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Application of Ink Jet Technology to a Word Processing Output Printer

Abstract: This paper describes a word processing system output printer that uses the electrostatic synchronous ink jet printing process. An overview of the ink jet matrix printing process is included, as well as brief descriptions of the elements of the printer. Printer performance objectives are outlined, and some of the design problems encountered during development are discussed.

Introduction

The descriptive term "word processing" is becoming as meaningful in the modern office environment as "data processing" is already in the environment of the electronic computer. A key element of the word processing system is the output printer, which, typically, has been an impact printer. However, new requirements are being set for system performance and for operating speeds that exceed the capabilities of most impact printing technologies. Ink jet printing offers the capability for increased performance to meet those needs. This paper discusses the use of ink jet printing as the basis for the word processing output printer that is a component of the IBM 46/40 Document Printer.

In ink jet printing, characters are formed from small ink drops, which can be produced at rates of about 10^5 drops per second. On the average, 10^3 drops per character are needed for "high quality" printing. Hence, rates of almost 100 characters per second can be achieved without dependence on the high speed operation of mechanical printing elements.

As a printer requirement, character image quality is also important. Using several measures of quality, ink jet printing has proven to be at least as good as that produced by impact printers, such as electric typewriters.

We felt also that such an output printer should be capable of producing a variety of character styles, including those needed for all languages based on the Roman alphabet and special symbols in 10-pitch, 12-pitch, and pro-

portional spacing character widths. Since generation codes for ink jet printed characters are stored digitally in compressed form, it is possible to print several styles and widths using a single machine configuration.

The output printer for a word processing system is expected to function reliably at usage rates that are much higher than those normally encountered by the office typewriter. Nonimpact printing involves fewer moving parts, lower mechanical impact forces and, consequently, less associated wear and fatigue problems; thus nonimpact printers can reasonably be expected to meet system reliability requirements.

The acoustical noise generated by a word processing system must be minimal to be compatible with the low background noise levels in office environments—the nonimpact ink jet printer meets this need.

The development of a word processing printer using ink jet technology required the solution of a variety of problems in such diverse disciplines as fluid mechanics, aerodynamics, electrostatic fields, acoustics, mechanics, and chemistry. For example, it was necessary to develop techniques for manufacturing nozzles with orifice tolerances on the order of tens of nanometers and to design a low cost digital-to-analog converter with slew rates of 2×10^8 V/s and an output range of approximately 200 V.

In this paper we present a general description of the ink jet printing process, relating the technology to print-

quality considerations for a word processing output printer. We also discuss some of the design problems involved in applying ink jet technology to a practical, reliable printer for use in an office environment. Other papers in this issue describe some solutions to specific problems in development of a printer, as well as some more general problems in our continuing efforts to understand the phenomena involved [1-3].

Ink jet printing process

In the early 1960's, Sweet [4-6] developed a method of forming, charging, and electrostatically deflecting a high-speed stream of small ink drops to produce high frequency oscillograph traces in a direct-writing, signal-recording system. Each drop is given an electrostatic charge that is a function of the instantaneous value of the electrical input signal to be recorded. The drop is then deflected from its normal path by an amount that depends on the magnitude of its charge and in a direction that is a function of the polarity of the charge. As deflected drops are deposited on a strip of moving chart paper, a trace is formed that is representative of the input signal.

Lewis and Brown [7] extended Sweet's technique to permit the printing of characters. Character images are stored in binary form in a character generator. An encoded signal addresses the character generator to select a desired character. The binary image of that character is then used to generate the drop charging signals necessary to deflect drops to the appropriate character matrix positions. This is the general approach taken in our printer, although numerous problems had to be solved to apply it in a reliable device intended for high quality commercial use.

Basically, the printing process operates as shown in Fig. 1. Conductive ink under pressure is forced through a small nozzle to form a jet. The jet would normally break up into a stream of drops of quasi-random size and spacing, but drop formation can be controlled by vibrating the ink within the nozzle cavity at a fixed ultrasonic frequency. The pressure waves cause the jet to break up into a stream of drops of uniform size and spacing at a well defined distance from the nozzle.

A voltage applied to an electrode surrounding the breakup point induces an electrical charge of a specific, predetermined magnitude on the forming drop. This charge is retained by the drop throughout its flight to the paper. The stream of drops passes through an electrostatic field formed by a fixed high voltage across a pair of horizontal deflection plates. Because the charge on each drop is controlled individually, a drop can be deflected vertically a desired amount. In the case of our printer design the drops are deflected vertically from bottom to top, and one column of dots and/or spaces is

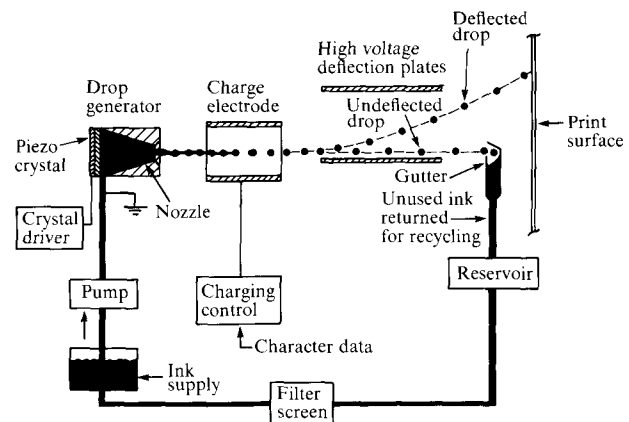


Figure 1 Electrostatically deflected ink jet printing process.

referred to as a scan. If in forming a character a particular space in a scan is to be left white, it is blanked by leaving the drops uncharged. These undeflected drops are intercepted by a gutter and recycled to the ink reservoir.

As drops are deflected vertically, the printhead is driven horizontally at constant speed. Thus, drops are deposited in appropriate positions within a raster area to form the desired character. (Key variables and parameters in the ink jet printing process are listed in a glossary in the Appendix.)

Printer performance requirements

• Overall considerations

The application of ink jet printing in a word processing environment required high quality printing at high speed. Also, characters within a 0.42-cm (1/6-in.) high matrix were needed so that the printing would be compatible with standard typewriter fonts. This character matrix height required a maximum drop deflection of 0.51 cm (200 mils), since 0.09 cm was needed in our printer configuration to clear the gutter. Although speeds in excess of 100 characters per second were desirable for this application, the emphasis on high quality printing required some compromise in this goal.

• Print quality

The final product from a word processing printer is, of course, the printed document. Because this output in some sense personally represents the document originator, quality becomes an important factor. However, print quality is a subjective matter—a function of paper, type style, and the image-forming mechanism. Some quantifi-

able criteria include edge definition and relative optical density of the character, composition and surface characteristics of the paper, and the limits on character line weight variations and curvature (type style range) imposed by the printing system. Another parameter is the vertical and horizontal resolution of the character space (picture elements per unit length (pel/cm)).

The most common standard of print quality in word processing applications is given by the office typewriter, an impact printer that transfers ink through contact and deformation to the paper. This process yields a result that is generally recognized as good quality printing through a wide range of type styles. We used this standard to judge the quality provided by our ink jet printer.

Resolution

Ink jet printing is, in effect, matrix printing. A principal determination that had to be made was thus the resolution needed to achieve the desired print quality. The ultimate choice was a compromise between print speed requirements and the type styles desired. We chose a resolution of 94.5 pel/cm (240 pel/in.).

An additional quality requirement is to have solid area fill within the character. Resolution (R) defines the center-to-center dot spacing on paper; this spacing, together with the degree of dot overlap desired, governs the choice of dot diameter (d_{dot}). Minimum dot diameter for solid area fill is $d_{\text{dot}} = \sqrt{2}/R$; thus a 0.15-mm (5.89-mil) dot was chosen. Another factor in the choice of dot diameter is the undesirable ink mist (fog) that is generated when an incoming drop overlaps a wet dot on the paper. Ideally this condition is avoided by specifying an ink spread factor that prevents dot-to-incoming drop overlap.

Drop placement accuracy

Quality in matrix printing depends heavily on the accuracy with which individual dots are placed on paper. Vertical placement errors are primarily caused by the ink jet system and horizontal errors by printhead velocity variations. Dot placement errors fall into two general classes: those that affect all dots uniformly (either vertically or horizontally), causing size variations either in height or width of the character being printed, and those that affect the placement of individual dots relative to neighboring dots.

A relative dot placement tolerance [8] of ± 0.033 mm (± 1.3 mils) and a character height and width tolerance of 0.076 mm (3 mils) were considered necessary to meet print quality requirements. Tolerances on relative dot placement are stricter than tolerances in character height and width, because the parameters that control height and width tend to change slowly. Thus, if these character dimensions do not vary greatly during page printing, quality is not perceptibly reduced.

Misplacement of dots relative to adjacent drops can cause raggedness of the edges, voids, and loss of optical density (failure to achieve necessary ink overlap for solid fill). In some cases, dots may be grossly misplaced, but even relatively small placement errors can cause noticeable degradation in print quality. At 94.5 pel/cm (240 pel/in.) the resulting dot spacing is 0.106 mm (4.17 mils); thus a misplacement of 0.025-0.05 mm (1-2 mils) can cause voids, depending on ink spread and drop size.

Optical density

A significant aspect of print quality is the impression of blackness of the printing. Whiteness of the paper, character edge definition, and spurious background marks (spatter) combine with the optical density of the ink to create the perceived blackness of characters. Pigments or dyes used in the ink affect optical density. In fabric ribbon impact printers, optical characteristics are largely determined by pigments such as carbon black. However, due to potential long term stability problems with pigments, it was decided in this case to use a water soluble dye as the ink colorant. It was recognized that greater optical density was more easily achievable with pigments; however, the inks developed for use in the ink jet printer were carefully formulated to overcome the density problem [9].

Because the eye tends to integrate over large areas to judge density, voids in the character tend also to degrade its blackness. In addition, edge definition, a measure of the intrusion of the white of the paper into the black of the character, reduces perceived blackness.

Another problem inherent in ink jet printing is spatter. When ink drops impinge on the paper, shock waves are produced within each drop, which can cause the formation of much smaller drops having a slight electrical charge and low kinetic energy. Some of these smaller drops are attracted to the paper, forming spatter, but most remain in the air until air currents cause them to drift into the printer mechanisms. Spatter presents a print quality problem by graying the area around the printed characters.

Development of an ink jet printer

Performance requirements for the ink jet printer were reduced to a set of design goals related to print quality objectives and to the environment in which the printer would operate. This design effort, divided into four major areas, covered the printhead, the printhead transport system, the ink, and the ink handling system.

• Printhead design

In an ink jet printing system several parameters determine system operating characteristics. Here we first dis-

cuss functional requirements and then relate them to the basic printhead parameters. The rationale for choosing individual parameter values is included, and some of the problems in achieving them are described.

Drop generation parameters

In the previous section we discussed our choice of dot diameter. Dot diameter is a function of an ink spread factor that is related to ink and paper characteristics, as well as to drop volume. Drop volume is equivalent to that of a cylindrical section of the jet that is equal in diameter to the jet (d_j) and as long as the drop-to-drop spacing shortly after jet breakup (λ). Thus, a combination of jet diameter and drop spacing is chosen to yield the desired dot size. In our case, the printed dot on paper is produced by a 0.063-mm (2.5-mil) diameter drop, which, in turn, results from a 0.033-mm (1.3-mil) jet diameter and a 0.15-mm (6-mil) drop spacing. To meet the requirements for resolution, maximum print height, and burst print rate, we chose a drop frequency of 117 kHz.

Satisfactory drop generation is defined by a set of parameters including drop frequency (f), drop velocity (v_d), and jet diameter. In addition to providing required performance, the combined set of drop generation parameters must satisfy the Rayleigh instability criterion [10] and must allow reliable drop formation over the required range of temperature without the presence of satellites (extra drops between the major drops that make the jet unsuitable for printing). Because of the small size of the jet a scale model approximately fifty times prototype size was designed and constructed to evaluate the effect of nozzle and fluid properties on drop formation [11].

Drop velocity may be closely approximated by jet velocity when the square of jet velocity is much larger than the square of the velocity of capillary waves on the jet [12]. Jet velocity is a function of drop spacing and drop frequency: $v_j = \lambda f$.

Minimum jet velocity considerations include longitudinal stability of drop formation, drop frequency requirements, and drop-to-drop interactions. Upper jet velocities are limited by fog and spatter generation, deflection sensitivity, and drop disintegration.

Drop deflection parameters

The deflection of a single drop (assuming parallel deflection plates and a uniform electric field and neglecting aerodynamic effects) is

$$x_d = \frac{Q_d}{m_d} \frac{V_{dp}}{s_{dp}} \frac{1}{v_d^2} l_{dp} \left(z_p - \frac{l_{dp}}{2} \right), \quad (1)$$

where Q_d is drop charge, m_d is drop mass, V_{dp} is deflection plate voltage, s_{dp} is deflection plate separation,

l_{dp} is deflection plate length, and z_p is throw distance (distance from deflection plate entry to paper plane).

Drop charge must be variable over a sufficient range to allow vertical deflection of drops over the height of the character matrix. In our printer, a maximum charge electrode voltage of 200 V is needed to charge drops over a range of 80-550 fC. One upper limit on charge is the value necessary to "explode" the drop. If the electrostatic energy exceeds the energy due to surface tension, the drop disintegrates.

Another limit on charge is that the mutual electrostatic repulsion among drops may become so large that drop alignment relative to the jet axis becomes unstable. If this were to occur, a small radial disturbance on the drop at breakup would cause the stream to disperse at some distance down the jet axis.

Relative positioning of the ink jet printhead elements between the nozzle and the paper plane is critical. The charge electrode location relative to the nozzle was chosen to center the electrode around the stream breakup point. In addition, the spacing between the nozzle and charge electrode had to be sufficient to prevent arcing. Charge electrode length was chosen to prevent drop charging efficiency variations that could occur with changes in stream breakup distance. Also, the electrode length was a factor in isolating the breakup point from the deflection field.

Maximum deflection plate voltage was limited by voltage breakdown constraints. Minimum deflection plate spacing, as well as the separation between the charge electrode and the deflection plates, was also governed by breakdown considerations. Clearance requirements between the top deflection plate and the highest drop trajectory was another constraint on minimum deflection plate spacing. In our printer a deflection plate voltage of 3300 V and a plate spacing of 1.6 mm (63 mils) satisfied these requirements. In addition the required clearance at the deflection plate exit was obtained by slanting a portion of the top plate upward. This plate configuration enabled maximum allowable electric field strength over most of the deflection plate length.

Drop deflection increases with both l_{dp} and z_p , but more rapidly with l_{dp} . The maximum value of z_p is fixed either by mechanical constraints or, more likely, by the fact that, due to aerodynamic effects, drops following similar trajectories tend to merge, a tendency that increases with increasing z_p . Theoretically, the maximum value of l_{dp} is z_p , which means that the deflection plates extend to the paper plane. However, in practice, space is needed here to accommodate the gutter and a device for collecting fog to prevent deflection plate contamination. A 1.3-cm (500-mil) deflection plate length and a 2.3-cm (900-mil) throw distance were chosen to meet these requirements.

A fundamental consideration in printhead design was the drop placement scheme, i.e., the time sequence in which generated drops are spatially placed on the printed page. A method was developed in which uncharged drops are inserted between deflected drops [13] to prevent drop merging due to aerodynamic interaction effects. This does lower the drop utilization efficiency which, together with drop frequency, resolution, and character height requirements, determined the burst printing rate (92 twelve-pitch characters per second).

Undesired aerodynamic and electrostatic drop interaction effects are compensated by adjusting the charge on individual drops; thus, the appropriate charge electrode voltages were needed for all allowable sequences of drops within the placement algorithm. Accordingly, an automated system was developed to measure empirically the charge electrode voltages required to place drops accurately in the character matrix despite these drop interactions.

To ensure that drop placement errors are held within a specified range for the population of machines to be produced, guidelines were established for setting manufacturing and assembly tolerances on the important printer variables [8]. Designed experiments were utilized to identify the variables that significantly affect drop placement and mathematically relate these variables to dot-to-dot spacings at the print plane.

Deflection maintenance

In an ink jet matrix printer, character height variations are caused by changes in deflection system parameters that affect the charge-to-mass ratio of the drops, the time spent by the drops in the deflection field, and the strength of the deflection field. The ink jet printhead is expected to operate in temperatures varying from 16°C (60°F) to 38°C (100°F). Drop deflection depends heavily on drop velocity (see Eq. (1)); since drop velocity is very sensitive to temperature effects on ink viscosity, significant character height variations (up to 30 percent) could result if these temperature effects were not compensated. Since aerodynamic drop interaction effects are influenced by temperature-induced velocity changes, uncompensated temperature variations would also adversely affect print quality.

A deflection servo system was designed for the ink jet printer; it maintains drop deflection height within 2 percent [14]. This system is also used to synchronize the drop charging signal with drop breakup.

• *Printhead transport system*

Since printhead velocity variations could cause horizontal drop placement errors, printhead motion must be consistent with the established print quality require-

ments. Moreover, the printhead must be capable of starting and stopping in order to print individual characters (character-by-character mode); must have a maximum print speed consistent with drop availability; and must be returned to the next line in the least time possible.

To place drops accurately in the horizontal direction in conjunction with the character-by-character printing mode, we use a horizontal displacement transducer. An electro-optical transducer is mounted on the printhead, and a stationary plastic strip with 60 lines per inch is mounted across the printer frame. This displacement feedback capability greatly relaxes the requirements on printhead velocity control. In addition, the feedback arrangement keeps track of the absolute printhead position by providing two signals from the transducer—one shifted 90 degrees in phase from the other—to detect direction of motion.

We determined that a ± 6 percent velocity variation could be tolerated, which allowed use of a low cost drive configuration of proven design. The electronic controls consist of only three low-power magnet drivers. Basic power for the drive is obtained from a fractional horsepower ac motor.

A detailed analysis of the relationship between printhead velocity and character distortion resulted in increased print speed. In some cases, overspeed of the printhead could result in distortion of a character. This would occur if the number of print drop times required exceeded the time available. We incorporated a control arrangement that allows the printing function to lag behind the printhead position during overspeed and then catch up later. All coded characters have been analyzed to assure that distortions are not detectable.

The printhead is returned at a velocity 4.5 times that of the print speed (89 cm/s or 35 in./s). However, significant time was lost in overshoot at the left margin in early experimental models. To minimize this lost time, the overshoot distance is measured by means of the displacement feedback device during a start-up calibration sequence. The measured stopping distance is used to disengage the return mechanism prior to the desired stopping point.

• *Ink*

We met two separate sets of requirements with the specially formulated jet printer ink [9]. In addition, the ink constituents had to be selected to resolve such system problems as deposits inside the nozzle and ink drying during machine shutdown. The printing process requires an electrically conductive, low viscosity, nontoxic, nonflammable ink capable of being broken up into discrete uniform drops. These requirements were met by using a water based ink. To minimize the potential for nozzle

clogging and to meet print quality requirements, a water soluble dye was used for the ink colorant.

• Ink handling system

The ink handling components deliver ink to the drop generator at a precisely controlled pressure; control particle size in the ink; turn the stream on and off with minimal contamination of the deflection assembly; capture and recirculate unused ink drops; and provide for operator resupply of ink [15]. Since an analysis of printer drop utilization indicated that only about two percent of the drops were used for printing, we decided to recirculate the unused ink. Another critical aspect of ink handling is the control of stray ink (fog) in the printer, which is discussed later.

Ink filtering is critical to the reliability of the printer [9]. Because the orifice in the ink nozzle is 0.033 mm (1.3 mils) in diameter, particles in the ink that size or larger must be prevented from reaching the nozzle. Particles small enough to enter the nozzle and cause short-term jet velocity variations that affect drop placement accuracy must also be controlled.

A diagram of the ink flow path is shown in Fig. 2. The ink is drawn from a replaceable container through filter (A) to the pump. The ink flows through another (2- μ m) filter (B) before entering the valve and drop generator. Ink in the drop generator flows through a final filter (C) before reaching the nozzle. (The final filter was placed in the drop generator to allow field replacement of the drop generator without danger of contamination.) The ink leaves the nozzle as the jet that subsequently breaks up into drops. As indicated earlier, the undeflected drops are intercepted in the gutter, and the ink in the gutter accumulates in a sump and is drawn by the pump back into the ink container through a screen.

A solenoid-driven pump pulsed at 60 Hz, an element of the deflection servo system mentioned previously, provides a stable pressure source, which is electronically controlled by varying the amplitude of the 60-Hz signal. A hydraulic filter removes the 60-Hz pressure ripple before the ink reaches the drop generator. The pump was placed on the carrier and close-coupled to the valve to minimize the effect of mechanical vibration on ink pressure. The close coupling limits the volume of ink under pressure, thus reducing the exposure of ink damage in the event of a rupture. Another benefit of the close coupling is to reduce the response time of the system to pressure changes during servo operations. Two bubble catchers are incorporated into the suction line, one at filter (A) and the other on the carrier. The bubble catchers trap air bubbles that may form in the suction line, thus preventing the pump from becoming air locked.

The stream valve must turn the jet on and off with extremely short pressure rise and fall times to minimize

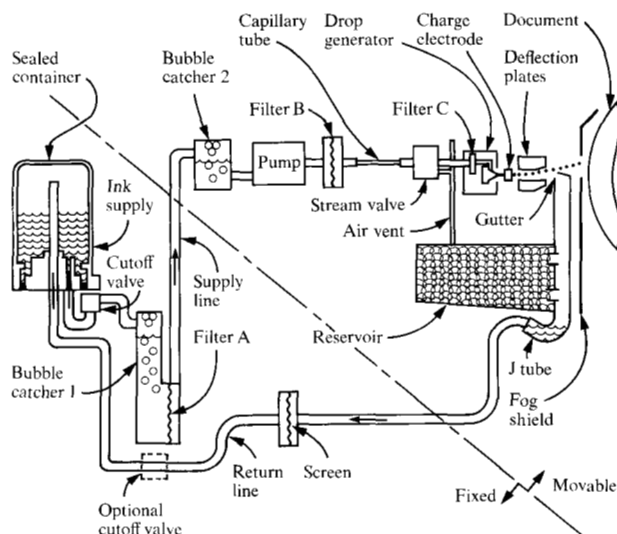


Figure 2 Ink circulation system.

deflection assembly contamination. Because of surface tension effects at the orifice, the direction of the ink stream at low stream velocities is unpredictable. It is therefore necessary to spend as little time as possible at low drop generator pressures. To facilitate achieving short rise and fall times the valve was physically attached to the drop generator, thus minimizing the volume of ink under control. To further promote a short fall time, a vent passage in the valve is opened as the inlet flow is stopped. (The vent passage is quite large in comparison to the nozzle orifice.)

The ink container, designed to permit easy replacement of ink in the printer, holds six ounces and is equipped with self-sealing rubber plugs in its base. Among the other advantages, these self-sealing plugs make replacing the ink container a clean, simple procedure. When the container is inserted in the machine, two hypodermic-like needles pierce the plugs. Ink is drawn into the pump by one needle; the other returns unused ink from the gutter to the container. An ink level detector indicates the need for container replacement.

As ink flows from the nozzle to the gutter, part of the solvent (water) is lost due to evaporation. Also, airborne contaminants can enter the gutter and be returned to the container. For these reasons ink in the container becomes increasingly concentrated and contaminated. To maintain the ink concentration and viscosity within acceptable limits, the ink container is replaced before all the ink is used. Thus the system does not require periodic flushing, and experience indicates that the filters do not require maintenance.

The design of the ink handling hardware is strongly influenced by the requirement of compatibility with the ink [16]. Since the ink must be conductive, it can act as the electrolyte in a galvanic or electrolytic cell. Therefore, the selection of materials and the mechanical configuration must be such that galvanic cells are not set up, that there are no forced electrolytic cells due to electrical short circuits, and that crevice corrosion sites are not created.

Three critical contamination areas exist in ink jet printers: 1) nozzle and fluid system clogging due to foreign particles, fungal and/or bacterial growth in the ink, crusting at the nozzle orifice, or deposits on the orifice; 2) contamination of the deflection assembly by stray drops during stream start or stop; and 3) contamination of all areas of the printer hardware due to fog produced when drops impact the paper. The first two problems can be controlled by proper design of the ink [10], the ink filtering system, and the valve. The fog problem is much more difficult to handle.

The amount of fog generated by drops impacting the paper depends on drop kinetic energy, ink spread on the paper, dot overlap on the paper, ink characteristics, environmental conditions, and electrostatic charge on the drops. If the fog were allowed to persist, it would contaminate machine parts, paper, and the environment. An effective solution was devised for this printer. An absorbent shield placed on the printhead carrier near the paper protects the printhead from contamination. Fog is prevented from drifting throughout the machine by an air intake duct several inches above the print line. As the low-velocity air around the print line moves into the duct, it carries the drifting fog into a collecting filter.

Summary

In this paper we have described the electrostatically deflected ink jet printing process. Performance requirements for a word processing output printer have been presented, including quality considerations for matrix character printing. Major areas of the printer development effort have been outlined, and some of the design problems encountered have been discussed.

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Appendix: Glossary

R	resolution
d_{dot}	dot diameter
d_j	jet diameter
v_j	jet velocity
λ	drop-to-drop spacing; wavelength
f	drop frequency
v_d	drop velocity
m_d	drop mass
ρ	ink density
Q_d	drop charge
V_{ce}	charge electrode voltage
s_{ce}	charge electrode plate spacing
l_{ce}	charge electrode plate length
x_d	drop deflection
l_{dp}	deflection plate length
s_{dp}	deflection plate spacing
V_{dp}	deflection plate voltage
z_p	distance from deflection plate entry to print plane

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