Particle Tolerant Architecture

Peter M. Burke and Tim L. Weber
Hewlett Packard
Corvallis, Oregon

Abstract

In 1994 all 300-dpi thermal ink jet pens manufactured by HP had firing chambers with a single inlet. With this design, particles are a major contributor to yield loss and quality degradation. Particles can lodge in an inlet channel, block ink from entering the chamber, and result in a scrapped pen. Particles also float in and out of channels and cause intermittent defects in print quality.

The authors were challenged to design a pen that would be robust to particles with no degradation to manufacturing yield, pen fluidic performance, or print quality. The project started with simple hydraulic modeling, concept development, and peer review. Then design proliferation began. Since the pen was in manufacturing, the challenges normally present in an R&D project (no printer, no ink, no print quality standards, no printer drivers) were absent. Approximately 50 designs were created, built and tested in 6 months, leading to the successful design, which was ultimately patented. Since then, about ten other particle-tolerant architectures have been designed and introduced into manufacturing. The design concept has proved successful over drop weights from 5 to 150 nanograms. The concept not only guards against particles but facilitates control of drop trajectory and pen operating frequency.

Introduction

From the earliest days of ink jet printing it has been obvious that smaller dot sizes will lead to great improvements in image quality, and more and faster nozzles will lead to increased printing speeds. The following Table 1 lists the evolution of Hewlett Packard printers and print cartridges. The nozzle count has increased from 16 (HP original ThinkJet) to over 500, and the drop volume has decreased from 180 picoliters to 5. These design efforts have met with great success, as revealed by the many choices in inkjet printers.

A simple diagram of the pen firing chamber, Fig. 1, reveals the vulnerability of the design to particles. Any object that can block ink flow to the firing chamber causes a weak or missing nozzle. Any particle or fiber that partially clogs the bore causes a misdirected nozzle.

Table 1: Evolution of Hewlett Packard print cartridges.

Printer	Year	nozzle count per chamber	frequency kHz	dot spacing dpi	drop volume pL
ThinkJet	1985	12	1.2	96	180
DeskJet Black	1987	50	5	300	85
DeskJet CMY	1992	16	3	300	85
DeskJet 1200C	1993	104	8	300	77
DeskJet 850 CMY	1995	64	8	300	30
DeskJet 850 Black	1995	300	12	600	35
DeskJet 720 CMY	1997	64	12	300	10
DeskJet 2000C	1998	304	12	600	8
DeskJet 970 CMY	1999	136	24	600	5
DesignJet 1000	1999	512	12	600	12

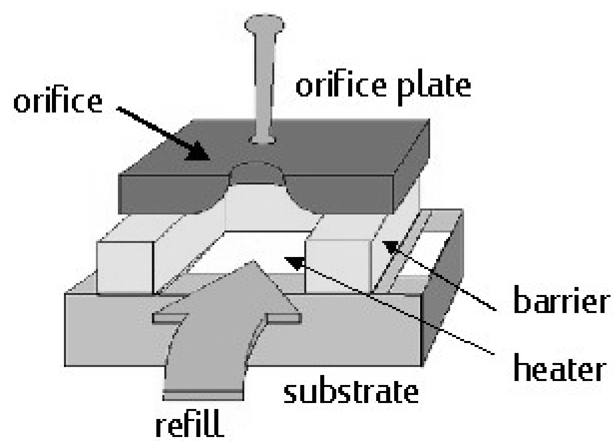

Figure 1. A schematic of firing chamber architecture (Beeson, 2000).

As the architecture dimensions decrease, the population of particles capable of clogging the print head increases dramatically, as shown by manufacturing data in Fig. 2.

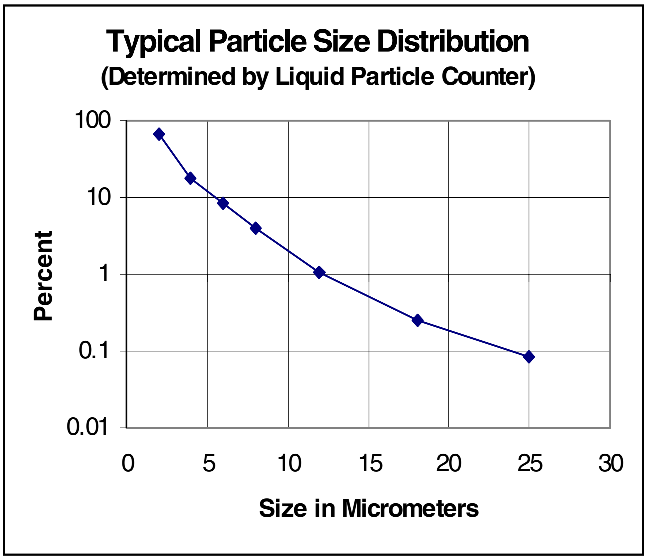

Figure 2. Size distribution of particles collected from print head assemblies using an isopropyl alcohol flush and a Met-One Model 2500 Liquid Particle Counter.

Common contaminants include ink residues, adhesives, stainless steel, skin, cellulose, glass rods, pen body material, and silicon chips. Any upstream process or material can contribute particles to the print head assembly. Photos of particles abound in our failure analysis laboratories, Fig. 3.

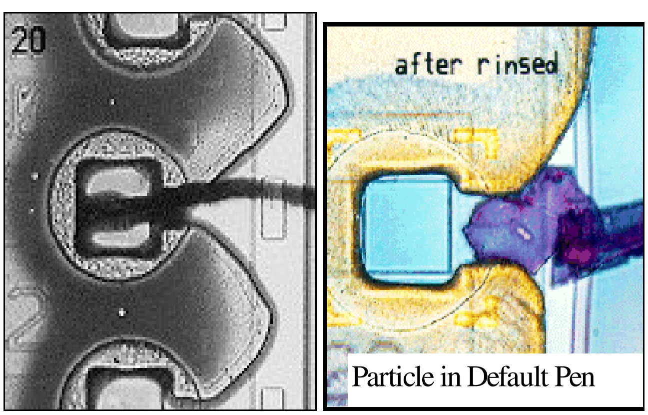

Figure 3. Fibers and particles trapped in single channel architectures.

Design of Particle Tolerant Architecture

The problem of particles in InkJet pens must be solved by a combination of approaches. Clean manufacturing is one approach. Ink filters, air filters, ionizers, and washing stations are all in use. A second approach consists of redesigning the print cartridge to reduce particle generation during assembly. Finally, the print head architecture can be designed to function even if particles make their way into the pen.

Two simple computations helped create the initial particle tolerant designs. A flow resistance calculation convinced us that the design could be achieved without sacrificing operating frequency. A probability calculation convinced us that two channels would offer significant particle protection.

One of the major concerns with two channel architectures was that the inlet channels would be smaller and not able to let ink refill the firing chamber quickly enough to operate at the desired operating frequency. In the absence of priority with the advanced fluid flow modeling group, the flow was modeled as an electric circuit in which the resistance to flow is proportional to the inlet channel cross-section divided by channel length. For a constant barrier thickness, the flow resistances for single channel design R_{sc} and dual channel design R_{dc} (Fig. 4) are given by:

$$R_{sc} = L / W \quad (1)$$

and

$$1 / R_{dc} = 1 / R_1 + 1 / R_2 \quad (2)$$

where

$$R_1 = L_1/W_1 \text{ and } R_2 = L_2/W_2 \quad (3)$$

For the first dual channel designs, R_{dc} was set equal to R_{sc} for the existing single channel design.

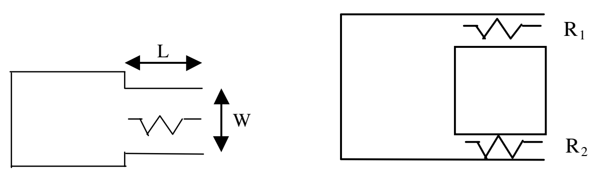

Figure 4. Estimate of flow resistance for single channel (left) and dual channel (right) architectures.

A simple probability calculation convinced us that using more than one inlet channel to the firing chamber would lead to great improvements in particle tolerance, see Fig. 5.

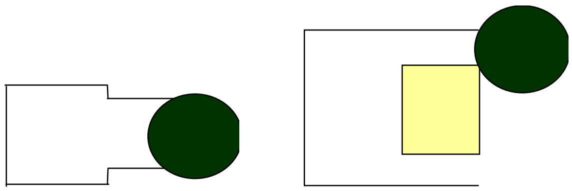

Figure 5. A particle completely blocks a single channel design (left) but only partially blocks a dual channel design (right).

Blocking a single channel firing chamber causes a highly noticeable white line across the print sample. Blocking one of two channels leads to a weak nozzle and a faint line across the print sample, often not noticeable. A two-channel architecture will be blocked only if both channels have particles.

Assuming a pen with 16 nozzles and 2 particles, the probability for firing chamber blockage for a single channel architecture is given by

(2 particles / 16 channels)
= 12.5% nozzle yield loss (4)

The probability for firing chamber blockage for a dual channel architecture is given by

*(2 particles / 32 channels) * (1 particle / 31 channels)*
= 0.20% nozzle yield loss (5)

This represents a 60-fold improvement over single channel architecture. This degree of improvement increases as the nozzle count goes up.

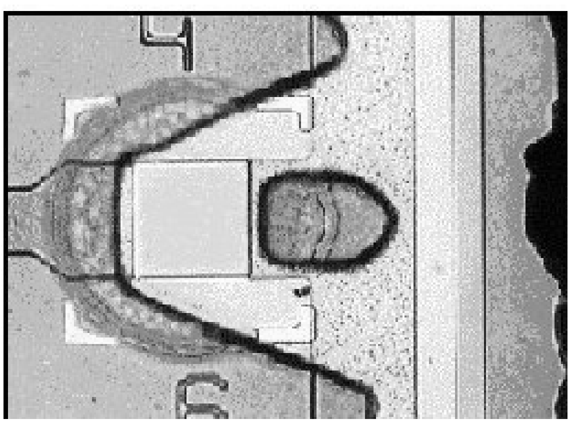

Figure 6. The first successful particle tolerant architecture introduced into Hewlett Packard inkjet manufacturing.

Based on the above calculations as well as results of brain storming and peer review, many designs were fabricated and tested, culminating in the design shown in Fig. 6 (Burke and Weber, 1997).

This design was introduced into Manufacturing as backward compatible to the DeskJet printer in 1994. Yields improved up to 30% and the operating frequency increased, Fig. 7. The operating frequency increased because the time to refill the firing chamber decreased. Direct observation of drops in flight, Fig. 8, reveal needle-shaped drops for the single channel architecture, indicating that the firing chamber was only partially refilled at the time of firing. The dual channel architecture shows fully formed drops, indicating that the firing chamber had refilled completely before firing.

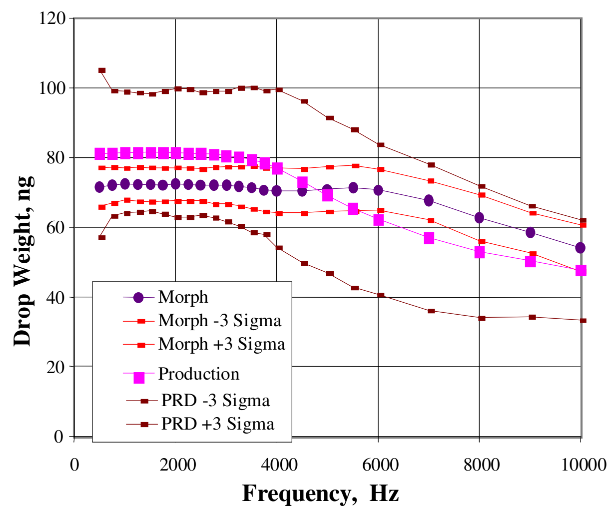

Figure 7. Comparison of drop volume – frequency curves for single channel (Production) and dual channel (Morph) architectures.

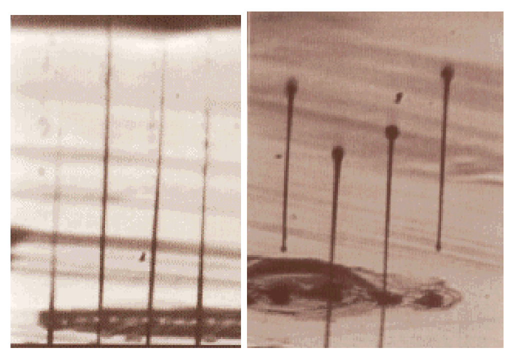

Figure 8. Direct observation of drop ejection for single channel (left) and dual channel (right) architectures, both firing at 6 KHz.

Continuation of Particle Tolerant Designs

A recurring and annoying problem with the first dual channel design was that fibers could penetrate through one channel and make their way into the bore, see Fig. 9. This prompted efforts to design an architecture in such a way that fibers could not bend around the corners of the inlet channels and get to the bores. The resulting design, shown in Fig. 9, included curved channels and a row of barrier islands. It was released to manufacturing along with the DeskJet 850 printer in 1995 (Weber and Burke, 1998).

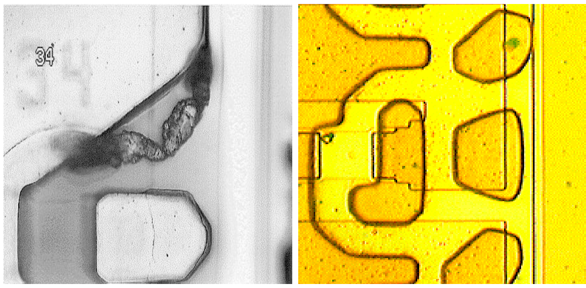

Figure 9. A polysulfone particle created during ultrasonic welding of the pen body assembly (left). A 'particle proof' design which blocks both particles and fibers (right).

Since introduction of the original particle tolerant designs, other Hewlett Packard engineers have used the concept over drop volumes from 150 picoliters down to 5 picoliters. A few examples are shown in Fig. 10.

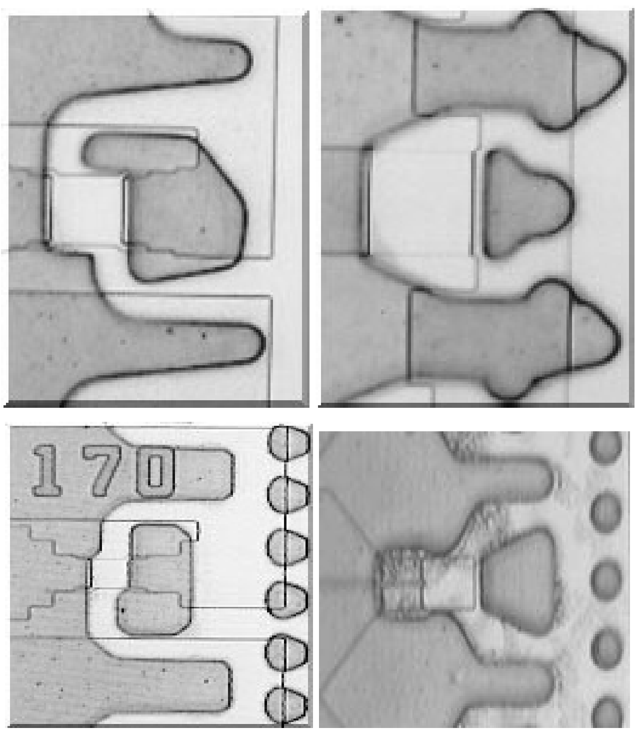

Figure 10. Four more particle tolerant architectures designed and introduced since the original work by the authors (MacLeod et al., 1999).

Innovation within Manufacturing

Four factors contributed to the success of this project.

First, we had excellent management support. Because of yield and quality problems encountered in the manufacture of a released product, the project was staffed from Manufacturing and fully supported by Production managers.

Second, the senior and junior authors had an excellent mentoring relationship. The senior author was well versed in inkjet technology and the junior author, a new hire, was very strong in fluid dynamics. Since we were both assigned to the same project, the mentoring relationship was easy to establish and maintain. Topics included inkjet technology, working at Hewlett Packard, and career considerations.

Third, we were bold. Some of the obstacles to overcome were the concepts that the role of designing pen architecture 'belonged' to R&D. Furthermore, the design concepts we initially proposed were rejected by R&D as having already been tried and proven unworkable. In addition, many manufacturing managers and engineers feared that we might make something worse and reduce yield and quality still further. We adopted the attitude that the manufacturing line was an excellent laboratory for design innovation provided we acknowledged the constraints and worked with dozens of people up and down the line.

Fourth, the infrastructure to enable creative exploration was in place. We already had a design that, at its best, was very good. The ink, the drop weight, and the operating frequency were proving successful in the market place. Second, the printers, the print files, the grading criteria, and the test equipment were all available to support new design efforts. Finally, as we discovered, old concepts that had not worked in the past were now attainable because of many independent improvements in materials and processes that had gone on over the past few years.

Summary

The original design of particle tolerant architecture was guided by simple flow resistance and probability models, followed by much empirical work. The manufacturing environment proved to be excellent for innovative and efficient design efforts. Two particle tolerant designs were developed without sacrificing operating frequency or drop volume. These designs set the stage for many new designs since then.

References

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Biographies

Peter M. Burke received his Ph.D. in Materials Science from Stanford in 1968. His experience includes 13 years in cathode ray tube and integrated circuits manufacturing with Tektronix and six years as Professor of Mechanical Engineering at Oregon State University.

For the last 13 years he has been with Hewlett Packard in inkjet cartridge design and manufacturing. He was a member of the R&D team for HP's first three-color plain paper inkjet cartridge. He transferred into Manufacturing and, with Dr. Tim Weber, developed particle tolerant architectures leading to significant improvements in pen reliability and manufacturability.

Tim L. Weber received his Ph.D. in Mechanical Engineering from Oregon State University in 1986. For three years we was a Technical Specialist in Flying Qualities at Boeing Helicopters. He then transferred to Hewlett-Packard in Inkjet Manufacturing and worked with Dr. Peter Burke to develop particle tolerant architectures leading to significant improvements in inkjet pen reliability and manufacturability. Currently he is an R&D Program Manager in Technology Platform Development.