFULL the control system notifies the operator and shuts down the printer.

The sensor is an open-faced stack of E-shaped laminations with a coil wrapped around the stack (Fig. 7). As the developer level varies, more or less of the open face is covered, and the inductance of the coil is affected. The coil is connected in parallel with a capacitor and the pair is driven by a frequency source as shown in Fig. 8a.

If the sensor is not covered by any developer mixture the coil inductance is lowest. The output voltage plotted as a function of frequency would be like curve 1 in Fig. 8b. If the sensor is covered with developer mixture, the inductance increases and lowers the resonant frequency. A plot of frequency versus output voltage would now appear like curve 2 in Fig. 8b.

What is of interest is the voltage across the RLC network when operating at a fixed frequency, f_1. As can be seen in Fig. 8b, the output voltage at f_1 varies with the coverage of the sensor. Thus the amplitude of the signal V_{out} represents the level of developer mixture. This fixed-frequency signal is amplified, peak-detected, and filtered before being measured by the analog-to-digital converter. This system provides continuous information over the range of mixture levels.

Specialized High-Speed Electronics for Document Preparation Flexibility

by Philip Gordon

THE ELECTROPHOTOGRAPHIC technology selected for HP's 2680A Page Printer offers high dot resolution (180 dots per inch) and speed (45 pages per minute). It was the intention of the digital design team to build a sophisticated controller to harness the imaging potential that the technology provides and make the resulting print features easily available to the user. The design objectives included rotation of the print page in any of four orientations, multiple pages of text per physical sheet of paper (i.e., page reduction made possible by the small dot size), completely variable character set sizes and fonts alterable on a character-by-character basis, proportional spacing, overlapping and superposition of character elements, electronic forms overlay, and complete freedom to place a character of any orientation at any position on the page. The digital system that implements

these features is called the data control system (DCS). Support duties such as monitoring and controlling the actual printing mechanism are assigned to a separate microprocessor-based system called the machine control system (MCS). The MCS will be described in next month's issue.

Why a New Architecture Was Needed

The DCS design team had to decide how best to realize the desired user features within an imposing framework of aggressive performance requirements. Although there are in reality many different performance limiting situations, two quite visible targets that were established early are the following:

1. The DCS has to be able to print over 15,000 very small characters, excluding blanks, within an 8½×11-inch physical page, at 22.5 characters per inch. This is an extreme situation that can be approached when a user has requested the highest-density four-to-one page reduction format. At 45 pages per minute, 15,000 characters have to be processed in 1.33 seconds, allowing about 90 μs per character.
2. Each physical page space has 2048 dot positions along the longer laser scan direction and 1536 dots along the shorter direction. Three million dot decisions have to be made in 1.33 seconds, allowing about 400 ns per dot.

The first target roughly establishes minimum performance requirements for ASCII data byte processing, and the second does the same for character dot image processing. For comparison, a 900-line-per-minute dot matrix impact printer using a fixed 5-by-9-dot character font with none of the key features of the HP 2680A would have to perform similar computations at an average speed of 500 μs and 11 μs, respectively.

The design team examined not only many different hardware configuration possibilities, technologies, and firmware algorithms that might have achieved the above goals, but also the higher system-level ramifications. It was concluded that just two fast, highly tuned processing systems could meet the objectives.

The first processor coordinates the entire DCS operation, but its principal responsibility is to organize the incoming ASCII print data according to the rules of the print environment selected by the user (i.e., page rotation, reduction or multiple page factor, form overlay, etc.). It does this by viewing the print page as a quadrant in a Cartesian coordinate system. This processor is called the data processor, and its general performance criteria were established by target 1 above.

While the data processor is charged with the more complicated decision-making tasks, a second processor, faster yet, maps the organized data into the appropriate pictorial dot image. This is the character processor, and its general performance criteria were established by target 2 above. Both principal processing systems, the HP-IB I/O interface (HP's implementation of IEEE Standard 488), and the interface to the machine control system are positioned along a single bus for convenience and flexibility.

Centralized Memory

The last question was memory. In addition to small temporary storage buffers, most dot matrix printers include at least two major memory systems. One is a read/write memory (RAM) that holds the ASCII data and control bytes and possibly print position and format information. The second memory consists of ROM (and perhaps configurable RAM) that holds the standard and optional character set dot image patterns. In addition to the character sets and ASCII data storage, the 2680A needed a memory for the organized data, electronic forms overlay buffers, and tables for the page environment and composition. Furthermore, while traditional line printers need to store only several lines of data, the 2680A needed to buffer multiple pages of print data.

A common read/write memory offered several advantages. First, there will be greater demands for many character sets of different sizes, fonts, and rotations than ever before in an HP printer, since users will want to request different character sets and page formats for each job. Because of the high dot density, several large ROMs would be required for each resident character set. RAM, reloaded for every job from the HP 3000, seemed more appropriate than many ROMs. Second, applications that require many different resident character sets are not likely to request a large number of printable characters on the page. Conversely, high-density page reduction formats that call for a lot of data on each sheet will probably require only one small character set. A universal memory gives the design team the opportunity to allocate memory space dynamically among needs based upon the job environment. Third, if a forms overlay buffer is not required for a job, the space can be used for another purpose. Finally, the manufacturing costs for one large array are significantly less than for several localized memories. The principal disadvantage is that there maybe some performance degradation when the data processor and the character processor are vying for memory resources. Although a universal read/write memory is not traditional for a printing system, its advantages seemed to dominate.

Because it is used for so many different purposes and is accessed independently and randomly by more than one processor, the memory has to be not only large but also reasonably fast. The memory controller and memory array products that were designed for and are used in the present family of HP 3000 Series 40/44 Computer Systems were selected. This memory is fast, consumes little power, has high storage density, is reliable (it has single-bit error correction), and required neither additional development nor
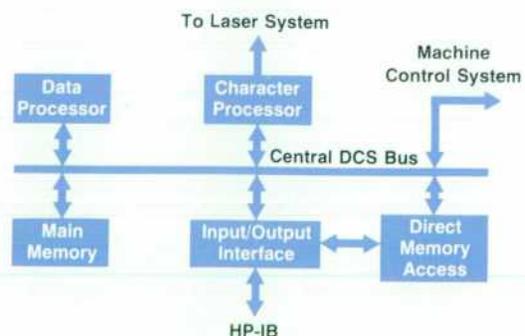

Fig. 1. *Block diagram of the data control system of the 2680A Laser Printer.*

manufacturing investment. The minimum 2680A config- uration consists of one memory controller and one 128K- word memory array module that uses dynamic RAM com- ponents. Expansion is accomplished by simply adding higher-density or additional arrays.

Adopting these assemblies constrained the size for the card cage and the backplane electrical definitions and pin- out positions. The board size was quite amenable to the evolving packaging arrangement. The backplane definition and protocol, called the intermodule bus, was the result of careful thought by HP 3000 design engineers to establish a flexible, high-performance, low-noise backplane. The 2680A backplane could be easily planned around the hand- shake and operational methodology already defined.[1] The resulting overall block diagram of the DCS is illustrated in Fig. 1.

Data Processor

None of the highest-speed single-chip LSI microproces- sors could come close to meeting the performance require- ments for the data processor. Furthermore, a good, solid design using multiple single-chip microprocessors could not be envisioned. Fortunately, bipolar bit-slice processors were gaining greater acceptance and use as multiple vendor sources, lower costs, and more powerful support chips were being made available. Bit slices are LSI building blocks that can easily be cascaded to implement processing logic. They do require a moderate amount of support logic, yet the result can be a system virtually as powerful as a discrete implementation for less cost. The principal speed advan- tages of bit-slice versions stem from the fact that the hardware design can be optimized to complete the critical computational tasks in an efficient manner, and that low- level microinstructions can be programmed directly and finished in one cycle. In the case of the single-chip micro- processor, the structure is fixed by the manufacturer and high-level program code requires multiple minor cycles to execute one instruction. The 2900 family of components was chosen.[2,3]

Selection of the HP memory system dictated a 16-bit data bus. Directly addressing the maximum memory eventually planned within the system requires 20 address bits. Be- cause speed is important and memory accesses by the data processor are frequent and critical, two cycles to load a 20-bit memory address each time cannot be afforded. Either a 16-bit data processor with a supplementary memory map- ping system or a 20-bit data processor could have been designed. Because bit-slice processors are easily expand- able, the latter alternative is less costly, conceptually more simple, and requires no periodic overhead to set up memory maps. Five four-bit slices compose the kernel of the data processor.

The many pointers required to address memory are fre- quently modified to access stored data and operands. To maintain speed, the solution was to add a local 256-word 20-bit memory that is immediately accessible. The structure of the data paths of the data processor is illustrated in Fig. 2.

While in a single-chip microprocessor the programming language and rules of behavior are absolutely defined, it is up to the designer of the bit-slice processor to do likewise. The format selected is optimized for the frequently per- formed computational tasks and is patterned into a 32-bit word. Two bits determine the type of word structure used, that is, how the other 30 bits are to be interpreted. This represents a compromise between a purely horizontal struc- ture (with a high degree of functional parallelism) and a vertical structure (which keeps firmware costs low and microprogramming techniques relatively simple). 10K 32-bit words of firmware are required to implement the data processor functions.
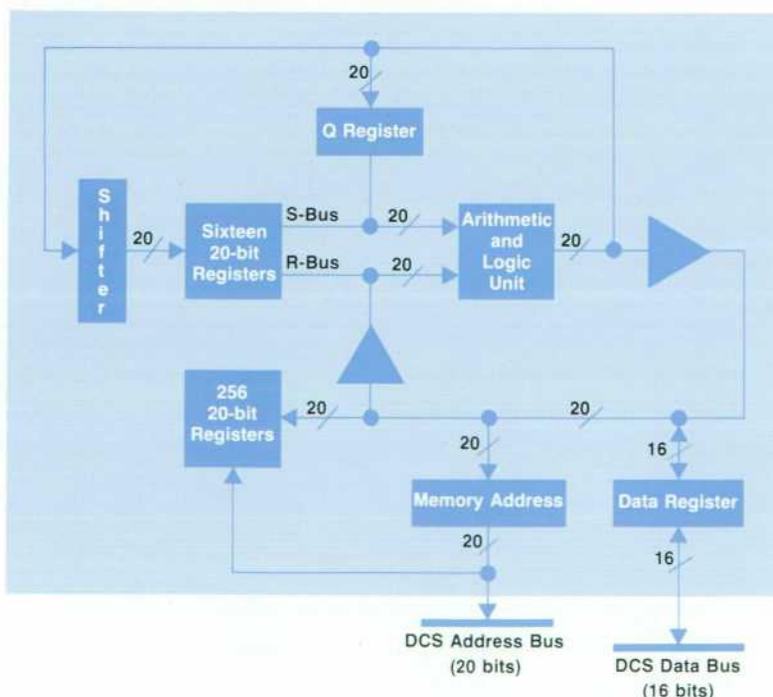

Fig. 2. Data processor data paths.

Character Processor

The 2680A electrophotographic process will not permit pausing in the middle of a print page. This could happen when the dot image is late in arriving at the laser system because data is still be being sent from the computer or the ASCII-to-image mapping is not finished. There would certainly be no problem if an entire page of data were completely buffered in its dot image representation, but this would require nearly 200K words of memory with up to twice that additionally required for a swing buffer to ensure full-speed operation. In the 2680A, the data processor initiates the page printing operation only when all characters for the page have been received and stored in ASCII format. This eliminates dependence on the computer system and limits memory requirements. It does require a more complex character processor that will not be overrun by the laser printing system.

The character processor consists of three individual subsystems that are overlapped and pipelined to achieve the necessary speed. Fig. 3 illustrates the major data paths. Like many dot matrix line printers, the character processor works by completely building one dot image raster line at a time before preparing any others. The input buffer memory holds the organized data for characters that are active on the raster-scan line under consideration. When the character processor has finished constructing a dot image raster line, it interrupts the data processor. The data processor compares the raster line number that the character processor has just finished with the actual line that the laser system is optically imaging. The character processor line number should always be greater than the laser line number or a fatal overrun condition has occurred. There is an eight-line first-in, first-out buffer for raster dot image data, so if the character processor is seven lines ahead of the laser, there is no room left in the buffer and the character processor must wait until the laser finishes its line. If there is room in the buffer, the data processor searches within the main memory for new characters that begin on the scan line that the character processor will build next. If found, the data processor outputs these to the character processor, which searches through its buffer memory to find vacant character locations to accept them. If there are no new characters, or when all new characters have been passed to the character processor, a final command is given indicating to the character processor that it has permission to build the next line of dot image data.

Consider the small dot matrix 4 in Fig. 4a. The number is 10 dots wide and 12 dots high and can be visualized as the bit pattern of Fig. 4b. With two blank dots between each similar cell, the character set will have a pitch of 15 characters per inch. So as not to waste main memory, the character cell row segments are tightly wrapped sequentially through memory as in Fig. 4c. Character cell compression algorithms are not used because they would have saved only a nominal amount of memory in the very largest of cell sizes.

The data passed from the data processor to the character processor is not necessarily exclusively conventional text cells. The character processor does not know that these cells may represent forms components (lines, boxes, shaded rectangles), special symbols, letterheads, graphics, or pictorial elements. This data is usually supplied to the character processor as a forms overlay which is simply a collection of data cells of any or all of these types that can be merged easily with the more variable but similarly represented text.

Character Control Subsystem

The three subsystems of the character processor are the character control subsystem, the alignment and mask subsystem, and the laser buffer subsystem. The responsibility of the character control subsystem (CCS) is to read the raw dot image data from main memory. It fetches the characters from the buffer memory and determines their character set
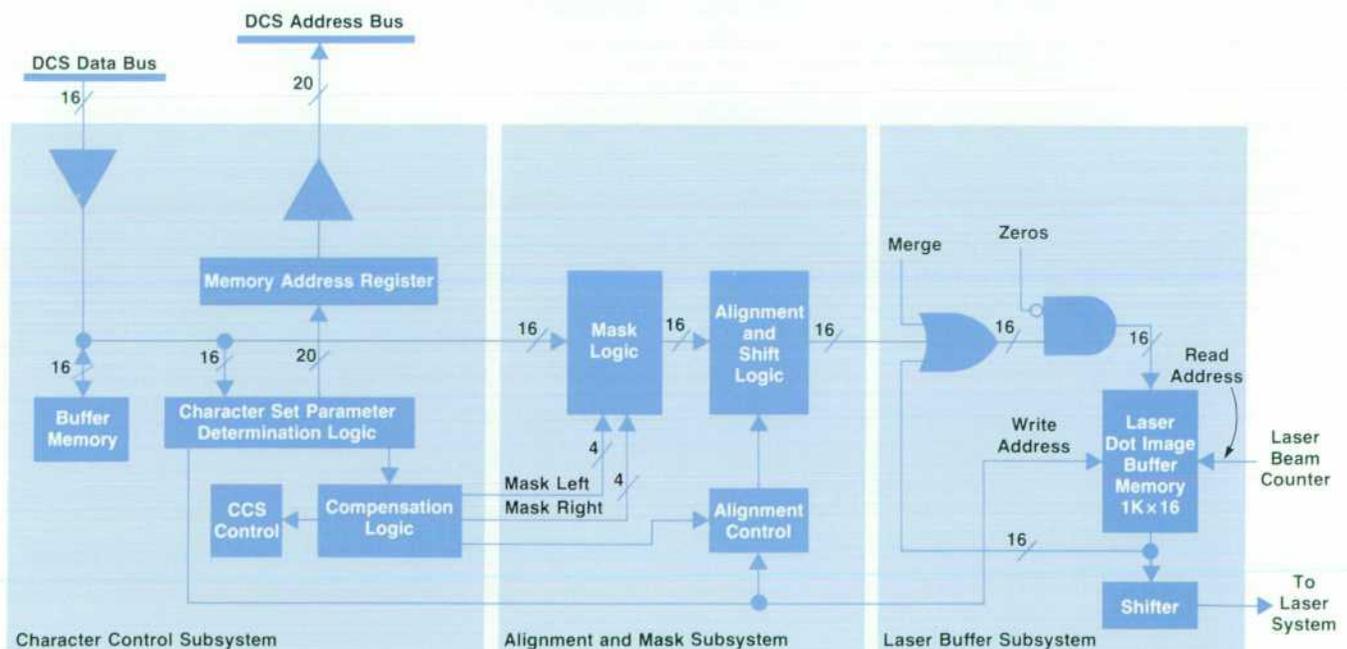

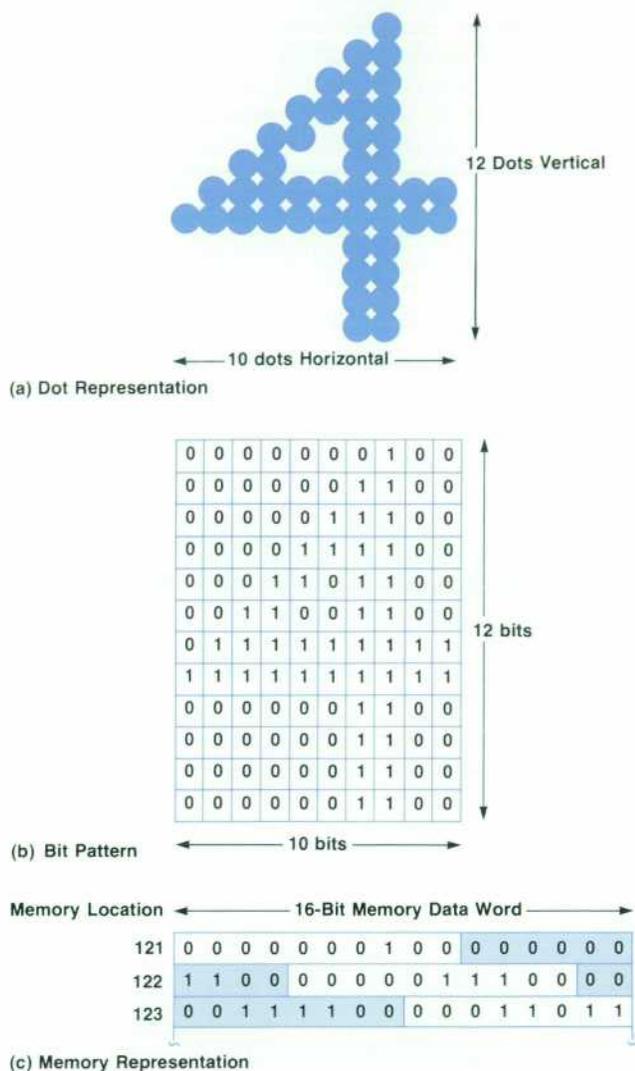**Fig. 3.** *Character processor block diagram.*

Fig. 4. *Representations for the number 4. (a) Dot representation. (b) Bit pattern. (c) Memory representation.*

parameters and positions on the page. From the horizontal width of a character, the CCS knows exactly how many bits need to be retrieved from memory. The CCS asserts on the bus the proper memory address for the first location of the dot image for that character, and requests a main memory read cycle. Returned dot image data is passed to the alignment and mask subsystem, and the memory pointer can be modified. The memory reads continue until all of the required bits for the present raster line for that character are sent to the alignment and mask subsystem. A vertical count is decremented and the organized data is collected and saved back into the buffer memory as a suspended character. The character being processed is now ready to be accessed later when the character processor builds the next line of raster data. The CCS proceeds with the next character in the buffer.

The horizontal width of the character cannot uniquely indicate to the CCS how many accesses of main memory need to be made. For example, when the first raster row of the 4 in Fig. 4c is retrieved from memory address 121, all ten bits are received, along with six additional bits not required

now. When the second raster line is later processed, the CCS must be smart enough to know that six bits are at address 121 and four bits are at address 122. A supplementary offset index and computational logic in the CCS compensate for the irregular wrapping of character set images in memory.

Alignment and Mask Subsystem

The alignment and mask subsystem (AMS) performs the bit shifting and masking operations that are required to arrange the dot image data read from memory into the proper orientation for placement in the laser data buffer. The bit masking function is fairly simple. When the first 16-bit dot image data word is received by the AMS from the CCS, there may be extraneous bits that are not part of the particular raster line being processed, but are left over from the previous line. Similarly, when the last 16-bit dot image data word is received by the AMS, there may be extraneous bits that are part of the next raster line. All undesired bits must be masked to zeros. The special compensation circuits in the CCS have the information to invoke the required selective character image masking circuits.

The data alignment task is the most time-consuming function the AMS performs. The reasons for aligning may not be completely understood until the structure of the third subsystem, the laser buffer subsystem (LBS), is examined.

Laser Buffer System

The laser system visualizes the LBS as a shift register of 2048 bits organized into eight rows. But the AMS requires random access when it writes dot image data into the LBS, since there is no guarantee as to the order of characters within the buffer memory (i.e., the first character on the raster scan line to be processed may not be the leftmost on the page). Hence, a group of shift registers, although perhaps economical, would not be proper for this application. Instead, a 1K-word-by-16-bit RAM is divided into eight sections of 128 words each to model each raster row.

The laser system is a synchronous system. When it is actively scanning across the page area of the photoconductive drum it needs data in 2048-bit bursts at 6 MHz. A 16-bit parallel-loading shift register at the RAM output is used to deliver the required bit stream. Just before the shift register is exhausted, another read cycle is begun to fetch 16 bits from the next sequential laser buffer memory address. Retrieving laser dot image data is not really just a simple read operation. After the read, 16 bits of zero must be written back into the same location so it will be ready for new dot image data in a future raster row.

The AMS writes 16 bits at a time into the LBS. Some or all of the bits may be important dot image bits for the character being processed. Since masking has been performed, irrelevant bits are zero. Writing new data into the buffer memory is not really a simple write operation, either. The new data must be merged with the data pattern already residing in the buffer memory. Therefore, a buffer read operation is performed first, followed by an inclusive-OR operation, and finally a write back of the merged dot image data. The need for this is easy to understand, since overlapped and superimposed characters are permitted in the 2680A. However, the most common need for this capability

is when adjacent characters of text separated by blank dot columns have to share the same location in buffer memory. The rightmost bits of the character on the left may be stored in the leftmost bits of the buffer memory word. When the character to the right is processed, its leftmost dot bits may also be stored in the rightmost bits of the same buffer word. The rightmost bits of the first character entered are preserved by the merging.

Data Alignment

The main memory containing the character set dot images is organized into 16-bit words. However, because the character cell row images are tightly wrapped sequentially through memory (Fig. 4c), this memory must be accessed on a bit-addressable basis. Extracting a single raster row of a particular character means retrieving up to two partial words (the first and last bits that make up the raster row) and up to sixteen full 16-bit words (the middle bits of the character). A similar situation exists at the LBS, where the dot image buffer memory is also a traditional word-addressed RAM. Since the 2680A Laser Printer can print any character at any location on the page, segments and words retrieved from the main character set memory must be placed in the dot image buffer memory in a different bit-addressable fashion. Since neither of these two memories is bit-addressable, it is the principal job of the AMS to compensate for the multitude of possible bit orientations between the two subsystems. The AMS electronics includes decision-making control logic, a 16-bit shift register, and a 15-bit shifting accumulator with programmable wraparound.

The character processor can limit the throughput of the DCS when the highest data compression is requested by the user. This is when 256 characters are printed across every raster line with a small 22.5-pitch character set. The character cell dot width is seven dots with a single additional blank dot. In this case, each subsystem may take from 0.5 μs to 2.5 μs to perform its individual processing duties. When handshaking overhead is considered, some character images may exceed 2.5 μs net processing time if their topological configurations are difficult. At the goal of 400 ns per dot, eight dots should be processed in 3.2 μs. But internal DCS overhead, such as occasional loading of new characters and interrupt handling, reduces the allowable processing interval to about 2.5 μs. This average execution time is successfully achieved by pipelining the state machines.

Direct Memory Access Processor

The direct memory access (DMA) logic was added to the DCS after the initial prototype was built. The initial design fell short of performance goals because the incoming print data overhead penalties were underestimated. Each individual data byte from the HP 3000 was transferred across the HP-IB via the I/O interface which then interrupted the data processor. The data processor saved its present operating state, programmatically read the incoming data byte and stored it into main memory, and then restored its suspended state to proceed with the processing task at hand. In limiting applications, the data processor lost 25% of its available time to this operation.

DMA capability is the standard solution to such a problem and it worked quite successfully here. The DMA sub-

system contains the required address and byte count registers and the interface logic under state machine control. It accepts incoming bytes from the I/O interface, packs two into a local 16-bit buffer, and writes them into main memory by stealing a cycle on the DCS bus. Each word transferred is transparent to the data processor program, which is interrupted only when an entire data record is completed. Performance degradation of less than 1% is attributed to DMA cycle stealing.

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Philip Gordon

Phil Gordon received his BSEE degree from the University of California at Berkeley in 1972 and then joined HP's Data Systems Division where he worked as a development engineer on the HP 1000 M-Series Computer. He later designed the HP 1000 E- and F-Series Computer processor, and is named inventor on a patent on an aspect of that design. Phil received his MSEE degree from Stanford University in 1979. He was project manager for the 2680A data control system and was responsible for the design of the character processor electronics. A native of Los Angeles, he now lives in Boise, Idaho.

The People Who Made the Product

by Billie J. Robison
2680 Program Manager

A very large number of people contributed to the development of the 2680 Laser Printing System and everyone's part was important and appreciated. However, I want to give special acknowledgment to a number of individuals and groups whose efforts and contributions were especially important.

Roger Archibald did the fusing and effluent control system design and development. Dan Battazzo did the mechanical design of the paper feed and path, assisted in the final structural frame development, and helped assure a smooth transition into production. C.S. Chan designed the toner collection system. Bob Cort did the final development of the powered paper stacker. Charles Ewert did the mechanical design and development of the electrostatic monitor and the paper retraction system, and did the initial stacker design and development. Dale Grooms worked on the mechanical design details of all the coronas. Lynn Hessing did development work on the toner cleaning system and was involved with initial fusing concepts. John Huffman designed the cabling routings and did a lot of the optics development work. Marc LaBarre did the mechanical design of the optical densitometer and the final frame and cover development. John Lewis developed the laser optics assembly and did the initial supporting frame design. Mike Okamura designed and developed the toner loading system. Ron DeLong and Warren Wardlow were responsible for the detailed design and development of the structural frame and its myriad details. Jim Langley was responsible for the design and development of the digital control system firmware. Jim Crumly worked on the high-voltage power supplies, the optical densitometer, MCP diagnostics and DCS firmware. Von Hansen designed much of the machine control system hardware and firmware. Greg Slansky, Gary Sherwood, Eric Miner, and Ernie Covelli were instrumental in doing a very thorough job of conformance and performance testing. Allan Walthers played a key role in the digital control system firmware design and the 3000 spooler modifications. George O'Connor modified the 3000 spooler to support the 2680. Phil Gordon was responsible for the design and development of the digital control system hardware. Jerry Stolle was responsible for the data processor electronics design. Eiichi Nakamura of Yokogawa-Hewlett-Packard designed the print control electronics. Jon Gibson developed and helped design the print control electronics and DMA logic and assured a smooth transition into production. Dellas Frederiksen finished the development of the electronic hardware for the machine control system and developed the stacker firmware. Bob Hay was responsible for the overall electrophotographic system hardware. Erwin Schwiebert worked on the fundamental understanding and development of the overall electrophotographic process and did process control algorithms. Tom Camis was responsible for the transfer and development portion of the electrophotographic process and for controlling the print quality. Paul Spencer was responsible for achieving the required drum potentials and the component development of corona devices. Gary Holland was responsible for paper drive electronics, the electronic control of the laser optics system and RFI control. Ron Juve did the fusing system electronics, ac power electronics and RFI control. Alvin Scholten developed the diagnostics firmware for monitoring print quality and assisted in

the development of the high-voltage power supplies. Bill Pierce designed and developed the high-voltage supplies. Special thanks go to Tony Barrett for valuable inputs and tireless testing efforts throughout the development cycle that helped improve the operation and reliability of the 2680.

Rich Pearson and his team at Computer Systems Division were responsible for HP 3000 enhancements. Rich served as system manager for project coordination among the various HP divisions involved in integrating the HP 3000 and the 2680. Dave Cassafer developed the 2680 driver and Jim Chiochios did the on-line verifier for the HP 3000. Bill Dalton's team, including Bill Tyler, Steve Zink, John Cohen and Larry Byler, modified the HP 3000 spooler and file system. Ted Workman's QA team, responsible for 2680/3000 hardware and software quality verification and system environmental testing, included Mike McCaffrey, Jim Brannan, Bob Woodhouse, Vince Roland, and Bob Heideman. Larry Goldman's team did MRJE and RJE enhancements for the 2680. The very powerful applications software is the work of Rich Simms and his team at Information Networks Division. Rich's team included software designers Kathy Fitzgerald, Glenn Entis, Michael Sherman, and Tom Spuhler, QA tester Cherie McKinney, and product marketing engineer Chris Kocher. Ted Renteria, Judy Anderson, and Al Inhelder's team in the Corporate Industrial Design Group designed the character sets which make an excellent contribution to the quality of the 2680A's output.

Jim Boyden's team at HP Laboratories gave invaluable technical and moral support from inception throughout the product's development in all areas fundamental to electrophotography. Jim's group included John Vaught and Bob Moody, who designed and developed the optics assembly casting, authors Larry Hubby and Dave Donald, Larry Hanlon, Garry Garrettson, Brian Leslie, and others. Manufacturing engineers who played key roles in the 2680A development were Ken Heath, Abdul Yoonas, Chris O'Connor, John Arterberry, Susan Evans, and Don Jackson. Pete Loya, Karl Gyllenberg, Jim Obendorf and their production team gave a lot of valuable input and support to the lab during the development cycle. Riley Lovvorn, Terry Nelson, and Mike McGee gave valuable help in modifying designs to assure that performance specs were met during turn-on. Gary Ferguson and Preston Frey helped shape our designs for serviceability. Carolyn Spitz served as the first customer in a production environment, and Phil Wilson and John Ramuta contributed testing, ideas, and enthusiasm. Boise and Computer Systems Divisions product assurance groups were instrumental in overall testing, assuring compliance with regulatory agencies and overall system integrity. As always, our model and fab shops, lab printed circuit group, and product support group were key parts of the team. Jim Hall as the initial project manager and later as the lab manager contributed ideas and enthusiasm to the design and development of most 2680 designs but especially to the original overall printing system design.

The large, complex task of developing the 2680A was made possible by the talent and dedication of everyone involved; it exemplified HP teamwork. I feel fortunate to have had the privilege of working with this outstanding group.

PRODUCT INFORMATION

HP Model 2680 Laser Printing System

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