

# TECHNOLOGY report

COMPANY CONFIDENTIAL

TEK'S FIRST

## INK JET

HIGH MANUFACTURING YIELD  
THROUGH BETTER ENGINEERING

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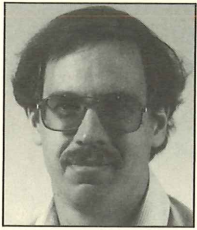
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# Tek's First Ink Jet: High Manufacturing Yield Through Better Engineering



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On Tek's History poster, the ink jet copier is the milestone for 1982. When Tek introduced the 4691 color ink jet copier, few companies had ink jet products on the market. Today, more than thirty companies make or sell printers, copiers, or marking machines that exploit the modern ink jet's ability to economically write, draw, and image the outputs of computer-based systems. It's a rapidly developing technology, with eight to twelve U.S. patents granted each week. However, the basic technology predates today's advanced devices by well over 100 years.

The personal computer created the need for printers versatile enough to handle color, graphics, Kanji characters, and multiple-font character sets. It was low price that set off the explosive growth of ink jet products. Ink jet printers can be implemented cheaply. Epson retails one for \$200; for under \$600, you can get a color printer from Canon, Radio Shack and Quadram. The Hewlett-Packard ThinkJet, with a disposable print head and ink cartridge, sells for under \$400. Excellent cost-to-performance, versatility, and quiet operation often make ink jet printers the printers of choice.

The modern ink jet is a tiny, electrically controlled fluid pump which ejects a stream ("jet") of ink. The surface tension of the ink naturally causes the stream to break into tiny droplets with diameters on the order of 150 microns or less. Using various means, these droplets are directed, in a selective manner, towards a printing medium to form an image. The keys to the technology are the drop-formation process and the means by which droplets are selected to create the image.

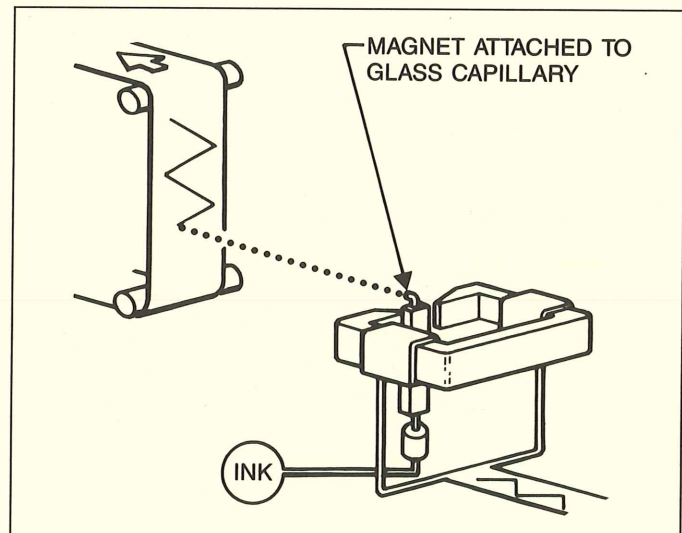
Ink jet technology is rich in diversity. Currently, there are more than eight distinct ink jet technologies discussed in the patent literature with many of the variations invented within the past fifteen years. All of these technologies can be identified as being one of two basic types: continuous or drop on demand. The continuous jet is the older technology and may be considered near maturity. Drop-on-demand technology is relatively new with many of the recent ink jets being variations of this type. In this article we will explore how both technologies developed, showing how changes in applications have led to new variations.

## Continuous Ink Jet Technology

A French investigator, F. Savart, performed the earliest studies of a fluid stream back in 1833.[1] He investigated the relationship of the unbroken length of a jet stream to jet velocity. Later, during the 1870s, Lord Rayleigh worked on the instability and breakup of fluid jets by capillary forces.[2] In the same decade, Lord Kelvin described a drop-charging technique and outlined the first basic ink jet printer.[3] This early work, however, did not immediately result in products.

In fact, it wasn't until the 1930s that ink jet devices[4,5,6,] were first patented. These patents described ink jets used as printing devices for facsimile printers. The actual writing process was accomplished by deflecting a continuous stream of ink to record a trace on a moving substrate.

The first commercial ink jet recorder, however, was not marketed until 1951. This device, an oscillograph based on the Elmqvist technology,[7] was marketed by Siemens under the name Oscillmink (see figure 1). This print mechanism resembles a light beam galvanometer with the mirror replaced with a small nozzle from which ink under pressure is ejected. By replacing the pen with an ink jet, Elmqvist was able to decrease the inertia and thereby increase the upper frequency limit of a direct-writing oscillograph recorder to 1000 Hz, a tenfold increase over the conventional recorders at that time. From this point on, research and patent activity accelerated. New products, based on ink jet technology, began to appear on the market.



**Figure 1. Introduced in 1951, Sieman's Oscillmink Oscillographic recorder was the first commercial application for the century-and-half-old ink jet technology, first studied in 1833. The Oscillmink could record 1000 Hertz sinewaves, a ten times increase over the performance of pen-type devices.**



In 1964, working at Stanford University, Richard Sweet made a major advance in continuous ink jet technology. Sweet showed that a variable amount of electric charge could be placed on droplets that form out of a continuous pressurized stream of fluid. This charging process, Sweet discovered, could be controlled on a drop-by-drop basis up to droplet rates of 100,000 drops per second. When passed through a fixed electrostatic field these charged droplets were deflected to discrete positions on the recording substrate.

The similarity of this technology to a CRT is easily visualized. Unlike the electron beam in a CRT, however, the droplet formation process could not be gated on and off—there was no way to “blank the beam.” Sweet developed a blanking means by giving the droplets he wanted blanked the most charge. These droplets would receive the maximum deflection when passed through the fixed electrostatic field. A gutter was positioned to collect the blanked droplets which were then recirculated to the ink reservoir.

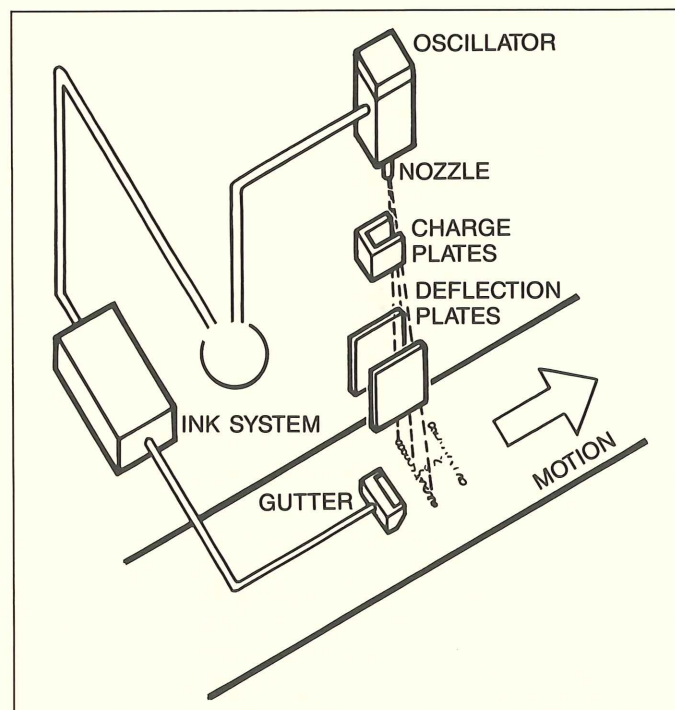
For Sweet's charge-and-deflection scheme to work, the droplet size and the droplet breakoff position (the position at which drops form and separate from the ink stream) had to be uniform in space and time. Sweet accomplished this by inducing droplet formation. This was achieved by mechanically disturbing the capillary stream at its natural frequency (see figure 2).

It was Sweet's droplet charging-and-deflection technique that made rapid printing of alphanumeric characters possible, facilitating the use of ink jet printers with digital computers. The AB Dick 9000 series printer, used for coding beverage cans and bottles, is based on this technology, as is the IBM 6640 document printer.

### They Made the Project a Success

Many individuals from Tek's Applied Research Laboratory, Display Devices Operation, and Peripherals Division contributed to the success of the Tek Ink Jet Project. However, a core of five individuals—Richard Marantz, Bruce Murdock, Brian Boso, Edward Hershberg and Philip Krein—made the project their life. By contributing insight, innovation, enthusiasm, evenings and weekends, they made the project a success.

During the 1960s, several variations of the Sweet technology were invented. C.H. Hertz[9] used an electrostatic charging process similar to Sweet's to modulate a free-running jet stream. During normal operation, the uncharged jet stream freely breaks into small droplets which pass through a small aperture in a masking plate (see figure 3a). When charged, the droplet stream disperses into a mist, and only a small fraction of the original stream passes through the control aperture (see figure 3b).

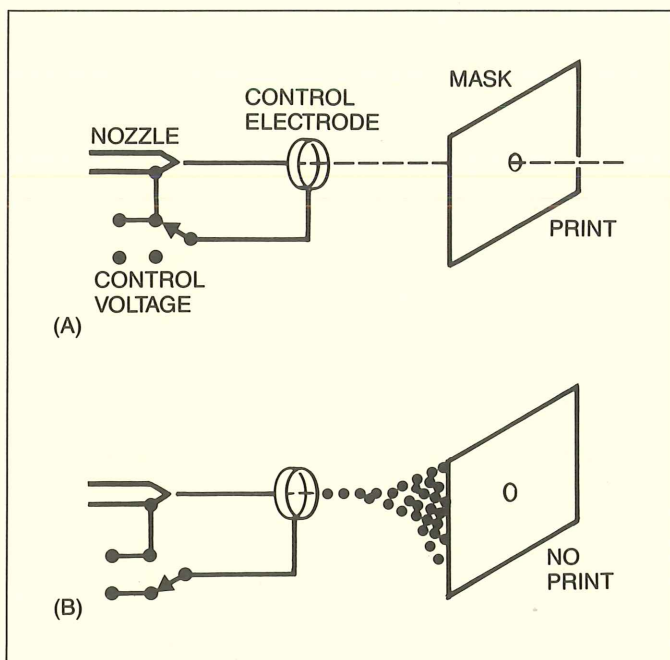


**Figure 2. In this continuous ink jet printer, droplets of ink are charged and deflected using CRT-like deflection plates to create images.**

The Mead Corporation simplified the Sweet technology by making the deflection process binary. Undeflected ink droplets go to the printing substrate (paper); deflected droplets go to a gutter from which the ink is filtered and reused. The Mead technology, unlike the others previously mentioned, incorporates a multiple-nozzle print bar (a 512-orifice array) instead of a single orifice. This increases the rate at which a document can be printed by a factor of 512.

Continuous ink jets are noted for their high rate of droplet production (100,000 drops/second) and for high-quality text printing. This quality results from the analog nature of the droplet-deflection process, which allows for a high degree of overlap between adjacent dots on the printed page. However, all continuous jets are plagued with implementation problems. Electrostatic and aerodynamic interactions between charged droplets in flight allow, at best, only every other droplet to print. The remaining droplets must be blanked out. Likewise, all droplets emitted during pauses in printing must be blanked out. Discarding this ink would be extremely expensive and therefore it is recirculated. During recirculation the ink can become contaminated or change in composition, so it must be processed before being returned to the ink reservoir. Sophisticated reprocessing schemes have been developed, but all are expensive to implement. For this reason, continuous ink jet technology is used in only the most expensive printers.





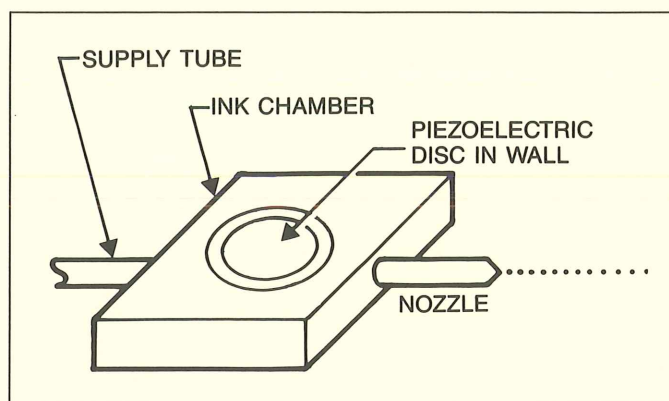
**Figure 3.** C.H. Hertz developed an alternative “droplet blanking” technique. When nothing is to be written, droplets are highly charged causing them to disperse due to electrostatic repulsion. Thus, most droplets do not pass through the aperture.

### Drop-on-Demand Ink Jet Technology

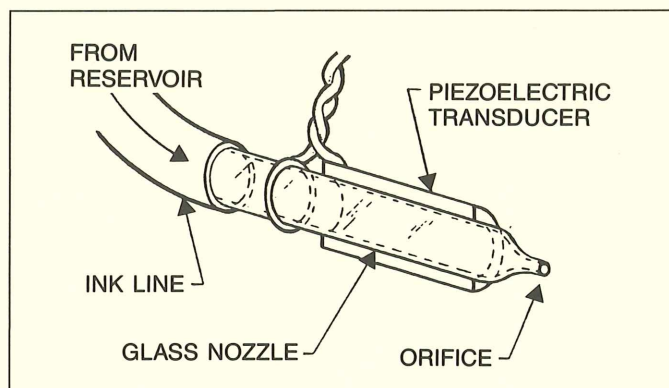
The history of drop-on-demand (DOD) ink jets is brief compared to continuous ink jets. These jets, which eject a droplet of ink only when required, were first discussed in the patent literature during the early 1970s. The many variations available today attest to the effort expended developing this technology. In all but two of the current variations, piezoelectric crystals cause the ejection of an ink droplet on demand. These crystals undergo dimensional changes when electrically charged (50-400 volts) and can be made to vibrate when addressed with an AC signal.

When coupled to a fluid-filled reservoir containing a miniature nozzle (25-75 microns in diameter), a vibrating piezo causes the ejection of a fluid column through the nozzle. This column naturally breaks up into one or more droplets. Since the ejected droplet(s) are not steered, the ink jet nozzle must be mechanically scanned across the media.

Kyser and Sears[10], in 1970, used a disk shaped piezoelectric crystal placed above a fluid-filled glass capillary having a small nozzle at one end (see figure 4). Applying voltage across the piezo sends a pressure pulse through the fluid, forcing a single droplet to be ejected from the nozzle. Zoltan modified this technology in 1972.[11] His device used a cylindrical piezo, concentric with a glass capillary (see figure 5). This technology was adopted by Siemens and is used in their PTxx printer product line.



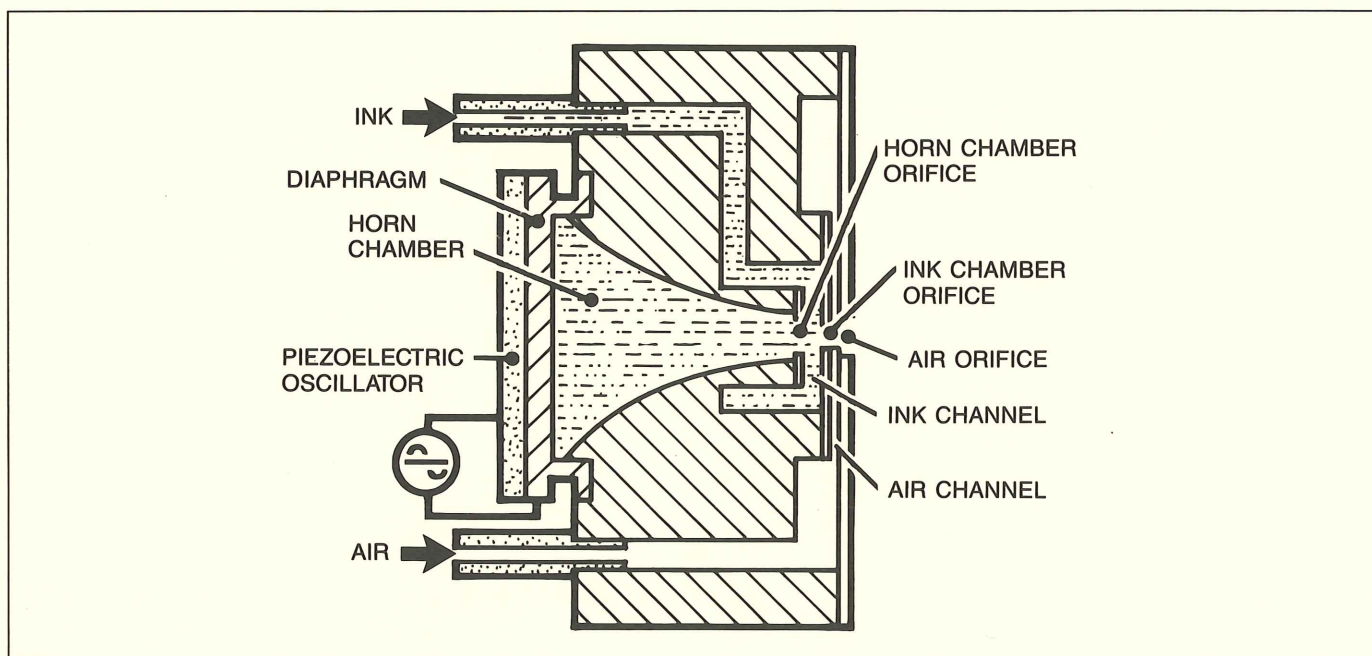
**Figure 4.** In Kyser and Sears' drop-on-demand ink jet, a piezoelectric disc bonded to a diaphragm delivers pressure pulses into the ink, forcing droplets out the miniature nozzle.



**Figure 5.** The Zoltan impulse jet, is another embodiment of drop-on-demand technology. Ink jets of this type are used by Siemens, ACT, and Printacolor.

In 1973, Stemme placed the piezo in line with the ink orifice and added a second chamber to the jet to increase the droplet emission frequency.[12] The additional chamber facilitated an increase in the rate at which the ejecting nozzle could be refilled with ink from the supply reservoir. Miura and other Matsushita experimenters[13] added a third chamber to the jet and obtained a maximum droplet frequency of 20 kHz (see figure 6). Since the speed of most ink jet printers and copiers is limited by the speed of the writing element, the high droplet frequency—that is, on/off frequency—achieved with the Matsushita technology allows for a higher-speed printer.

The outer chamber of the Matsushita jet is pressurized with air so as to create 1) a delicate pressure balance at the ink-emitting orifice and 2) a high-velocity air stream in which the ejected ink droplets are entrained and accelerated to the paper. The most widespread application of this technology is the Tek 4691 and 4692 color ink jet copiers.



**Figure 6. Matsushita ink jet. This high-performance technology was purchased by Tek and substantially modified to reduce labor costs and improve design reliability.**

The thermal jet is the most recent addition to the drop-on-demand family. A thin-film resistor is placed inside a chamber having a small exit orifice. Passage of current through the resistor superheats the ink in contact with the resistor, creating a rapidly expanding vapor bubble. This process expels a droplet of ink from the orifice (see figure 7). Although the maximum droplet-emission frequency of this technology is less than with piezoelectric technologies, multi-nozzle (array) fabrication is easier because semiconductor-type processes are utilized. This technology is employed in HP's ThinkJet (THERmal INK Jet)[14] and in Canon's Bubble jet.[15]

Electrostatic extraction is another recent variation of drop-on-demand technology. This technology, originally used in continuous jets[16], has recently been applied to drop-on-demand ink jets.[17] With this technology, charge is transferred into a fluid contained in a nozzle. A high electrostatic field exterior to the nozzle causes the ink to form a positive meniscus. Under high field strengths, a portion of the meniscus is pulled away from the bulk fluid. Unlike all other drop-on-demand technologies, the droplet-forming force is applied directly to the fluid meniscus. This has the advantage of being more efficient and therefore minimizes the hydraulic interaction between adjacent nozzles in multiple-orifice (array) ink jets. Although research activity continues, no commercial products employ this technology.

### Development of the Tektronix Ink Jet

The Tek 4692 ink jet copier is Tek designed and Tek made. Four drop-on-demand, 20-kHz, single-orifice jets (yellow, magenta, cyan and black) are used as the printing elements.

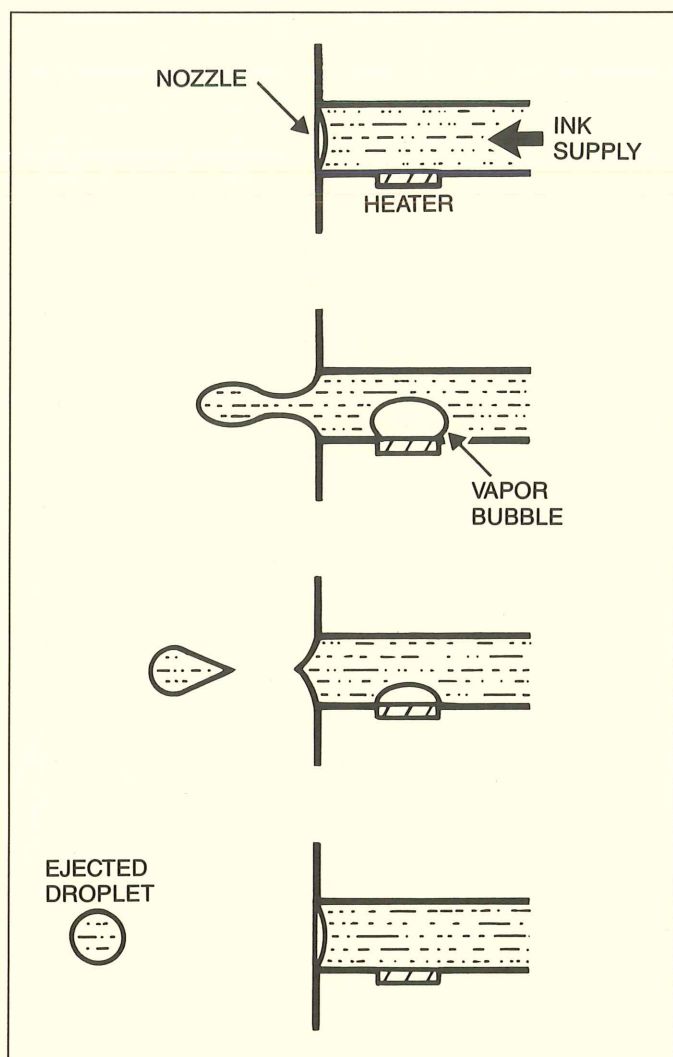
The 4692 was designed around an ink jet purchased from Matsushita[13] but with a plan to convert to a Tek-built version near the time of product release. The development of a Tek ink jet, identical in performance to the Matsushita technology, was a strategy to facilitate Tek's rapid assimilation of the new technology. By establishing design-and-manufacturing expertise Tek could become a leader in ink jet technology and insure its competitive edge in the color hard-copy market through the 1980s.

Because the Tek jet performance was to be identical to the Matsushita, a manufacturing and distribution license for the Matsushita technology was purchased. Tek also bought Matsushita's engineering data on the jet's design and assembly processes.

Unfortunately, these processes proved to be labor intensive and difficult to reproduce. Initial attempts to build jets using Matsushita's design and processes produced few jets that worked well. Thus, the Tek jet-development team had to establish processes that were not only less labor intensive, these processes had to consistently produce high yields. The magnitude of these process changes are best illustrated by reviewing the Matsushita design.

The Matsushita ink jet, on which the present Tek jet is based, is a three-chamber piezoelectric-driven device. The three chambers—the horn chamber, the ink chamber, and the air chamber—directly communicate with each other through two aperture plates. A final (third) aperture plate connects the integral chambers of the ink jet to the outside world (see figure 6).





**Figure 7. The bubble jet expels droplets in response to rapid localized vaporization induced by electrically pulsing a thin-film resistor. Approximately 36 microjoules (six watts for six microseconds) is dissipated to eject a single droplet.**

The large end of the horn chamber is sealed by a piezo/diaphragm, which is the jet's energy source. A charge imbalance, placed across the piezo, causes the piezo/diaphragm assembly to buckle slightly, changing the volume of the horn chamber. Under normal operation, the volumetric change is first positive then negative, creating a pumping action. This induces a fluidic pressure pulse, causing ink to be ejected through the horn-chamber aperture.

The ink chamber, which acts as both an acoustic filter and an ink reservoir, transmits the horn-chamber pressure pulse to the ink-ejecting aperture. The ink meniscus resides on the exit side of this aperture. Ink ejected by the ink jet is replenished by a supply line which feeds into the ink chamber. The ink supply is maintained at the pressure of one psi (27 inches of water).

The air chamber is connected to an supply of air having a static pressure of 30 inches of water. This is slightly higher than the 27 inches for the ink. This slight pressure difference helps to restrict the size of the ink meniscus, thus affecting the drop-formation process. The air stream flowing out of the air orifice also assists in forming and accelerating droplets out of the ink jet. (Although the pressure drop through the air orifice is small, the air stream reaches a velocity of 180 mph (80 m/s), accelerating the ink droplets to a velocity of 18 mph (8 m/s).)

The pressure balance across the ink-ejecting aperture is critical to the jet operation and must be maintained near zero. A positive pressure across the ink aperture plate can force unwanted ink out of the ink chamber. A negative pressure across this aperture can be catastrophic if it causes an air bubble to enter through the ink aperture. Because the ink jet is a hydraulic pump, an air bubble in either the horn chamber or the ink chamber can dramatically degrade jet performance.

The Matsushita device is composed of a rectangular stainless-steel casting (the body) with prepunched stainless-steel aperture plates and a machined stainless-steel diaphragm. The aperture plates and the diaphragm are attached to machined surfaces on the body using an oven-cured epoxy. For proper operation of the jet, the aperture plates are visually aligned such that the centers of adjacent apertures are concentric to within six microns (0.00025"). Each aperture plate must be aligned and the epoxy cured before proceeding to the next plate. Aperture plate movement during the epoxy curing process must be minimized so that the six micron concentricity error budget is not exceeded. It was excessive movement of aperture plates during epoxy curing that caused low assembly yields of Tek's first experimental jets.

To raise yields, laser welding and brazing were investigated as alternatives to epoxy bonding. Laser welding gave encouraging results in terms of seal quality. However, the high local temperatures inherent in laser welding deformed the aperture plates beyond the allowable plate-to-plate spacing tolerance of  $\pm$ five microns. The severity of this problem was not recognized until shortly before the deadline for shipping ink jet prototypes to the customer, Tek's Peripherals Division. Through an intensive effort, three team members developed the second alternative bonding process, brazing, in a period of two weeks.

In developing both the brazing and laser welding processes, the aperture concentricity tolerances could not be conveniently achieved with fixturing. Thus these processes precluded the use of preformed apertures, as Matsushita recommended. However, brazing was not a dead end.

In previous experiments, Applied Research Lab (ARL) investigators had shown that high quality micro-holes could be formed using electro-discharge machining (EDM). With this method, precise aperture-to-aperture alignment could be achieved by straight-line drilling after assembly. Here the first indication of the interrelationship between process and design became evident.



Because brazing as a bonding process has a long history in CRT manufacturing, Tek had much of the equipment and knowledge necessary to do general brazing. However, the jet's design required nonstandard processes, which had to be experimentally verified.

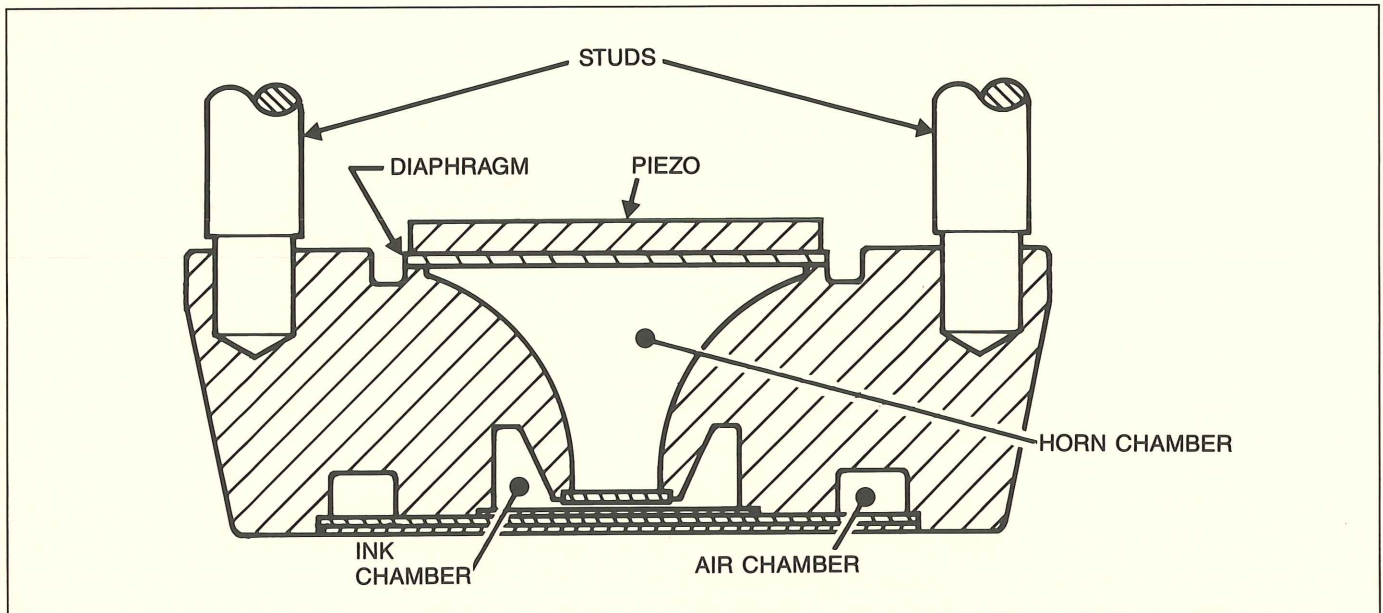
The Tek Jet assembly process requires each jet to undergo three successive brazing cycles. The apertures are drilled after the second braze. Thus during the third braze cycle (attachment of the studs and diaphragm) it is required that none of the previously brazed aperture plates reach the braze melt temperature or they could become mobile. By proper selection of braze material, the braze process insures that sufficient alloying occurs between the braze material and the stainless steel parts. This alloying significantly increases the braze remelt temperature; thus, once brazed, there is no remelting or plate movement during subsequent braze cycles. Figure 8 shows the completed assembly.

Using micro-EDM technology to form apertures was another major deviation from the Matsushita process. In electro-discharge machining, material is removed through spark erosion. The material to be machined (drilled in the case of ink jet apertures) is immersed in a kerosene bath. A spinning electrode, of a size comparable to the hole to be drilled, is advanced towards the work material until the gap between the two is reduced to approximately one micron. The field strength at this point (about 30 MV/m) exceeds the dielectric strength of kerosene. A discharge occurs, vaporizing a small quantity of the work material. A servo mechanism maintains the micron gap between the electrode and work material by advancing the electrode as material is removed.

Although micro-EDM drilling is more expensive than micro-punching, it has the advantage of allowing concentric drilling of all three apertures after they have been assembled. This eliminates the labor-intensive alignment processes. It also simplified experimental investigations as jets could be made with various aperture diameters, and if required, redrilled and retested. The hole quality achieved with the Panakron micro-EDM (see figure 9) surpasses that realized with all other hole-formation techniques we investigated: mechanical drilling, laser drilling, micropunching, and chemical drilling.

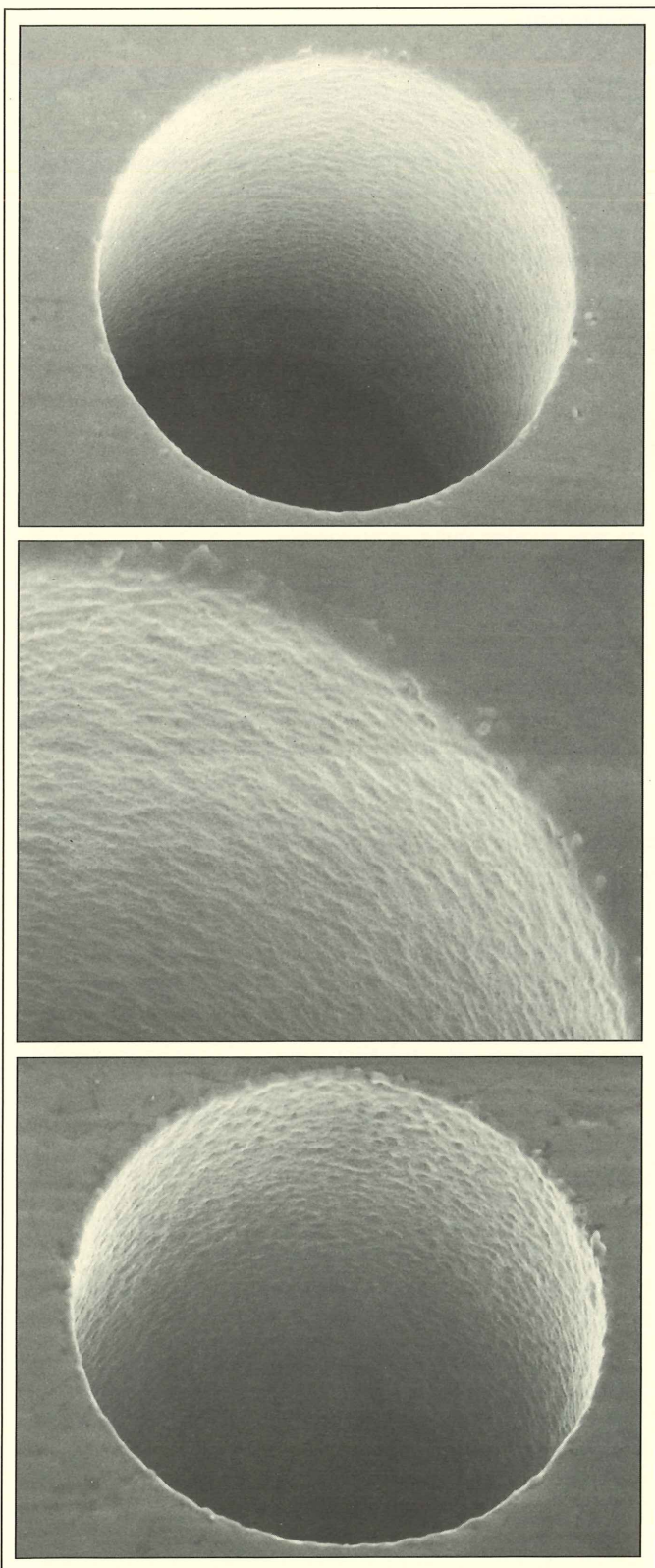
The last areas in the Matsushita device identified for modification were the body and diaphragm design. Matsushita recommended a rectangular body cast out of stainless steel. Although this process is inexpensive, subsequent machining such as deburring and complex porting are not. In addition, cast material is coarse grained and brittle. The potential for creating metal flakes in tapped ports after head assembly was unacceptable.

A cylindrical body design was chosen for the Tek jet since it could be machined to high tolerances and deburred using a numerically controlled lathe. A process was developed where the front (aperture plate) side, and back (horn chamber) side are each machined in a single step. The lathe is also used to place a reference mark on the back side of the jet for alignment during subsequent porting. All ports to the interior of the jet were designed to be straight and all but one originate from the same surface (figure 10). Only one port hole is tapped. Machining costs were further reduced by designing the jet to accommodate a flat-plate diaphragm (chemically milled), replacing Matsushita's more expensive machined diaphragm.

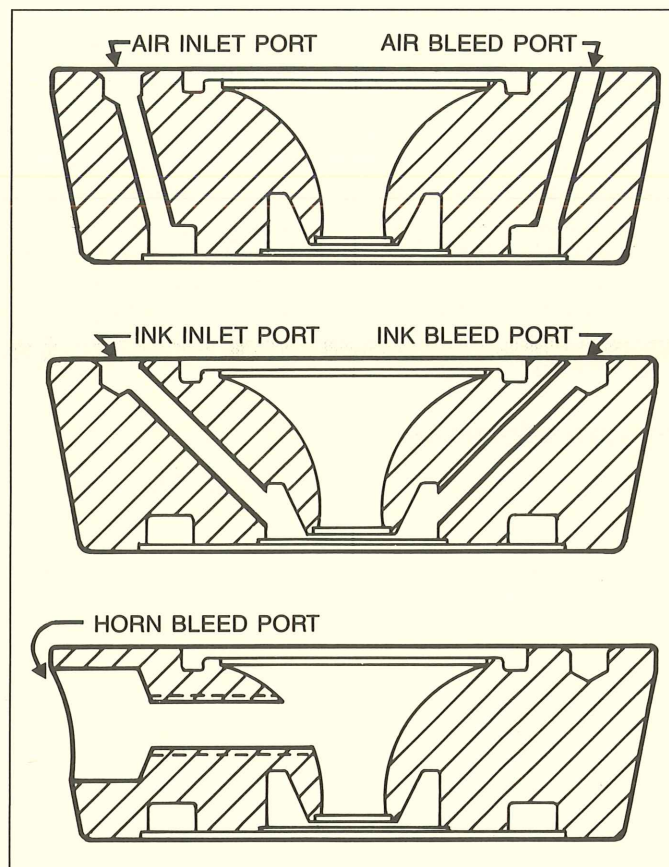


**Figure 8. The Tek jet is a cylindrical version of Matsushita's dimensional technology. The cylindrical shape is simpler to machine to tight (<10 microns) tolerances and also can easily be deburred. By drilling after plate assembly, using EDM, Tek greatly reduced labor, increased yields, and improved long-term reliability.**





**Figure 9. SEM photo of ink jet orifice formed by micro-EDM. Of special interest is the smoothness of the EDM surface and the lack of any residual burr or recast on either the entrance or exit side of the hole.**



**Figure 10. Crosssectional views of the Tek ink jet body. The air and ink ports (inlet and bleed) on the Tek jet are straight. The horn bleed port is the only port which is threaded. This reduced the head-manufacturing cost and the potential for generating troublesome metal chips within the ink jet. Jet clogging by metal chips has been a major failure mode of the Matsushita technology.**

The major design changes outlined above did not come without a cost. Jet performance was altered by these changes. The design of the Tek Jet had to be further refined to maintain performance consistent with the Matsushita technology. This was necessary as the two jets were to be interchangeable on the Tek 4692. The cause of performance differences had to be understood before adequate solutions could be developed. In so doing, project members gained a better understanding of the intricacies of the ink jet technology.

The success of a component development project is best told by the success of the manufacturing unit responsible for making the device. Although the ink jet was a totally new technology for Display Devices Manufacturing, they achieved a total process yield of greater than 70 percent within six months of PR. This overall yield represents better than 90 percent yield on all but one of the ten major assembly processes. Eight of these processes have critical tolerances of less than  $\pm 6$  microns. In manufacturing cost, we fell slightly short of our self-set ambitious goal. However, despite our inexperience as a manufacturer of ink jet technology, the Tek jet is produced at a cost comparable to that we would pay the more-experienced Matsushita.

Ink jets are a new venture for Tek, new in both the technology itself and the markets the technology opens to us. Ink jets also represent a substantial investment for Tek in terms of employee training and customer education. In both areas, the investment is starting to pay off. Through the work of Tek's Applied Research Laboratory, Peripherals Division, and Display Devices Operation, Tek is now an inventor of ink jet technology, not just an OEM user. These new technologies not only enable Tek to better address current markets but also allow us to pursue new markets. Tek—and our competitors—have proven that ink jet technology produces images of quality; quietly and reliably. Tek, through its efforts has laid the solid foundation needed to exploit the demand created.

### For More Information

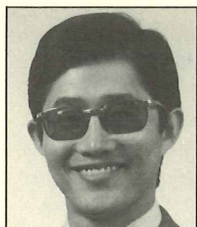
For more information call Gerhard Beenen, 627-2257 (50-271). □

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# New Algorithm Rapidly Estimates Sinewave Parameters and Determines a Digitizer's Effective Bits



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In many test and measurement systems, estimating sinewave parameters is a fundamental method of device characterization. A linear circuit (system), for example, can be completely characterized by driving the circuit with a sinewave and then measuring the parameters of the output sinewave. Deriving the effective bits of a waveform digitizer also requires the estimation of sinewave parameters.

A sinewave represented by  $A \sin(2\pi ft + \theta) + D$  has four parameters: the amplitude  $A$ , the DC-offset  $D$ , the frequency  $f$ , and the phase  $\theta$ . For sinewaves with unit amplitude and zero DC-offset, I had developed a precise frequency and phase estimator based on the weighted least square method.[1] Phil Crosby and I subsequently developed an algorithm for precisely estimating the DC-offset  $D$  and the amplitude  $A$  of a sinewave using a windowing technique. By combining the results of both estimators, we have developed a high-performance, complete algorithm for estimating sinewave parameters. This algorithm is both precise and faster than other algorithms.

Because estimation errors in this new algorithm are in closed form, they can be precisely controlled. Because the algorithm is noniterative, it is extremely fast. A 256-point fit takes only a couple of seconds on the IBM PC/AT using a Turbo Pascal implementation. A 10-point effective-bits plot of a waveform digitizer can be done in *seconds* instead of the *minutes—or even hours*—other iterative algorithms require.[3-4]

Before describing the algorithm and describing its performance, let's state the problem.

## Problem Statement

Given: a sinewave  $s(t) = A \sin(2\pi ft + \theta) + D$  with four unknown parameters  $A$ ,  $f$ ,  $\theta$ , and  $D$ . If we sample the sinewave  $s(t)$  at the rate  $f_s$  samples per second and collect  $N$  data points, we will have a data sequence  $S = \{s_k = s(k/f_s) = A \sin(k2\pi f/f_s + \theta) + D, k = 0, \dots, N-1\}$ . We would like to precisely estimate the values of  $D$ ,  $A$ ,  $f$ , and  $\theta$  from  $S$ .

## The Algorithm

Let us define a window sequence  $W = \{w_k, k = 0, 1, 2, \dots, N-1\}$  where  $w_k$  is given by the following equation,

$$w_k = 0.35875 - 0.48829 \cos(k2\pi/N) + 0.14128 \cos(k4\pi/N) - 0.01168 \cos(k6\pi/N), k = 1, \dots, N-1 \quad (1)$$

This window sequence is obtained by sampling the four-term Blackman-Harris window.[5]

The DC-offset estimator  $\tilde{D}$  is given by

$$\tilde{D} = \frac{\sum_{k=0}^{N-1} w_k s_k}{\sum_{k=0}^{N-1} w_k} \quad (2)$$

and the amplitude estimator  $\tilde{A}$  is given by

$$\tilde{A} = \left[ 2 \frac{\sum_{k=0}^{N-1} w_k (s_k - \tilde{D})^2}{\sum_{k=0}^{N-1} w_k} \right]^{1/2} \quad (3)$$

To describe the computational algorithms for the frequency estimator  $\tilde{f}$  and the phase estimator  $\tilde{\theta}$ , we need to define some notations:

$$\begin{aligned} s'_k &= (s_k - \tilde{D}) / \tilde{A}, & k &= 0, 1, \dots, N-1 \\ u_k &= 1 - (s'_k)^2, & k &= 0, 1, \dots, N-1 \\ x_k &= \arcsin(s'_k), & \text{subject to monotonic condition} \\ t_k &= k / f_s, & k &= 0, 1, \dots, N-1 \end{aligned}$$

Also let  $\text{Sum}U = \sum u_k$ ,  $\text{Sum}UT = \sum u_k t_k$ ,  $\text{Sum}UTT = \sum u_k t_k t_k$ ,  $\text{Sum}UX = \sum u_k x_k$ ,  $\text{Sum}UTX = \sum u_k t_k x_k$ , and  $\Delta = \text{Sum}U \cdot$

$\text{Sum}UTT - \text{Sum}UT \cdot \text{Sum}UT$ , then the  $\tilde{f}$  and  $\tilde{\theta}$  are given by the following two expressions, respectively.

$$\tilde{f} = \frac{1}{2\pi} \left[ \frac{\text{Sum}U \cdot \text{Sum}UTX - \text{Sum}UT \cdot \text{Sum}UT}{\Delta} \right] \quad (4)$$

$$\tilde{\theta} = \left[ \frac{\text{Sum}UX \cdot \text{Sum}UTT - \text{Sum}UT \cdot \text{Sum}UTX}{\Delta} \right] \quad (5)$$

## Precision Performance

Let  $W(\omega)$  be the Fourier transform of the window function  $w(t)$ . (In our algorithm,  $w(t)$  is the 4-term Blackman-Harris window whose samples are given by (1)) and  $\Delta D = D - \tilde{D}$ , then we have, as shown in [2],

$$\Delta D = \frac{AW(\omega_0)\sin(\theta)}{W(0)} \quad (6)$$

where the symmetry of  $W(\omega)$  is assumed.

A plot of  $|W(\omega)/W(0)|^2$  (figure 1) shows that if the data record  $S$  contains more than four cycles of the sinewave,  $|\Delta D|$  is less than  $|A| \cdot 10^{-9.2}$ . In practice, if we include the additive noise (such as the quantization noise introduced by the waveform digitizer), then we need to add an additional error term of approximately the size of  $\sigma(N)^{1/2}$ , where  $\sigma$  is the standard deviation of the additive noise.

We turn now to the amplitude estimator. Assuming that the error  $\Delta D$  in the DC-offset estimate is negligible, then the normalized error  $\Delta A/A = 1 - |\hat{A}/A|$  is given by the following expression [2],

$$\Delta A/A = \left[ \frac{|W(2\omega_0)\cos(2\theta)|}{W(0)} \right]^{1/2} \quad (7)$$

where the symmetry of  $W(\omega)$  is again assumed.

Under the same condition that the data record  $S$  contains at least four cycles, the normalized error  $\Delta A/A$  is upper bounded by  $10^{-4.6}$ .

As for the frequency estimator, as I described in a *Technical Report*, [1] the normalized standard deviation  $\text{std}(\hat{f})/f$  of the frequency estimator given in Eq. (4) is given by

$$\text{std}(\hat{f})/f = 2.2 \frac{\sigma}{(m \cdot n^3)^{1/2}} \quad (8)$$

where  $m$  is the number of samples per period,  $n$  is the number of half periods covered in the record and  $\sigma$  is the standard deviation of the additive noise. The exact form of the phase estimator error is not available, however, it can be shown to be in the order of  $\sigma/(N)^{1/2}$ .

### Speed

Assuming that in carrying out the algorithm, multiplications and divisions will be the most time-consuming operations; then, it can be easily estimated, using equations from the previous section, that the number of these operations is about  $20N$ . In this estimate each arcsin evaluation (subject to monotonic condition) is counted as eight operations. (We obtained this number by experimenting with the PC/AT.) Because a PC/AT with 287 coprocessor, takes about 200 microseconds to do one operation, this algorithm will take about one second for a 256-point data record. Of course, it will take a little bit longer to actually execute the algorithm, because of overheads and operations such as additions and data movements. Nevertheless, the analysis here indicates that execution should take only about a second; we confirmed this with the experiment with a PC/AT with 287 coprocessor.

### Examples and Conclusions

A program implementing the algorithm, written in Turbo Pascal and run on the PC/AT, confirmed both the precision and the speed predicted by the theory. We then used the algorithm to

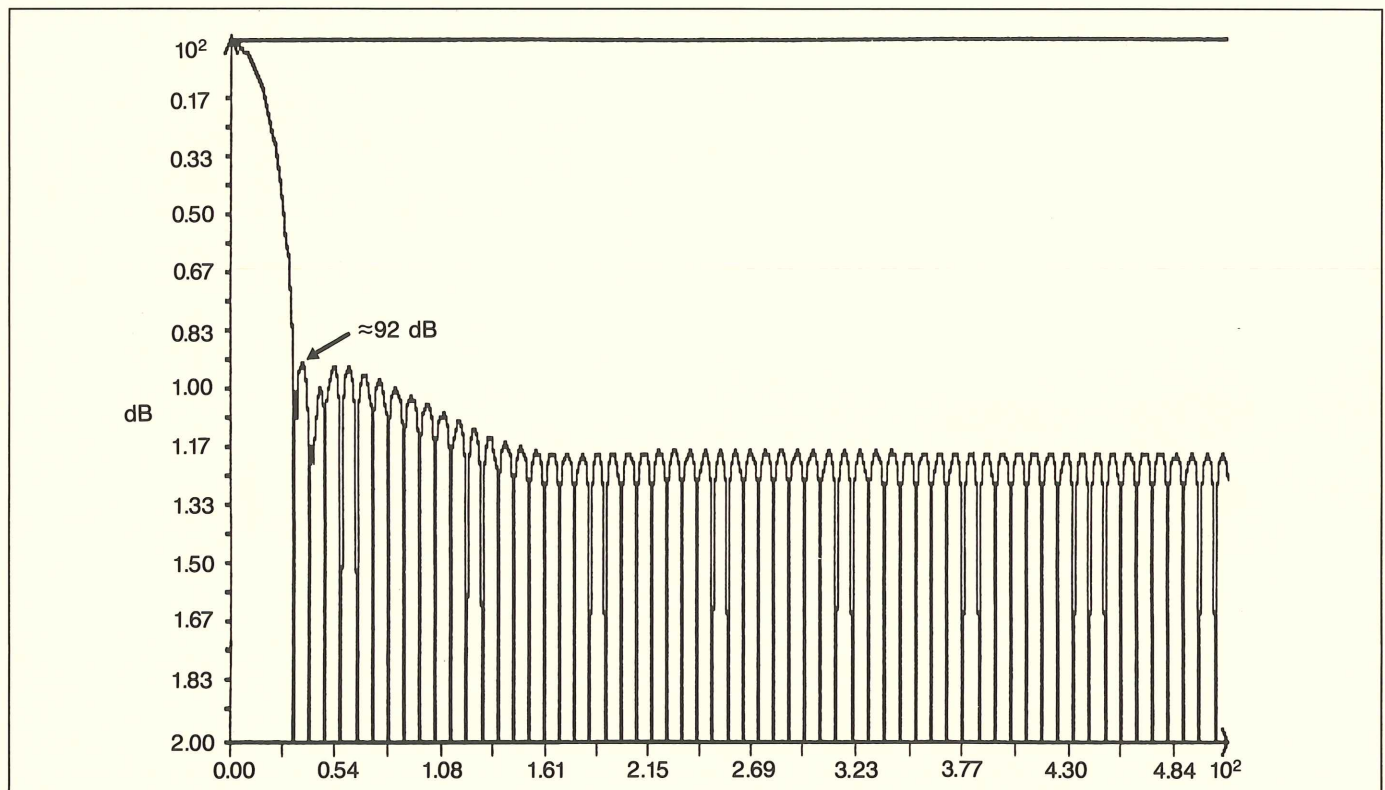


Figure 1. This plot of the window function  $wT$  shows the magnitude spectrum of the window.



estimate the "effective bits," as defined in the *Hewlett Packard Journal*[4], of a simulated ideal waveform digitizer having various number of bits. The results, summarized in table 1, confirmed the performance of this algorithm. Note that the "ideal

effective bits" start deviating from the "real" number of bits when the number of bits falls below 5. This deviation is due to the inaccuracy in the modeling of the quantization error of a sinewave as a white noise.

### For More Information

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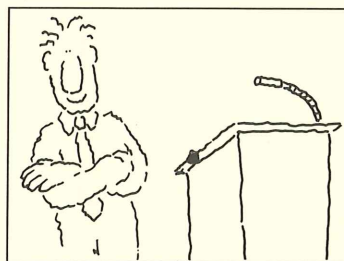
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NUMBER OF BITS	SIMULATED EFFECTIVE BITS	IDEAL EFFECTIVE BITS
12	11.99	11.99
10	10.00	10.00
8	8.03	8.01
6	6.01	5.98
5	4.99	4.94
4	3.98	3.91
3	3.02	2.87
2	2.18	1.81

**Table 1. Simulated and ideal effective bits as estimated by the new algorithm track "real" bits accurately down to six bits. Below six bits, quantization error causes the "ideal" effective bits to deviate during the modeling process.**

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# The Capture Bus Eliminates Speed Bottlenecks in Hardware Simulators



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**The Capture Bus is fast—fast enough for next-generation simulators, where a lot of data has to be transferred and speed is increasingly critical. The Capture Bus is fast because it is wide, it uses time multiplexing, and it carries data only—no data identifiers are used.**

Most hardware simulators achieve high speed by partitioning the logic network into  $n$  subnetworks and by simulating the subnetworks in parallel by  $n$  identical processing units. Partitioning imposes the need to communicate data among the processing units. It is the time spent in this communication that largely determines system speed.

Since the buses now standard in industry cannot transfer data fast enough, special-purpose communication structures have been proposed and designed. This article outlines some of these structures and examines the strategies underlying a promising new structure called the Capture Bus.

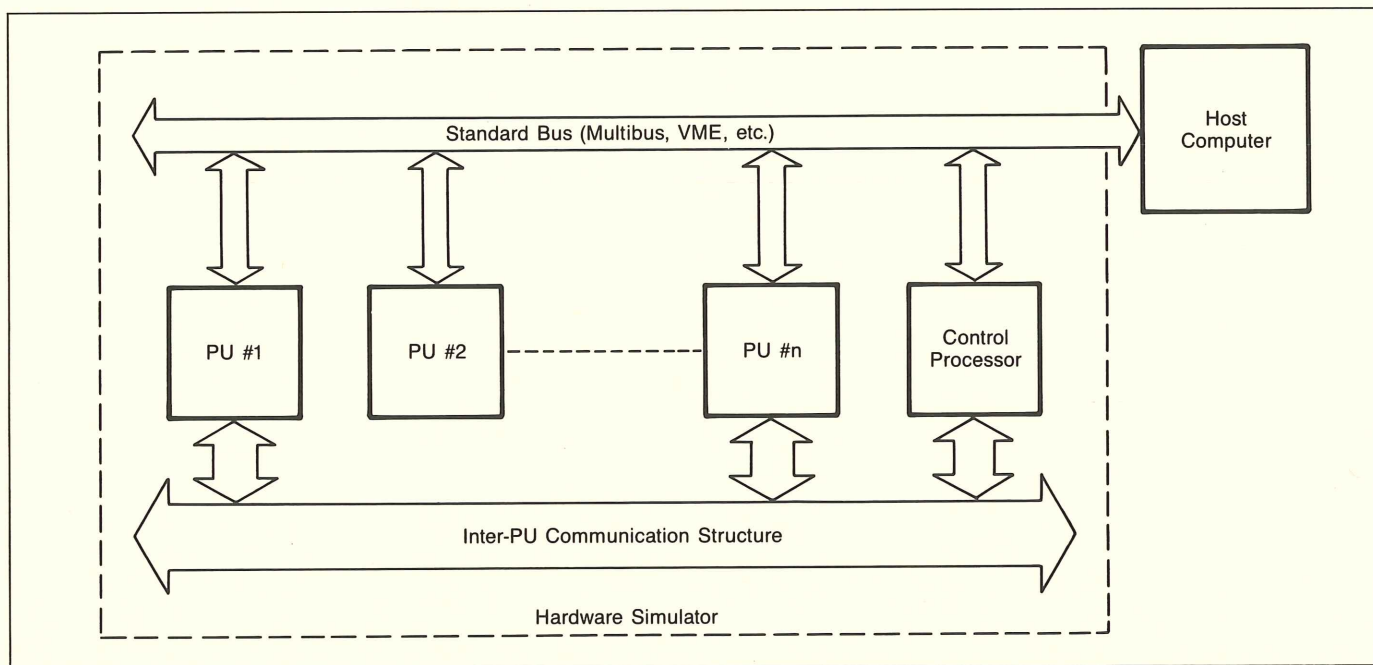
The Capture Bus is faster than previous methods because 1) it is wide and 2) it does not have to carry data-identification information because a special time-multiplexing protocol is employed.

## Hardware Simulators and How They Communicate

In a typical hardware logic simulator[1] (figure 1), the host computer is used to set up the simulator with the information required to simulate the logic network and for receiving user-requested information during and after the simulation. The logic network is partitioned into subnetworks and a subnetwork is assigned to each of the processing units (PUs). Each PU contains the circuitry necessary to simulate the subnetwork.

Due to partitioning, inter-PU data generated during simulation must be transferred through some communication structure. The controller is used to control the PUs and, by managing data transfers, reduce the interaction between the simulator and the host. Communication between the host and the simulator is by a standard bus.

For inter-processing unit communication, IBM's Yorktown Simulation Engine[3,4,5] employed the bus—or switch—shown in figure 2. Each PU executes up to 8K instructions. Because each instruction can be used to evaluate a gate, this simulator has a capacity of 8K gates/PU. As an instruction is executed, data from PUs are sent to the switch. The destination PUs are selected through addresses stored in the RAMs. In fact, for

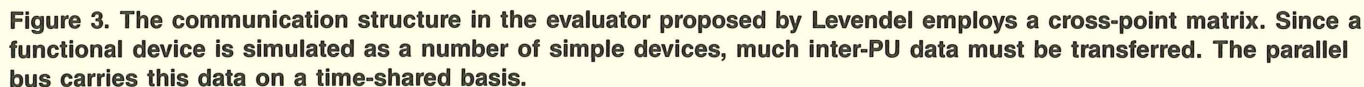


**Figure 1. In a typical hardware simulator, the logic network is partitioned into subnetworks and each subnetwork is assigned to a processing unit (PU). Too often the inter-PU communication in such simulators is slowed by both the communication structures and protocols employed.**



In the communication structure used by Levendel's functional evaluator[6] (figure 3), a parallel bus carries time-shared inter-PU data. Since a functional device is equivalent to multiple

unit. The inter-IO data consists of logic values for the next simulation cycle.



The communication structure used in HAL[7] (figure 4) is a router-cell network in which each router is a store-and-forward crossbar switch having two input and two output ports. Packets of information are sent in a parallel and pipelined fashion during a level-simulation cycle. A packet consists of the destination PU number, the address of the block, the input pin number, the new logic value of the pin, and a parity bit.

Different factors shaped the design philosophy behind each of these three methods: gate-level, unit-delay, rank-order simulation for the Yorktown simulator; variable-delay, event-driven simulation of devices on both the simple and functional level for Levendel's simulator; and block-level, zero-delay, level-ordering simulation for HAL.

#### *Typical operations in an event-driven, variable-delay simulator*

A simplified version of a typical PU's operation during a simulation cycle consists of these steps:

1. Retrieve active source devices.
2. (a) Evaluate fanout devices that are in the same PU subnetwork.  
(b) Send to other PUs the output signal values of those source devices that have the fanout devices in other subnetworks.

- (c) (i) Receive from other PUs, the input signal values of those fanout devices that have source devices in other subnetworks. (ii) Evaluate fanout devices.

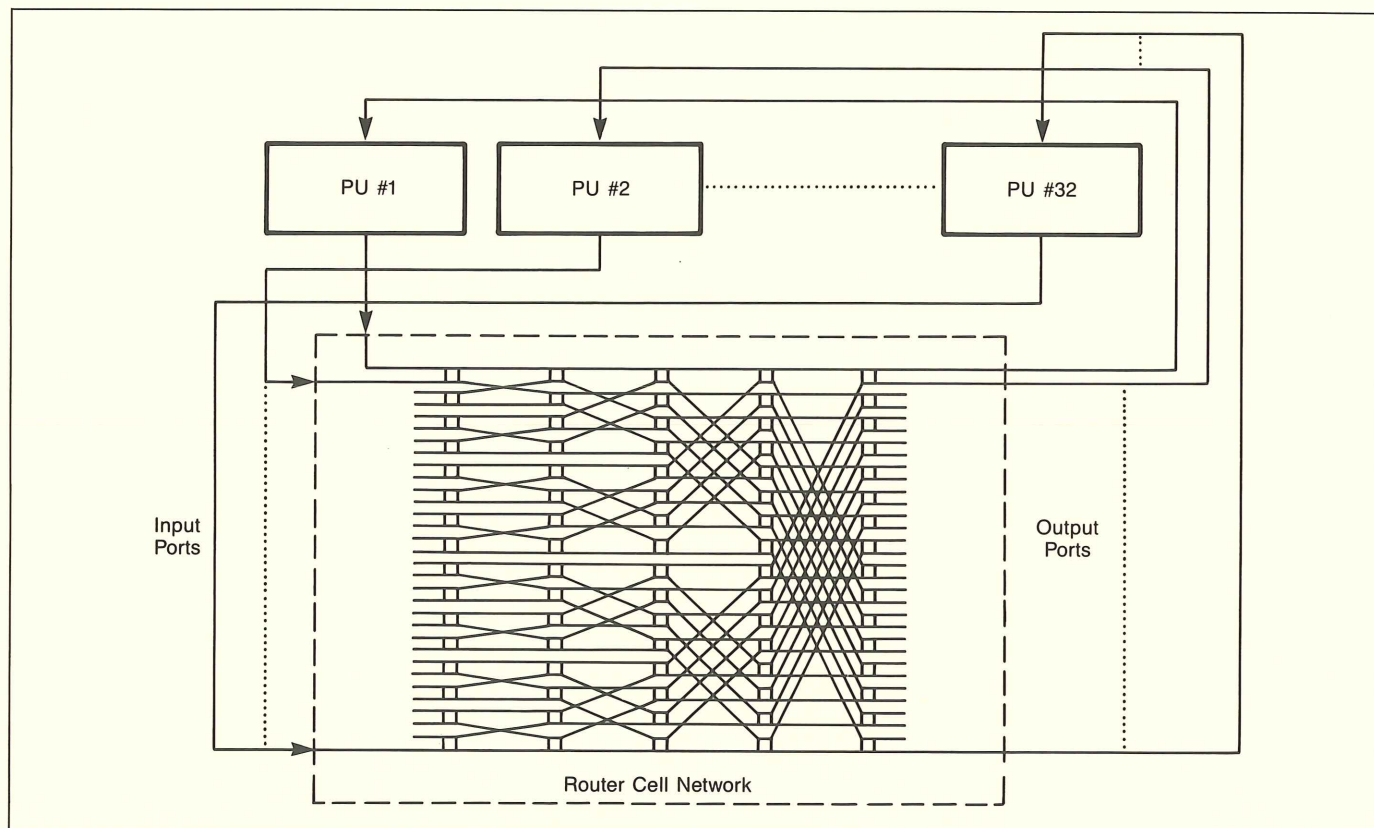
3. Schedule new source devices.
4. Move to the next simulation time to begin another simulation cycle.
5. Repeat (1) through (4) until the simulation is over.

The Capture Bus excels at accomplishing the inter-PU data communication described in steps (2b) and (2ci), and in determining the next simulation time in step (4).

#### **The Capture Bus Structure**

The Capture Bus has two control lines—CLOCK and DATA TRANSFER (DATA XFER)—and data- and check-signal lines.

The processing units use CLOCK to synchronize their communication of data on the bus. DATA XFER is used to signify data on the bus—the DATA XFER signal line is asserted when all the PUs pull this line asserted (possibly a wired-OR ECL implementation of DATA XFER in negative logic). Check signal lines are added to the data signal lines to increase the reliability of data transmission. CLOCK and DATA XFER are also used to determine the next simulation time.



**Figure 4.** In the high-speed logic simulator called HAL, packets of information are pipelined in parallel during a level-simulation cycle. Each router in the router-cell network has two inputs and outputs. Each router is a store-and-forward crossbar switch.



The Capture bus should be designed considering those factors that limit the speed of the bus: the number of PUs loading the bus, the technology and the hardware used to build the bus, and problems such as line reflections, crosstalk and skewing. Line reflections can be eliminated by terminating the signal lines with their characteristic impedance. Crosstalk between adjacent signal lines can be eliminated by using differential lines. Data skewing can be reduced by loading the signal lines equally. Finally, by using check signal lines, data errors can be detected and corrected.

### Protocol for Data Communication on the Capture Bus

The communication cycle consists of a fixed number of  $pw$  time slots, where each of the  $p$  PUs is allotted  $w$  time slots, each slot sufficient to send the maximum amount of inter-PU data involved.

When the PUs are ready, the communication cycle starts with PU #1 as the sender and the other PUs as the receivers. During the first  $w$  time slots, PU #1 sends  $w$  words of inter-PU data where each word is equal to the width of the data bus. The receiver PUs capture only those words that they have been programmed to capture. At the end of the  $w$  time slots, PU #2 becomes the sender and the other PUs the receivers. This process continues, with each PU taking turns as a sender, until the end of the  $pw^{\text{th}}$  time slot when the last PU (#  $p$ ) is done sending the data.

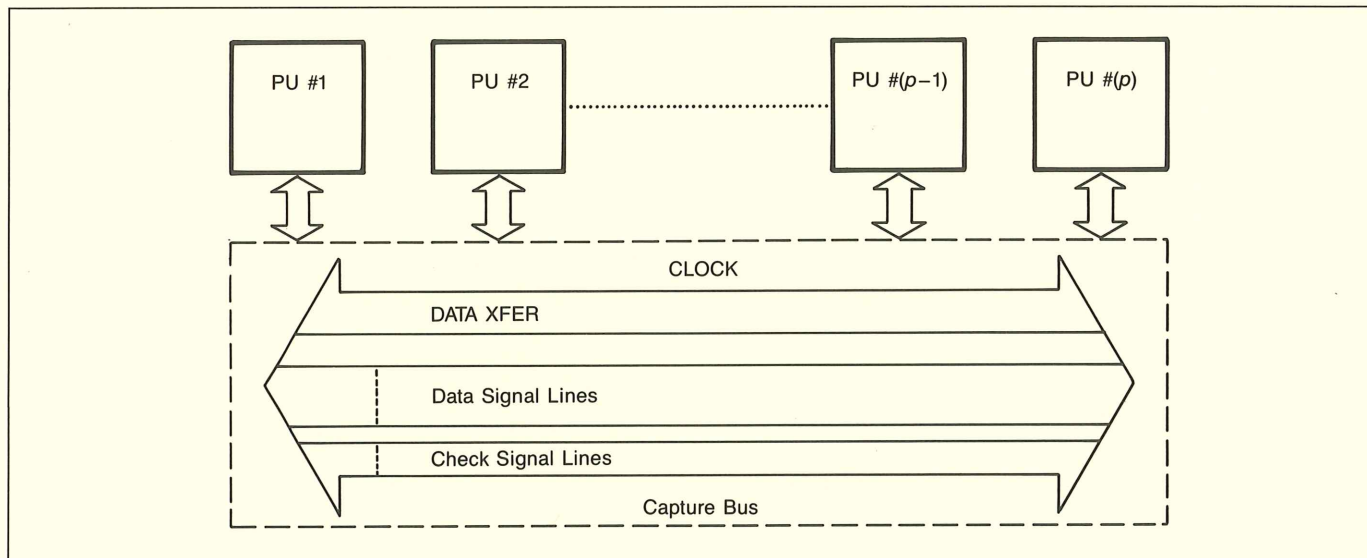
An example of the protocol is shown in figure 6. The wait states are required to allow the PUs to switch from the receiver to the sender. The waiting time can be exploited by making it asynchronous so that errors, such as out-of-sequence, can be checked. The PUs can get out of sequence, possibly by a

glitch in the CLOCK caused by a noisy environment. The logic level of DATA XFER changes after the rising edge of the CLOCK to avoid the metastable state that can occur. Two counters are required in each PU. One counter indicates the number of the PU that is sending the data and the other indicates the number of the word being sent.

The communication cycle of a typical  $n^{\text{th}}$  PU, connected to the capture bus, consists of this order of operations:

1. Assert the internal DATA XFER when ready for inter-PU data communication.
2. Wait until other PUs are ready. This is signaled by the assertion of DATA XFER.
3. Jump to step (6) if  $n=1$ ; that is, if the PU is the first PU. Otherwise, capture the required words between the first and the  $w(n-1)$  time slots.
4. Deassert DATA XFER and switch from receiver to sender.
5. Assert DATA XFER.
6. Send  $w$  words between  $w(n-1)+1$  and  $wn$  time slots.
7. Jump to step (8) if  $n=p$ , that is, if the PU is the last PU. Otherwise, receive data words between  $wn+1$  and  $wp$  time slots. Capture the required words.
8. Deassert the internal DATA XFER. (This marks the end of the communication cycle.)

Note that a unique value of  $n$  is assigned to each PU at the time of the design of the simulator. On the other hand, the values of  $w$  and  $p$  are programmable for the simulator and depend on the size and characteristics of the network to be simulated.



**Figure 5.** Several strategies enable the Capture Bus to eliminate speed-reducing bottlenecks: 1) By being wide, 64 to 256 bits, the Capture Bus can transfer large amounts of data per clock cycle. 2) In contrast to the earlier structures, in the Capture Bus architecture no processing unit communicates directly with another processing unit. The bus is lightly "loaded," carrying only the output logic values of those source devices that fanout to other subnetworks—the processing units know all other information automatically through the data protocol shown in figure 6.

The communication cycle is executed once during the simulation cycle and, once started, the protocol requires that communication should go uninterrupted. Since data errors on the bus occur infrequently, the normal operations of the communication cycle should not be interrupted. Instead, all error words should be recorded and corrections made after the communication cycle is over.

### Protocol for the Determination of the Next Simulation Time

A PU can start the next simulation cycle if it determines that the next simulation time is delayed from the current simulation time by the minimum possible delay of one unit of simulation time. However, if the delay is greater than one unit, the next simulation cycle cannot be started until the minimum delay among the PUs has been determined.

To determine the next simulation time, each PU performs the following steps in this order:

1. Determine the delay.
2. Assert the internal DATA XFER.
3. Wait until all the PUs are ready. This is signaled by the assertion of DATA XFER.

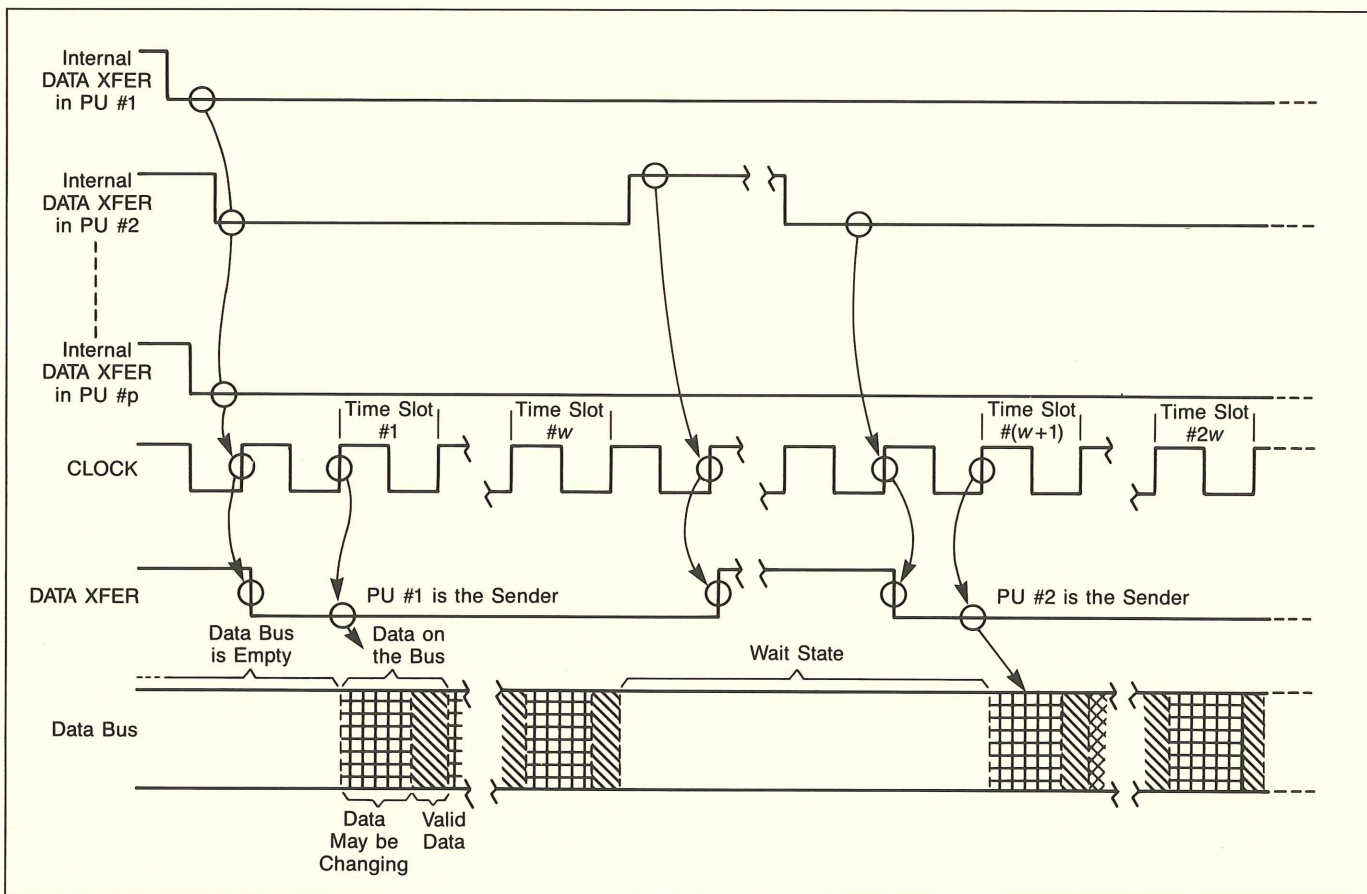
4. Count CLOCK cycles and do one of the following:
  - (a) Deassert DATA XFER if the delay is equal to the sum of the CLOCK cycles.
  - (b) Stop counting if DATA XFER is deasserted. The sum of the CLOCK cycles determines the minimum delay among the PUs, from which the next simulation time can be calculated.
5. Deassert the internal DATA XFER.

The minimum delay can be checked by having PU #1 send the delay on the bus and the other PUs acknowledge the delay if it equals the delay determined in step (4).

### Mapping Inter-PU Data

In the three architectures described in this article, the interconnections between the source devices and the external fanout devices are mapped into the communication structure. (External fanout devices are defined to have source devices in another subnetwork.) In the Capture Bus structure, the processing units do the mapping. Each PU is initialized with the transformation data to do the following mapping:

1. Map the output signal values of the source devices having external fanout devices to some storage. Note that during the communication cycle this data is sent to other PUs.



**Figure 6.** These sequences of steps illustrate Capture Bus protocol. By time share assignments, the protocol eliminates the need to communicate much of information—such as address, source device number, and so on—that burden other structures. Eight steps complete one communication cycle in which communication data consisting of logic signal values is transferred among processing units.



2. During the communication cycle, map the words on the Capture Bus to the subset of words to be captured and stored.
3. After the communication cycle, map those input signal values (captured in step 2) that have changed to the fanout devices.

## Conclusion

During logic simulation, much data must be transferred among PUs. Unless this transfer is fast, there will be a bottleneck in the system. The Capture Bus offers an economical way to speed data transfer. Its architecture can be implemented with advanced technology and hardware for maximum speed. Its protocol makes the communication systematic, thus allowing the PUs to communicate at high speeds.

The Capture Bus differs from other, earlier communication structures in architecture and protocol, and in how inter-PU data is mapped. The Capture Bus solves the communication speed problem using four methods; the earlier structures use at most only three of these methods:

1. The data bus (Capture Bus) is wide: in the order of 64, 128, or even 256 bits. This enables large amounts of data to be transferred in a CLOCK cycle.
2. There is no direct communication among the PUs. The protocol prevents bus conflicts thus eliminating the time required for arbitration.
3. Transmission on the bus is limited to the output logic values of source devices that fanout to other subnetworks. Any data identification—such as address, destination, source device number, pin number, etc.—is automatically known by all the PUs.
4. Synchronous and asynchronous features have been combined for high speed and reliability.

However, the capture-bus scheme has some disadvantages:

1. The communication cycle cannot start until all the PUs are ready.
2. All inter-PU data must be sent onto the bus, whether the data have changed or not.
3. All the PUs must participate during the entire communication cycle.

The effect of these disadvantages can be reduced by overlapping the communication cycle with the evaluation of those fanout devices that have sources in the same subnetwork.

Also, the data can be easily packed together in order to fully utilize the capacity of the bus. Finally, the fact that the communication cycle is short (that is, once started it runs quickly to completion) significantly reduces the effect of each disadvantage.

In conclusion, the Capture Bus prevents data-transfer bottlenecks. It does this by transferring inter-PU data transfer at the speeds logic simulation systems require.

## For More Information

For more information call Vineet Kumar, 627-7287 (02-305). □

## Acknowledgments

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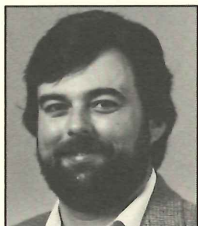
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# A Better Way to Teach Statistical Methods



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Between March and August 1985, the Inner Layer Business Element at Forest Grove and the Management & Training Services unit of Corporate Quality Assurance jointly conducted an experimental training program in the use of statistical analysis methods for achieving quality control.

The curriculum, which was developed jointly by the business-element manager and the consultant/instructor, was designed to meet the specific needs of the business element for improving its product quality level and made use of the "real world" knowledge of manufacturing personnel.

In this article, we will look at the initial basis for the training (and course development) and the results obtained.

## **Statistical Methods and Quality Improvement—A Hands-On Approach**

The traditional approach to manufacturing has generally been limited to depending on Production to make the product and then depending on Inspection to screen out items not meeting specifications.

A more effective and economical approach is a strategy of prevention based on statistical methodology. Statistics are powerful tools that enable personnel to (1) understand the causes of variation in output, and thus gain greater control over their production lines, and to (2) develop a more responsive quality management system that makes more efficient use of resources, thereby lowering costs and increasing earnings.

But how were these methods to be introduced to those not otherwise required to understand statistics?

## **Developing the Training Programs—A Learning Experience**

From the start, this course was experimental because it undertook to avoid the baleful limitations of traditional classroom training programs. Namely:

- Tools and concepts that are not always immediately relevant.
- Textbook examples that are necessarily (and unfortunately) oversimplified.
- Learning problems that are outside the learner/worker's experience – and, therefore, often looked upon as "a waste of time."

Throughout, the training was based on the proposition that statistical analysis methods are most useful when they are put into the hands of the people who actually do the production work. Our experimental course enabled technicians in the quality improvement group to both learn and apply tools to control and monitor their manufacturing processes. Traditional training programs are usually not accessible to technicians (due to work schedule and budget constraints.)

The curriculum was, therefore, designed around the actual situation.

## **Overall Strategies in Course Development**

The elements considered in developing the class format and contents were:

- Timeliness
- Relevance
- Specificity
- Flexibility
- Participation

*Timeliness* was a "Just-In-Time" concept (as borrowed from Production Operation Theory) of imparting and applying knowledge when it is needed, much like the technique of producing and delivering parts just in time for a product to be fabricated, assembled, and sold.

To that end, classwork began only after the student had designed and carried out basic data collection. To complement their understanding of the process, concepts were introduced and immediately applied to process data.

For example, a quick study of correlation was discussed early. For teaching purposes, predictable data – such as that which suggests that defect rates increase with a technician's workload – came in handy.



*Relevance* and applicability to real-life situations were assumed to be critical. And, since the data collected was to be used throughout the training sessions, the problems were selected to be within a technician's experience. As a consequence, the technicians were not only receptive to learning something, they all made valuable contributions. Moreover, discussions of authentic problems sparked imaginations and creativity.

The business element's regular weekly quality improvement meeting followed each class hour, providing valuable new material for the development of subsequent classroom subjects.

*Specificity* was achieved by discussing and proposing techniques relevant solely to the group's own problems. For example, the class worked out the elements of an experiment that would test the effectiveness of each of two treatments. They specified population and experimental unit characteristics, calculated the sample size, and discussed the risks to be taken in making decisions. Process capability, of little usefulness in this context, was mentioned but not applied.

Special attention was also given to class size. Since the intention of training was not just to teach statistical methodology to everyone, but rather to focus statistics on improving quality. A class size of six to eight persons was maintained. This manageable size allowed time for questions and attention to individual needs.

A down-to-earth ambiance was maintained; this provided two advantages. Informality made statistics approachable, rather than arcane. By using workplace terminology, we emphasized the logic and utility of the subject.

An elementary text, supplemented with handouts, focused on using readable text rather than on statistical calculations.

*Flexibility* extended throughout the sessions. The syllabus itself was determined by the process problems, within the context of the quality improvement project.

Fortunately, there was a wide variety of problems to illustrate a wide variety of techniques. So individual problems were not beaten into the ground by repetition.

Chewable bites of information were meted out week to week according to the students' needs. But more important, the amount of information was modulated to fall within their abilities to assimilate and integrate the concepts, while still doing their day-to-day jobs.

Another example of *flexibility* was achieved by the simple expedient of giving the course at the worksite and scheduling around the varying schedules.

A flexible time frame for course content, unhurried and yet not wandering, was maintained. Relearning was allowed for as concepts often came together days or weeks past the scheduled learning point. The manager and the students played the greatest role in determining the pace and often requested returning to earlier subjects to review difficult points.

*Participation*, perhaps the most important consideration in this experiment, was maintained in several ways—teamwork, for example.

Because teamwork is essential to process improvement (individual support of team goals being indispensable to executing newly changed processes) specific tasks for developing solutions were not assigned to only one individual, a specialist in diagnosis. Therefore, the analytical work needed to create new knowledge was done by all members of the team, and the responsibility for determining and implementing remedies remained with the team.

Teamwork also helped integrate many valuable pieces of information that were scattered and unusable.

Teamwork was enhanced through individual testing. Although technicians learned together, they were each tested individually, which gave each certainty that they were learning along with the group.

Role and responsibility were outlined for each member. This was essential inasmuch as statistical methods must operate within the overall quality management process – by themselves, statistical methods are not cure-alls. Each designated role or responsibility was actually incorporated into the syllabus, such as the job-description responsibility of technicians to meet quality specifications without inspection, rework, and scrap and to develop statistical control of work when applicable.

Manager attendance was undeniably the real key to the success of the educational effort. It produced several interesting and valuable ramifications:

- A common diagnostic frame for problem solving.
- Homework assignments, by the manager, that required the team members to think of possible applications of the concepts introduced.
- The addition of new sub-projects by the manager when new opportunities for quality improvements or for reinforcement of concepts arose.
- A learning pace consistent with the manufacturing unit's production goals.
- Opportunities to emphasize points or add locally pertinent interpretations of a concept.

### **The Objectives of Quality Improvement Met**

The successes of the experiment proved its potential by tangible improvements in skills, product quality, and commitment to continuous improvement.

Prior to the course, outgoing quality for the business element averaged 98.5% (a level which would satisfy nearly everyone!). However, even with such a level the cost of defects are considerable. The greatest proportion of these losses is due to the scrapping of entire lots (some defects may appear on every item in the lot).



As seen in figure 1, outgoing quality level from week 51 to week 23 experienced quite large variations, amounting to losses of several hundred boards per week. From week 23 to week 36, the average shows a slight increase, but most important, the variation has been decreased significantly: The losses were not as great because fewer boards and fewer lots were scrapped. Week 33, an exception to this brighter picture, was due to defective material, outside of the business element's control.

The major causes of defects were procedural, tooling film defects and laminate flakes originating at the laminator. Flakes deposited on circuit board layers and on film cause shorts and voids.

As a result of understanding the sources of these defects, the business element took a number of actions: The results became apparent beginning in week 24.

1. Using a wax to maintain film surfaces clean (see figure 2).
2. Adding film librarians to monitor film quality.
3. Instituting new work procedures (see figure 3).
4. Adopting a new film material, more resistant to mishandling.
5. Scheduling machines for regular maintenance.

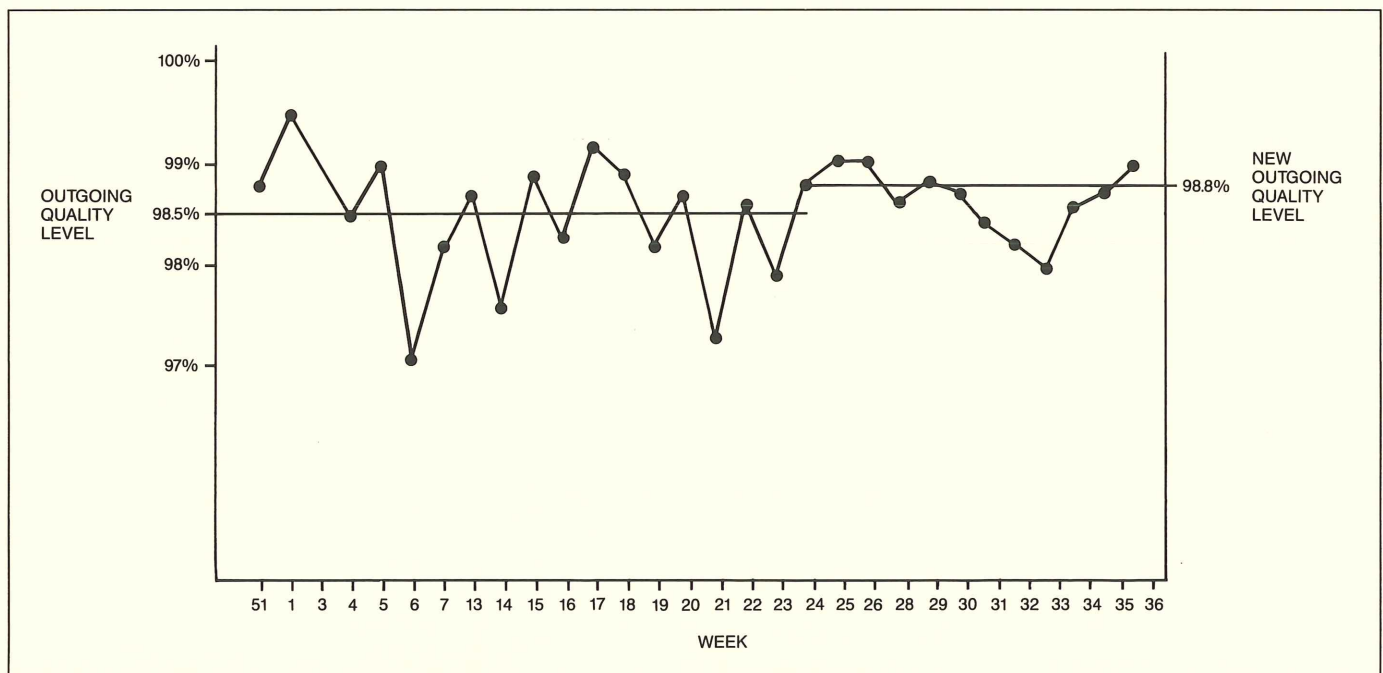
### Workmanship and Workers Both Improved

There is little that does more to enhance worker satisfaction than a method to make their work more effective. During the training experience, worker attitude and perspective obviously improved.

- Technicians, who might have dropped out of traditional courses, showed interest in learning more. As one observed, "We need to know more about the product we are building, why the boards are built the way they are. It helps to know the whole process. Also, this way we get to understand the whole plant." (David Eddy)
- Confidence itself helped improve manufacturing skills. The technicians' ability to grasp and effect change using the SQC techniques increased in equal measure. "I think of different ways to look at how to use what we are learning, how and what we can measure." (Brenda Wilson) "I see continued progress in the elimination of problems we have lived with. We can remove them so that they do not reoccur. We don't have to live with them." (David Eddy)
- Quality consciousness and motivation moved ahead equally too. "I have an increased awareness of quality and how to approach it." (Laurie Hill) "We continue to improve. There is no end to what we can try to change." (Carol Patterson) "I now take more time doing my tasks so that I do them right. I keep my quality as good as it can be. Before, I was more conscious about quantity than about quality. I put a good board through the first time rather than take three or four times to do it." (Brenda Wilson)

### A New Way to Meet Newer Challenges

Although the successes of this experiment can be calculated in the thousands of dollars, the successes enjoyed by team members cannot be overestimated. All were encouraged to think in terms of applying statistical analysis to identifying and



**Figure 1.** This scatter plot shows how effectively the Inner Layer Business Element (Forest Grove) used statistical tools to improve board quality. At week 24, the statistical tools the work force had acquired in down-to-earth on-site training started to show their effectiveness in two ways. First, 75% of the weekly quality-performance points exceeded the old outgoing quality level. Second, fluctuation ranges tightened, showing real control of quality.



removing all manner of production problems. Several projects have been initiated, such as assessing the cost of rework and its causes, identifying part numbers that have had historically low yields (and developing plans for removing associated causes), and monitoring self-inspection of check flats.

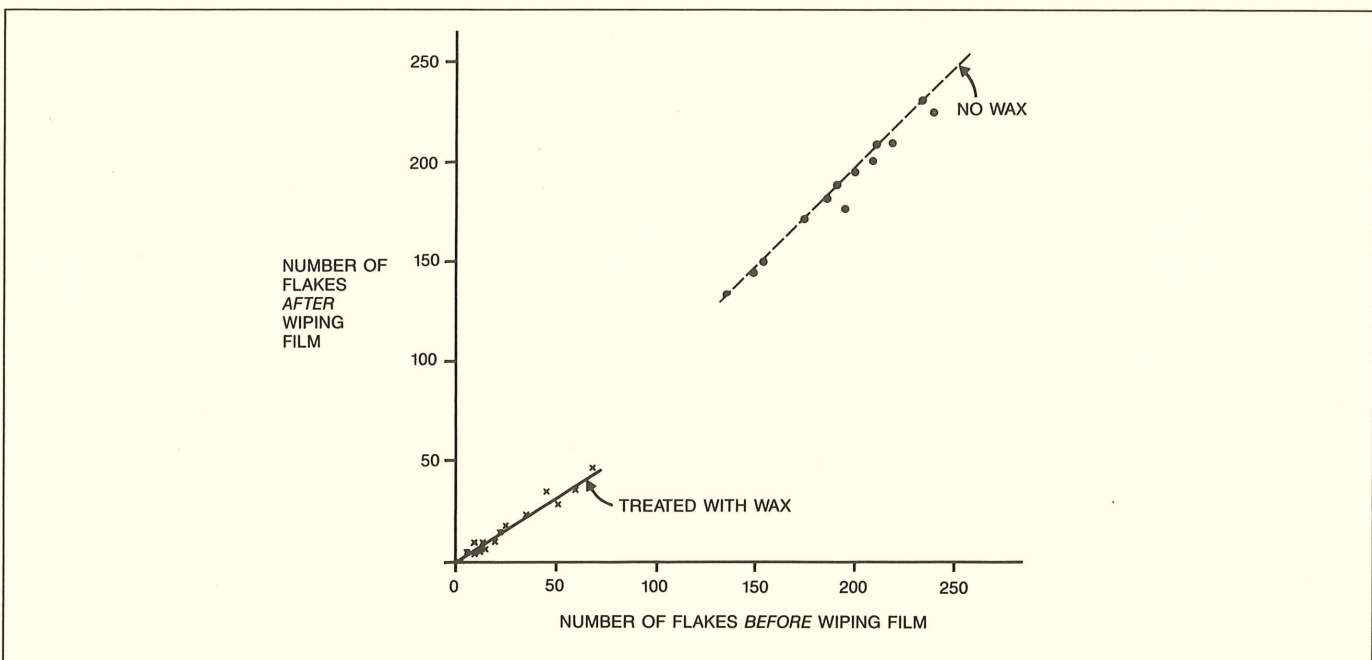
As significant as the practical and personal results of this effort were, and even though there remain countless other processes that this combination of analysis and learning can be applied to, one fact remains clear: reliance solely on either statistical quality control or any other single quality control method is not a panacea. Rather, the quality improvement process requires four elements in order to succeed:

1. Technicians selected for their dedication to quality and who show ownership of poor quality and responsibility for high quality.

2. Dedication and the active involvement of line managers (no delegation) is essential. Only few process troubles (industrial experience suggests about 15%) are correctable locally by the people directly connected with the operation. The majority (the other 85%) is correctable only by management action on the system. Upper management support must also be strongly committed to providing the environment suitable for such effort.

3. Statistical expertise must be involved at the outset to help production personnel identify and define production problems as well as help with data analysis and training (when needed). The statistician must, therefore, act as a team member, teacher and aide to management as well.

4. Assistance and support from Quality Engineering personnel (on location) is the remaining essential element for the successful quality-oriented training described here.



**Figure 2. The business element's workforce, using what they had learned in statistical training, proved with this graph that wiping with wax really did reduce flakes and, therefore, flake-caused defects.**

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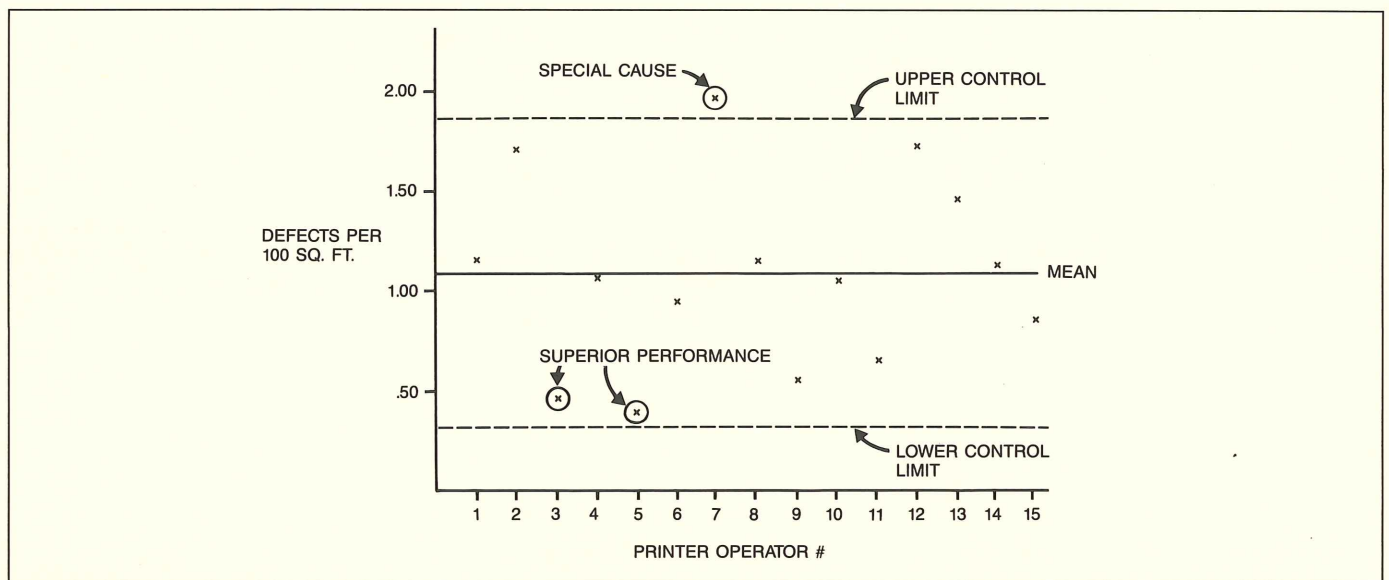
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**Figure 3. Certain operators had fewer defects. What were they doing better or (more important) differently? Using a metric of defects per 100 square feet, this graph singled out those operators who might be able to contribute process techniques that all could use. The operators having more defects were not “substandard” as they were working by the book or special causes beyond their control had raised their defect count.**

When these four essentials are brought together in the right mixture—with the correct respect for not only proper manufacturing methods but for the human component as well—success (based on the correlations learned within this experience) is the most predictable outcome.

And while it would be an overstatement to suggest that the process described above is a method for solving all production problems, we believe that a large number of production problems await this form of solution.

#### **For Further Information**

For further information, call Rick Edmiston at 640-2288 (F1-365) or Georgette Espeillac at 627-2383 (78-526). □

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