Progress in Manufacture of Flat Panel Displays Using Piezoelectric Drop-On-Demand Ink Jet

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Abstract

Piezoelectric ink jet offers a promising combination of productivity, reliability and uniformity that are appropriate for jetting organic electronic materials. Spectra is manufacturing a printhead specifically for display manufacturing. This printhead contains a robust material set and is intended to allow calibration of individual nozzles to meet uniformity requirements of +/-2% for display manufacture.

1. Introduction

Organic light emitting polymers are used in the manufacture of high resolution flat panel displays. These light emitting polymer materials can be applied with a series of imaging and coating processes, but this approach has many steps and is inefficient in its utilization of valuable LEP material.

Traditionally ink jet printheads are designed to eject small drops of fluid which create complex images with near photographic quality. Office and industrial ink jet printers operate with the high reliability rates required for production equipment. This makes the technology an ideal match for FPD manufacture, in which precise metering and deposition requirements of LEP material and the reliability requirements for a robust production process are of great importance. It is not surprising that the display industry is evaluating various ink jet printheads as manufacturing tools.

A practical functioning system for the manufacture of polymer based flat panel displays requires the integration of precision hardware, electronic fluids and specially designed ink jet printheads. Such a system may enable the production of low cost, efficient, high quality displays. This paper focuses on the ink jet technology that is essential to this ideal system. Advances in ink jet printing technology for this application include: robust materials, improved nozzle straightness, and a per nozzle calibration system to achieve uniformity requirements. These improvements have been incorporated into the Spectra SX-128 jetting assembly that is now being produced.

2. Ink Jet Attributes for FPD Printing

Though ink jet printing for graphic arts applications involves reproducing digitized images on paper, there are some similarities with electronic displays. Both technologies create color images with the presence of ink, or light, at precise pixel locations. In each of these systems, it is necessary to control the amount and location of the color material. In the case of the display, electricity is also required to generate the image. But now, the ink jet technology can actually be used to print the light emitting polymer materials. The SX-128 printhead can be used to deposit each of the RGB materials in their respective pixel locations. The PEDOT layer can also be printed with the same ink jet technology. An RGB flat panel display is comprised of three sets of ordered pixels, similar to a digitally rendered image in an ink jet printer. To build RGB color displays, each pixel must be filled with a precise amount of LEP material. Conceptually, ink jets are ideal precision metering devices in that they enable a data-driven, additive process for dispensing a variety of materials without contacting the substrate. Thus, the individual layers and pixels of the flat panel display could be printed with an ink jet system jetting solutions of LEP and PEDOT material.

Drop-on-demand ink jet technology allows the user to selectively generate drops according to a desired pixel pattern. This results in very efficient usage of the LEP material. Drop size, uniformity and placement accuracy requirements are determined by the desired resolution of the target display. A high resolution display with 200μm superpixels has only ~50μm for each RGB color cell. The remaining area is used by a structured photoresist coating that separates the RGB color cells. Important requirements for material deposition include: uniform pixel fill, even pixel wetting, and no cross contamination between color subpixels. These requirements can be translated into printhead, fluid, substrate and system specifications.

2.1 Drop Uniformity

RGB displays printed with LEP materials generate emitted light whereas ordinary printing on paper requires reflected light. Because the eye is more sensitive to changes in emitted light than reflected light, the uniformity requirements for LEP material dispensing are significantly more stringent than typical ink jet printing applications. In addition, as the solvent carrier evaporates, the remaining LEP material must spread and wet the cell evenly. Drop mass uniformity of 2% per nozzle is the target value for FPD manufacture.

2.2 Drop Size

Another important characteristic is drop size. To build flat panel displays with ink jet, it is necessary to create a thin uniform layer of material without cross-contaminating neighboring pixels Robust commercial printheads are available that eject drops in the 30-50 ng size range. These drops are too large for RGB manufacturing applications because of the push to increase resolution. A 10 pL ink droplet has a calculated diameter of about 27 µm. With a 50 µm pixel size, only 4 or 5 drops are needed to fill the cell with fluid. From Figure 1, it can be seen that drop diameter also influences the accuracy with which each drop must be placed to avoid cross-contamination.

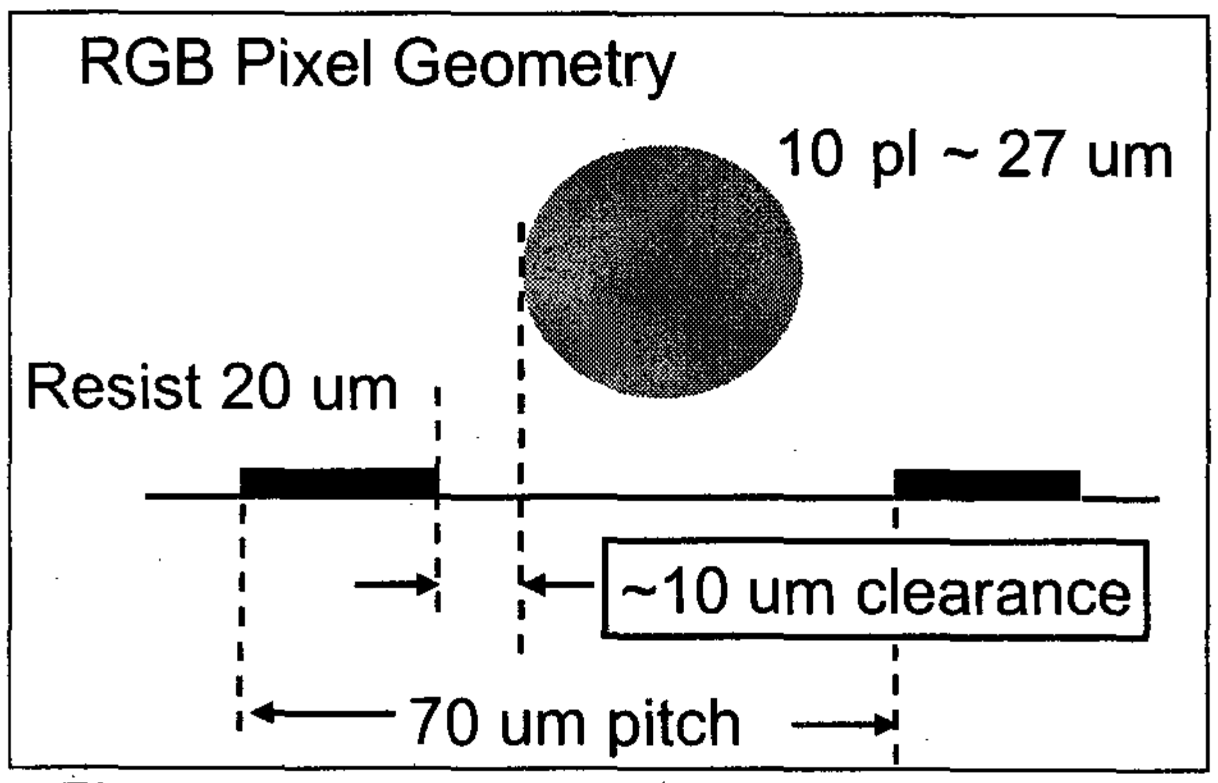

Figure 1: Pixel geometry for ink jet deposition

2.3 Drop Placement and Jet Straightness

The drop placement accuracy straightness requirements can be calculated using assumptions about pixel size and drop volume. For a 10 pL drop, a 27 µm sphere is placed in a 50 µm pixel, leaving only +/-13 µm for positional tolerance, also shown in Figure 1. Unfortunately, machine and substrate errors use up a portion of the 10 µm tolerance. As drop size decreases, the straightness requirements become more tolerant. If the pixel is filled using 5 pL drops, then the positional tolerance increases slightly as the drop is now 21 µm in diameter.

2.4 Target Specification

Combining the above criteria creates Table 2, which describes the target specification for an ink jet printhead targeting the RGB display application.

Table 2: Desired characteristics for ink jet printhead

Characteristic	Desired Value
Drop Placement	<1 degree (all jets)
Drop Volume	5-15 picoliter
Drop Velocity	3 to 8 m/s
Volume Uniformity	±2% from all sources
Operating Temperature	Ambient to 55°C
Materials Compatibility	Weeks or a few months may be acceptable
Life	>10 billion actuations / channel
Maximum Frequency	Up to 10 kHz

3. Advances In System Performance

Using a system approach, printhead improvements have been coupled with new ink formulations, and wave form modifications to meet the requirements for LEP manufacture. The SX-128 printhead, shown in Figure 2, was developed specifically to meet the needs of FPD manufacture by improving printhead performance attributes, such as jet straightness and drop volume uniformity. New drive electronics allow calibration of each of the 128 channels to achieve a high level of uniformity. Polymer inks can also be optimized to improve drop formation and provide uniform substrate wetting.

3.1 Ink jet optimization

In order to satisfy the production requirements for LEP display applications with a robust printhead that meets standards for practical manufacturing at high yield, a series of printhead design changes were implemented. The first challenge was to reduce the size of the drops generated by the ink jet. Modifications to existing 30 pl jet designs were shown to produce 10-12 pl drops with good jetting characteristics. A robust new material set was used in the printhead design to provide compatibility with light emitting fluids. Nozzle straightness specifications were improved by a factor of three. In order to meet drop volume uniformity requirements for electronic display manufacture, each channel in the 128 jet printhead can be individually calibrated.

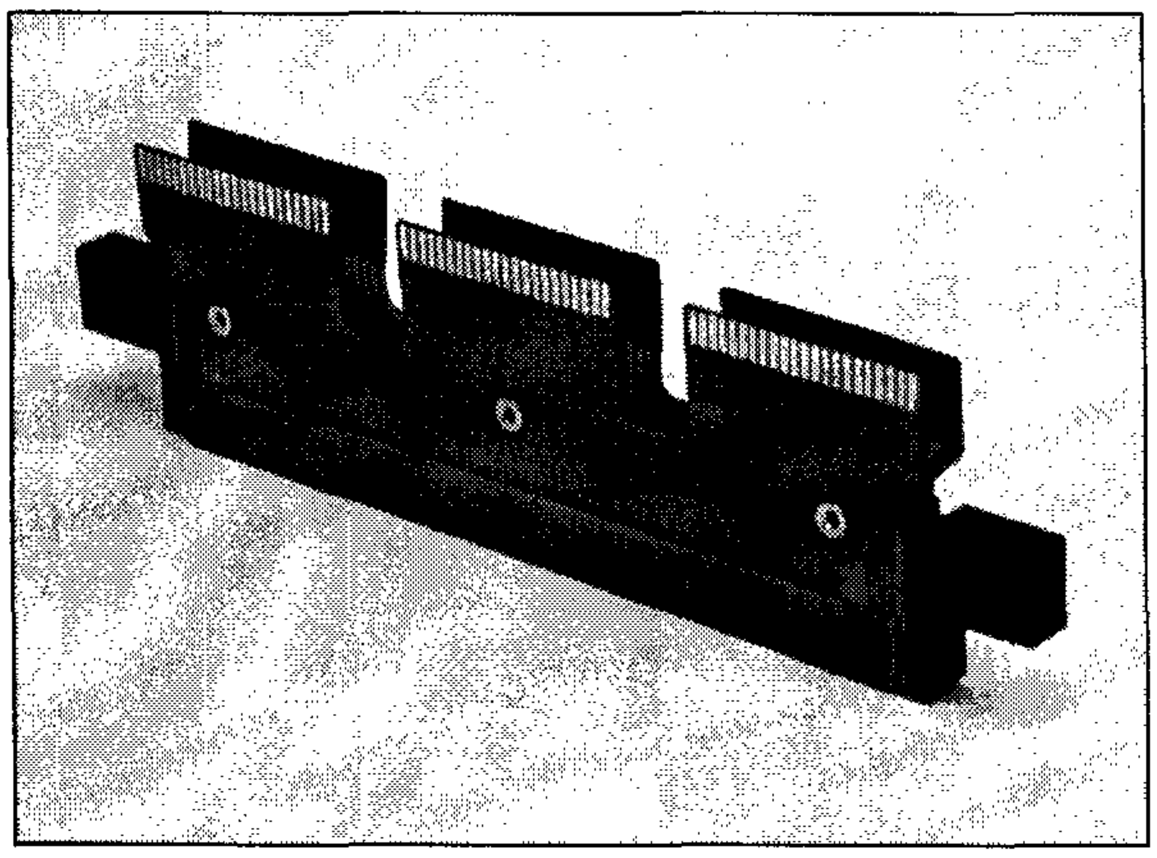

Figure 2: SX-128 printhead designed for FPD manufacture

3.1.1 Characteristic properties

Each drop generated by the firing of the piezoelectric channel has repeatable output for billions of cycles. Important drop characteristics include drop straightness, drop mass and drop velocity. Drop mass and drop velocity are typically linear with drive voltage. Figure 3 shows the relationship between mass and velocity, as a function of increased drive voltage. With high molecular weight polymers, it is likely that the best drop formations are found with lower drop velocities.

Operating speed of the FPD manufacturing line determines the required DOD print frequency. Many prototype systems require firing frequencies of only 1-2kHz, with production goals of 5kHz or higher. The SX-128 printhead is designed to provide uniform performance over a wide frequency range. The chart in Figure 4 shows drop velocity as a function of operating frequency. The diamonds indicate frequency response for a single jet and the squares give the frequency response for the same jet, while all 128 other jets are firing simultaneously. The lines are nearly coincidental and this suggests that the printhead output will be consistent, regardless of changing print cycles. However, jetting properties of the polymer fluids have a strong influence on the maximum operating frequency.

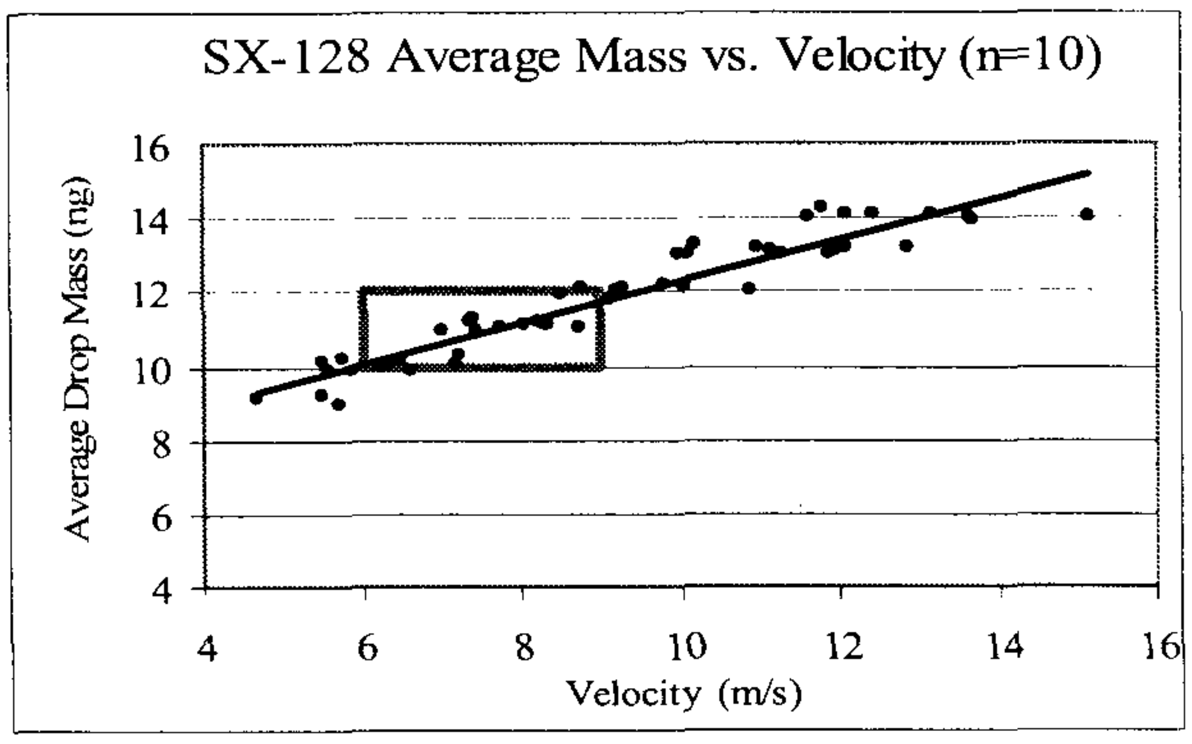

Figure 3: Linear relationship of drop mass and drop velocity.

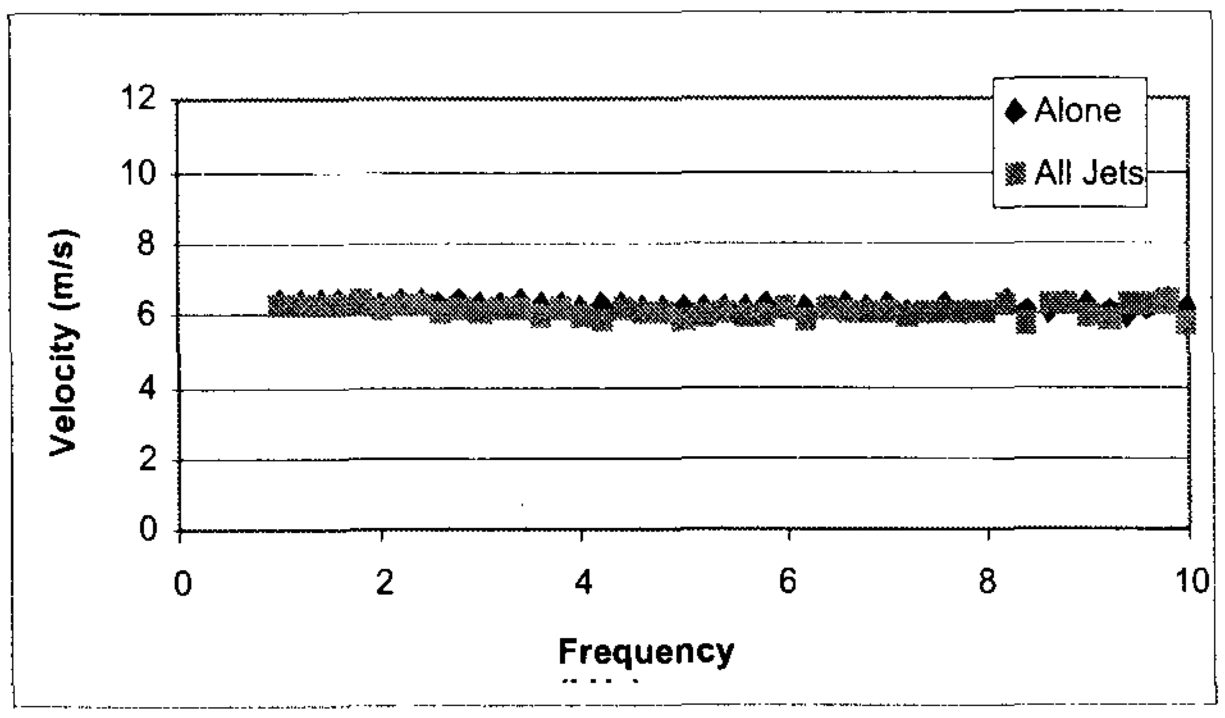

Figure 4: Frequency response of the SX-128 printhead

3.1.2 Ink jet materials

The specialty materials used for FPD manufacture provide another challenge for ink jet technology. The deposition of PEDOT requires that robust materials be used in the ink jet system. Extensive materials compatibility testing was required to qualify the optimal material set. This testing included soak tests of material coupons and printhead subassemblies, as well as extended jetting tests using typical LEP and PEDOT materials. A number of inert materials or protective coatings were used.

3.2 Drop Placement

There are two components that determine the drop location accuracy. The first is jet straightness and the second is the location of the jet with respect to the substrate. Improvements in drop straightness are critical to enabling the success of this application. In Figure 5, measurements of per nozzle straightness of the SX-128 jet printhead shows that error of all jets is about +/-0.3° with 1 mm standoff (5 mrads).

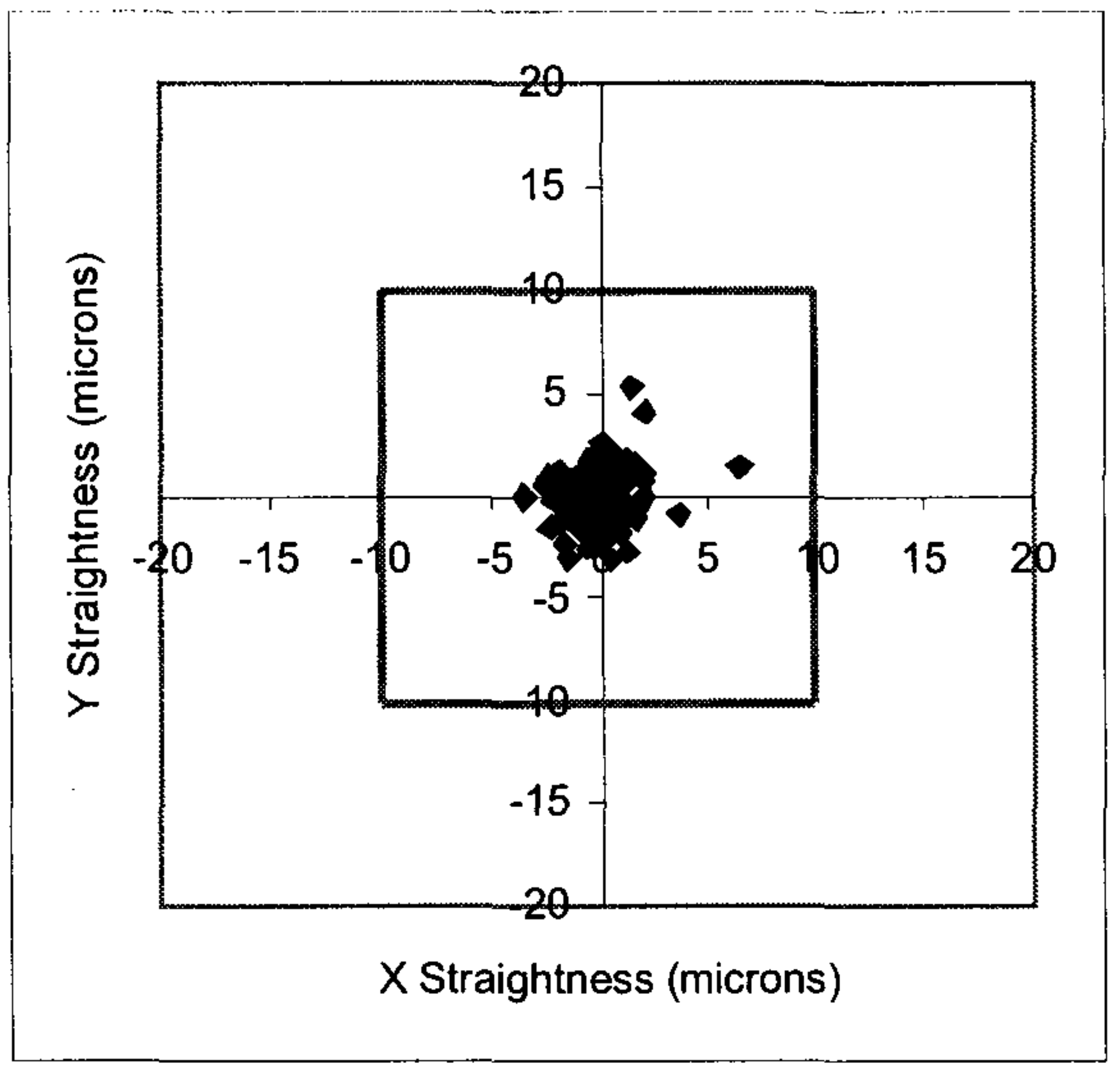

Figure 5: X and Y drop placement error for SX-128 printhead at 1 mm standoff

The second component of drop placement is the accuracy with which the nozzle is positioned relative to the substrate. Machine and staging errors will contribute to placement error. The flatness of precise display substrates allows for small standoff distances, which can lessen the impact of trajectory errors. Reducing the machine standoff has a linear effect on straightness errors, as shown in Figure 6; standoff does not affect errors due to nozzle plate manufacture.

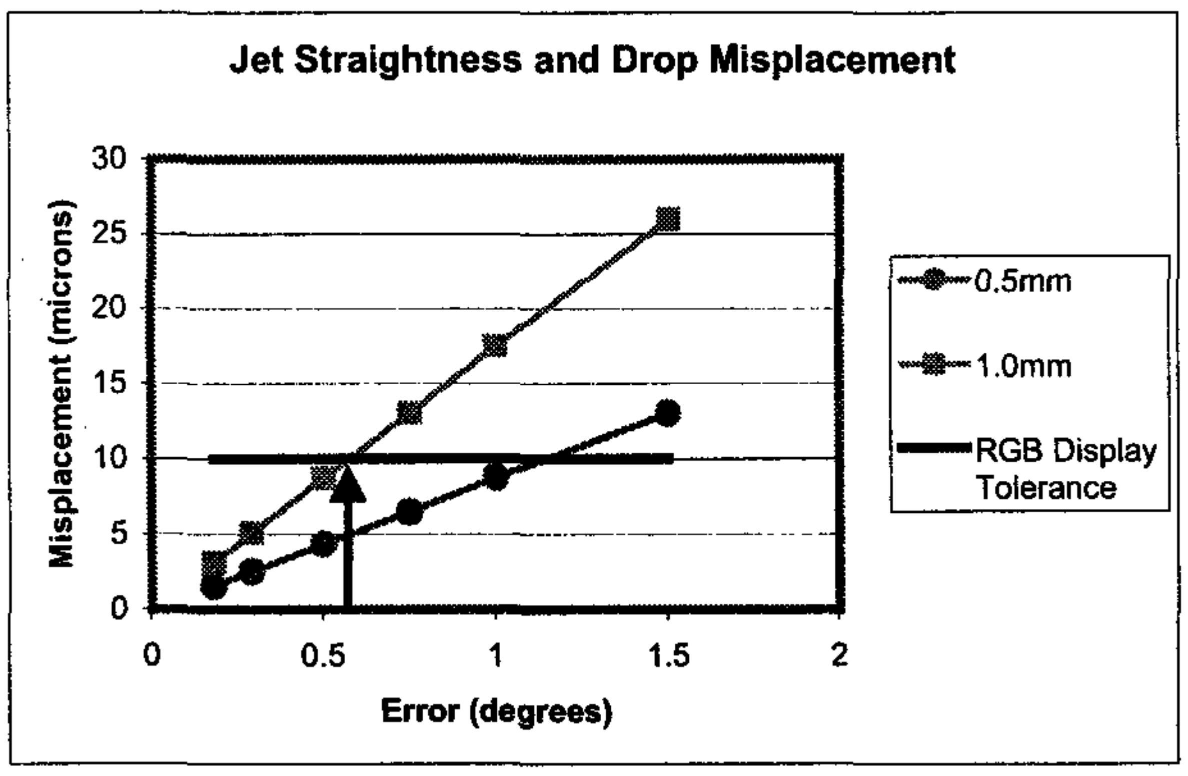

Figure 6: Effect of jet straightness error at two standoffs

3.3 Fluid Optimization

Drop formation is the combined result of jet dynamics and fluid properties. Because LEP materials have high molecular weights, their jetting characteristics tend to result in long ligaments[1] and erratic firing behavior. The combination of ink jet design and fluid formulation can be used together to optimize the firing behavior.[2] Fluid optimization is essential to attaining maximum system performance and reliability.

3.4 Jet Calibration

The SX-128 printhead provides direct connection to each of the jet channels, which means that each of the nozzles can be calibrated individually to permit improvement of drop uniformity and to eliminate that error contribution. There are two approaches for making this calibration: adjusting drop velocity and adjusting drop volume directly.

The data shown in Figure 7A is the velocity of each jet before the calibration process. All jets are performing within +/- 0.5 m/s. Voltage offsets are used to adjust slow jets by increasing drive voltage and to adjust fast jets by decreasing drive voltage. The adjusted data is shown in Figure 7B. Now all jets are running at +/-0.1 m/s. The resulting drop volumes are shown in Figure 7C.

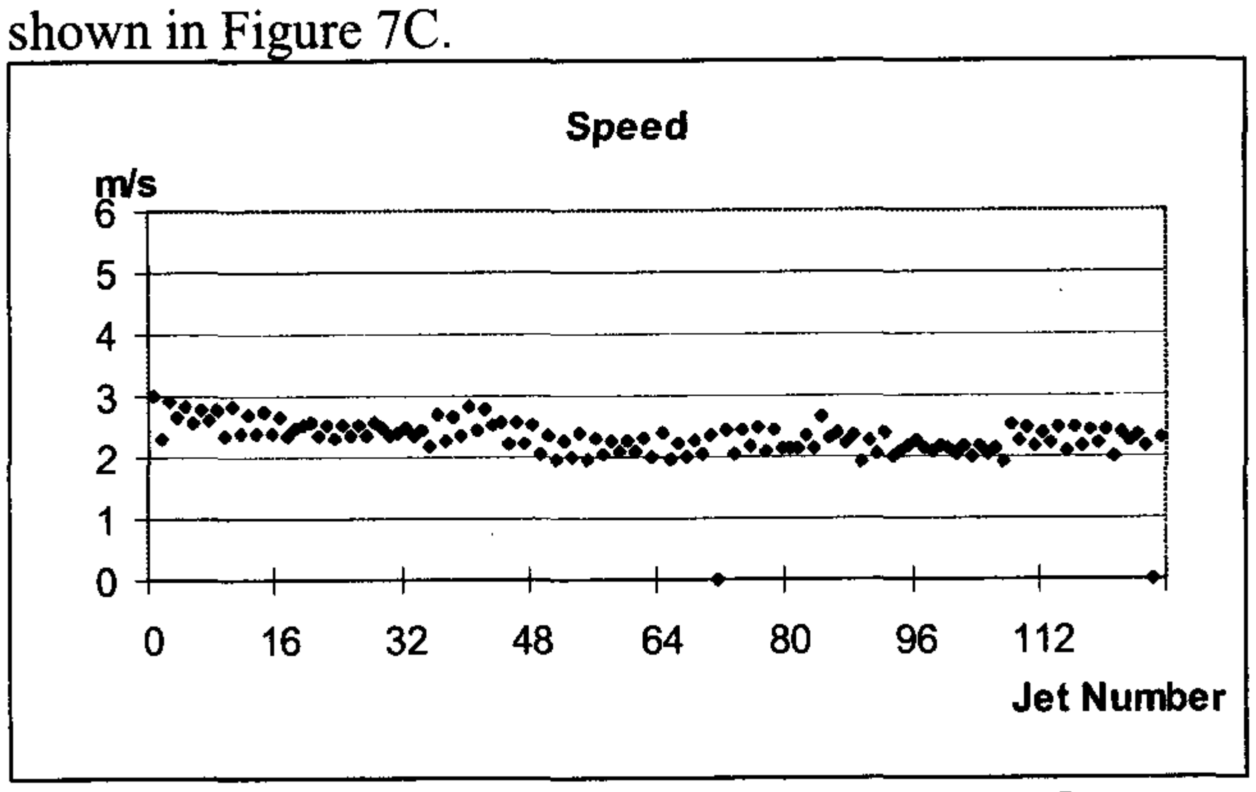

Figure 7A: Drop velocity vs. jet number for untrimmed head

[1] E.I. Haskal *et al.*, SID Digest 2002, p 776, (2002)

[2] L.T. Creagh *et al.*, IDMC 2003, Taiwan (2003)

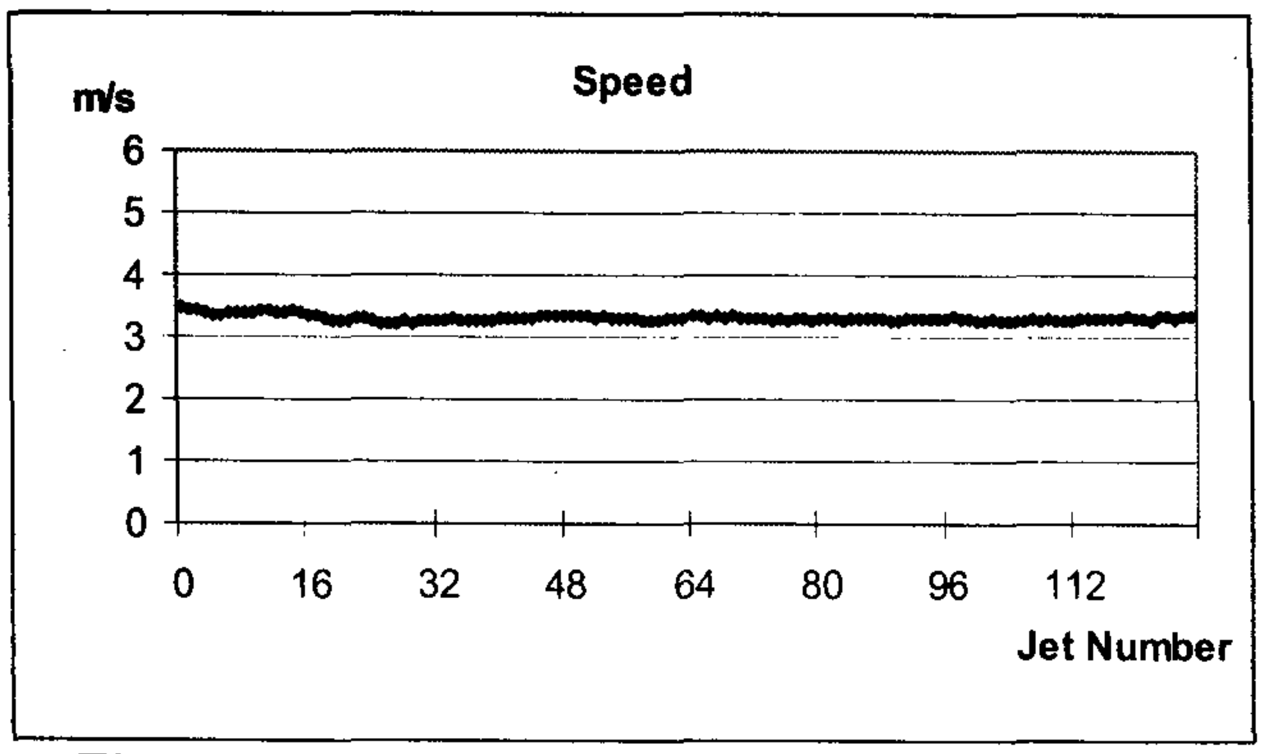

Figure 7B: Drop velocity vs. jet number after trimming

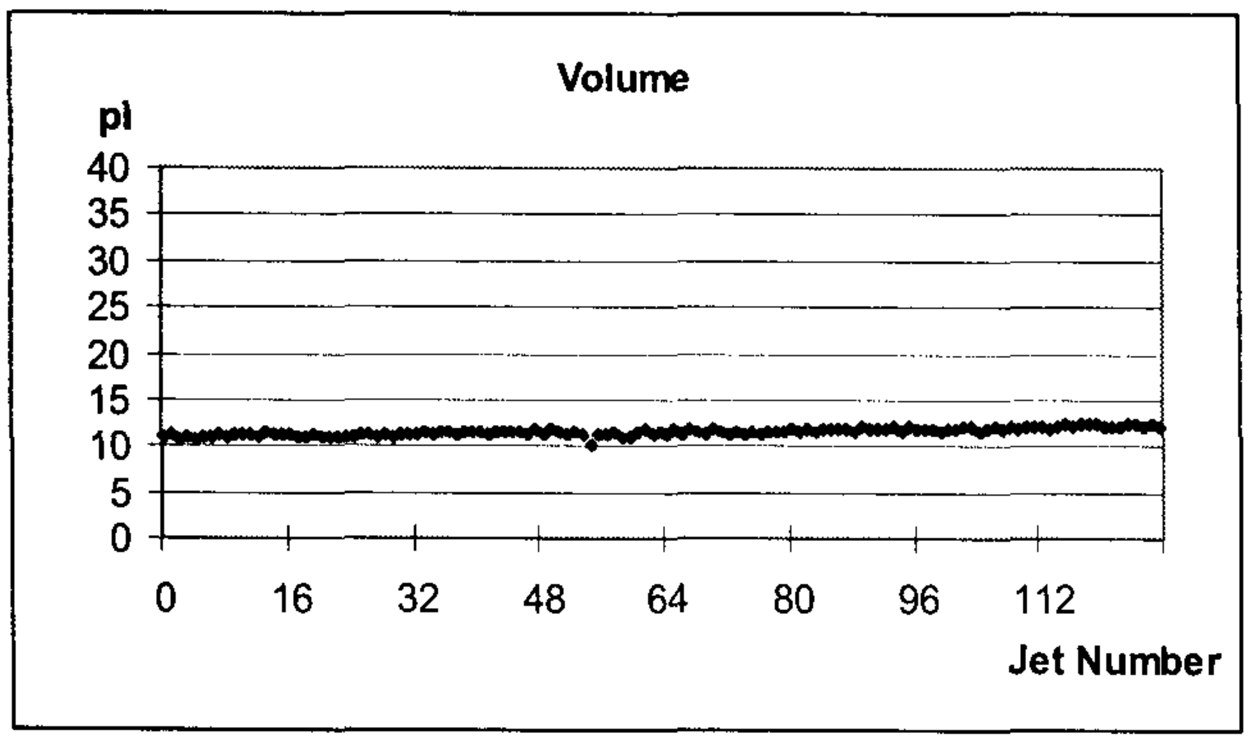

Figure 7C: Drop volume vs. jet number after trimming

It is also possible to tune the jets using drop volume. In this case, it is necessary to measure the mass or volume of the individual jets. Drop volume has a linear relationship with drive voltage and as drive voltage is increased, the drop mass will increase according to the curve shown in Figure 8. One method of measuring individual drop volumes is to use an optical imaging system to capture drops in flight, as shown in Figure 9. This technique requires high precision optics to produce repeatable results.

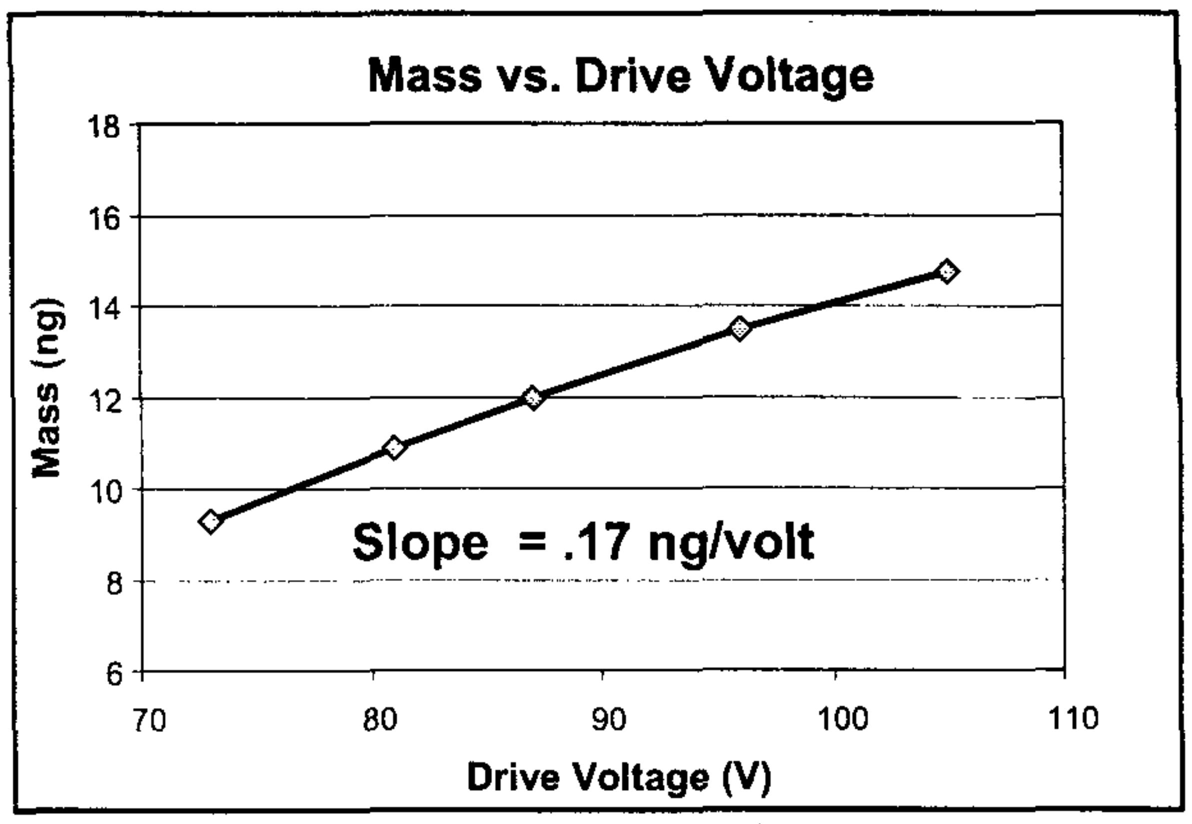

Figure 8: Drop mass as a function of drive voltage

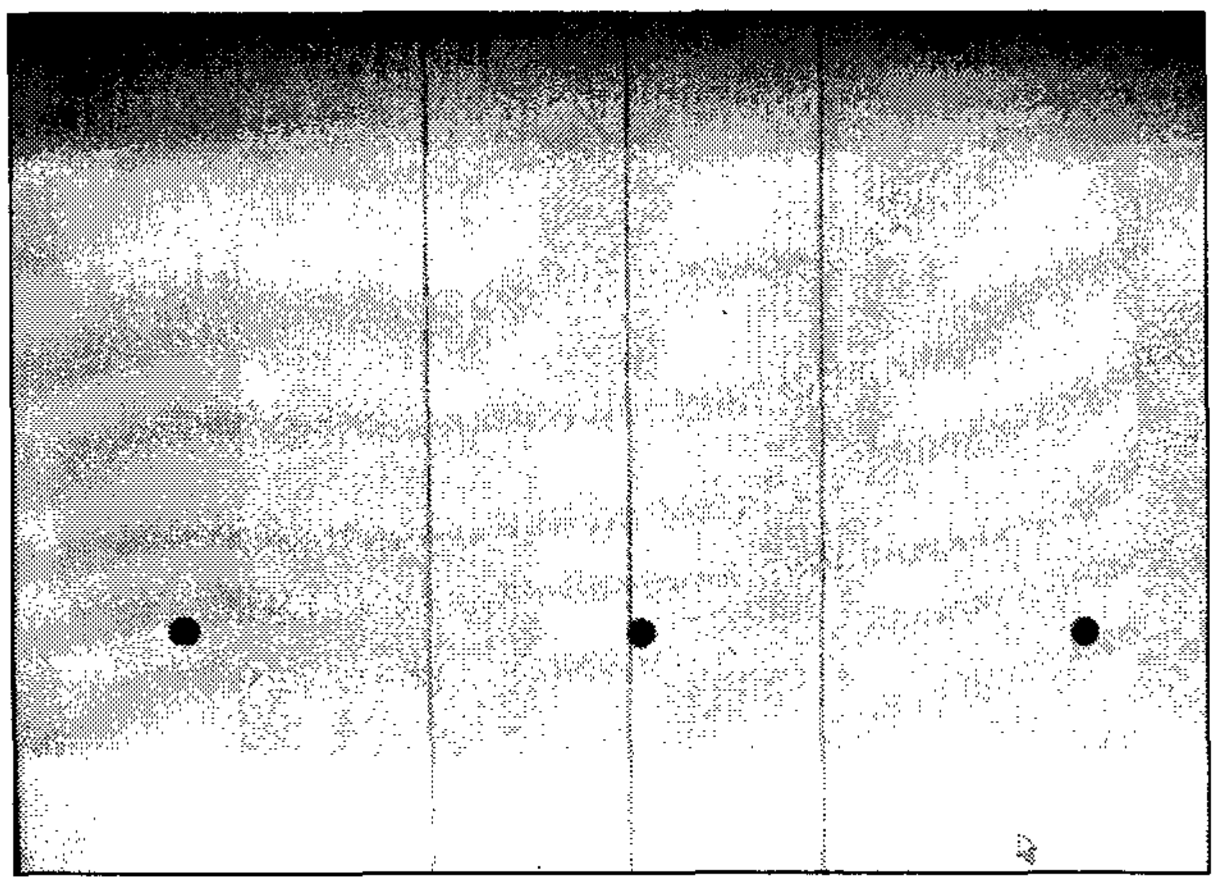

Figure 9: Three drop image used for volume and straightness calculations

The results of calibration based on drop volume and image analysis are shown in Figures 10A and 10B.

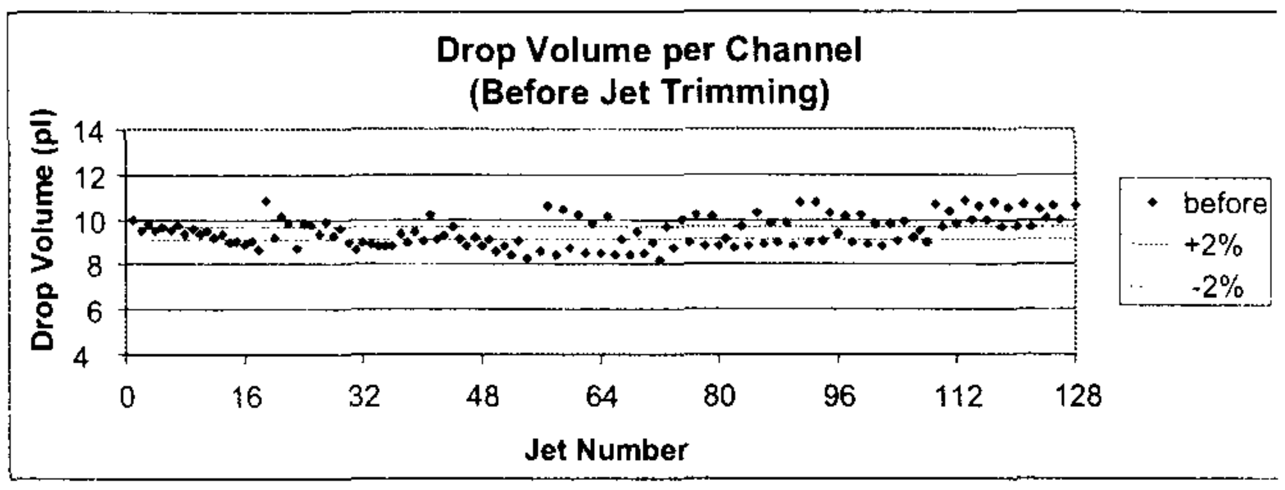

Figure 10A: Drop volume measurements before trimming

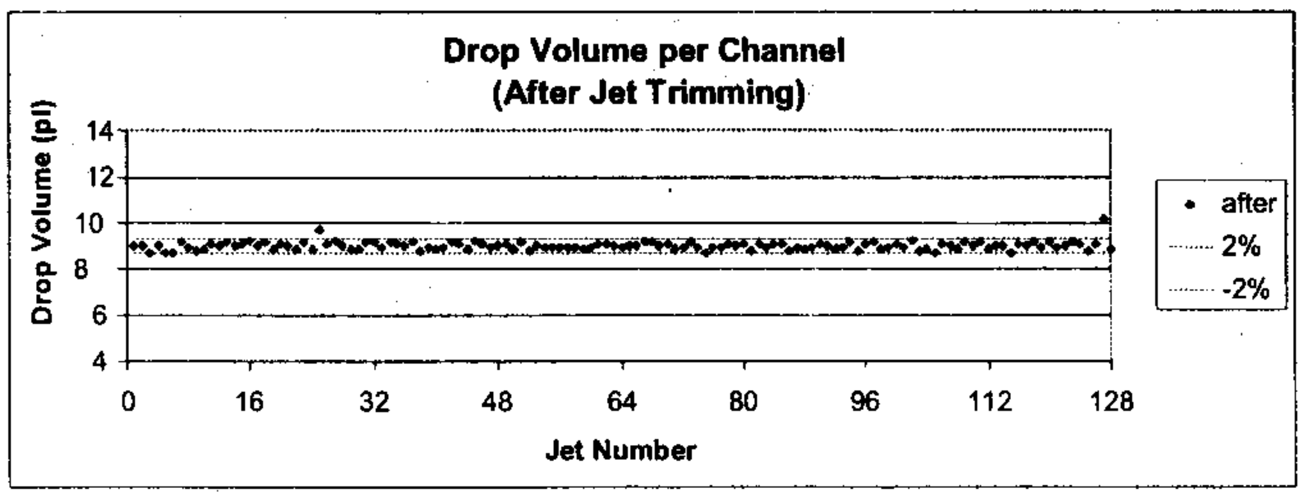

Figure 10B: Tight drop volume control via jet trimming

4. Conclusion

For ink jet printing of display materials to be a practical manufacturing process, the ink jet printhead must meet exacting specifications for drop straightness, drop volume uniformity and reliability. The SX-128 has been engineered to meet these specifications. Improvements in LEP fluids coupled with integrated precision hardware are now demonstrating required reliability in pilot manufacturing. As experience is gained with these precision drop ejectors, additional applications are likely in the manufacturing of LCD and PDP displays as well as other areas requiring reliable and accurate deposition of fluids.