Hitotsubashi University
Institute of Innovation Research

# Seiko Epson Corporation
# Development of an Inkjet Printer that Produces High-Resolution Text and Images

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Hitotsubashi University 21st Century COE Program
*Dynamics of Knowledge, Corporate Systems and Innovation*
*Research Project on Okochi Prize Cases*

*Seiko Epson Corporation*
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This case study is the result of research undertaken for the *Research Project on Okochi Prize Cases*, which is being conducted with financial support from the *Dynamics of Knowledge, Corporate Systems and Innovation* project under the 21st Century COE Program at Hitotsubashi University. The project prepares case studies of research efforts that have been awarded the Okochi Prize that provide overviews of technical innovations and analyze the development process, the details and results of commercialization and related topics, in cooperation with the Okochi Memorial Foundation and firms that have received the award. Together with creating a portfolio of case studies and accumulating case data on Japan's major innovations, the project performs cross-comparative analyses of cases and seeks to identify the characteristics and issues surrounding innovation efforts at Japanese firms (for details refer to the following website (Japanese only): http://www.iir.hit-u.ac.jp/reserch/21COE.html). The authors would like to express their deep appreciation for the extensive support and cooperation provided by the Okochi Memorial Foundation while pursuing this project.



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- Akio Owatari, Senior General Manager, CS/Quality Assurance, Environment Center, Imaging and Information Operations Division
- Kamihito Takeuchi, Manager, Corporate Business Planning & Management Division

## 1. Introduction

The printer business at Seiko Epson (Epson)[1] was launched with the selection of the company's Printing Timer for official timekeeping at the Tokyo Olympics. This company introduced the world's first mini-printer in 1968, and throughout the 1970s built its business base with mini-printers for calculators.

Following the introduction of the serial impact dot matrix printer (the SIDM printer) in 1979, Epson's business maintained a growth track. As businesses entered the 1980s, personal computers began to spread rapidly within the office environment. During the early stages of personal computer proliferation, the SIDM printer was widely installed in offices as the leading output device. Hand in hand with the office penetration of PCs, Epson's printer business also expanded rapidly. In 1984, Epson surpassed NEC Corporation to attain the world's highest share of the SIDM printer market, and both figuratively and literally the printer business became the primary business driving Epson's growth.

From about the mid-1980s, however, these circumstances began to change. Personal computers spread to homes, and demand for personal printers grew. In response to this change, Hewlett-Packard (HP) in the U.S. and Canon Inc. commercialized bubble jet-type[2] inkjet printers (IJ printers) that ejected ink using bubbles produced inside the ink chamber. These bubble jet IJ printers began to gain popularity in the personal printer market as an alternative to the SIDM printer. Although Epson also introduced an IJ printer that used the piezo method, the company lacked the cost competitiveness to respond to the needs of the personal printer market.

Furthermore, in the high-price market for businesses, printers utilizing methods other than IJ, such as electrophotographic methods, were being placed on the market. The laser beam printers made by Canon were especially well received by the market. Epson, however, did not achieve success with electrophotographic printer commercialization.

Thus Epson's printer business built around the SIDM printer was confronted with a serious crisis as it came under attack by laser printers from above and IJ printers from below. If Epson maintained its current course, a broad-scale contraction of its business would be unavoidable.

Consequently, toward the end of the 1980s Epson was compelled to focus on personal printers as a target market, and undertook a company-wide effort to improve its piezo IJ technology. Development of a new print head that would achieve lower costs and miniaturization, and enable Epson to support the shift to color printers, was the overriding imperative for this effort. As a result, Epson successfully developed a new print head capable of propelling small-volume ink droplets straight from the print head with only a tiny amount of voltage, despite a size just 1/10 the size of conventional print heads. This was called the MACH print head.

The first IJ printer to use the MACH head was the MJ-500, which was introduced to the Japanese market in 1993. The next product was the MJ-700V2C, which achieved a resolution of 720dpi with special paper and was introduced in 1994. This was an epoch-making product, with double the resolution at half the price compared with other companies' models, and secured an overwhelming market share worldwide. The MACH head evolved even further, and with the 1996 introduction of the PM-700C, which

[1] The forerunners of Seiko Epson were Suwa Seikosha Co., Ltd. and its subsidiary Shinshu Seiki Co., Ltd. Seiko Epson was born through a merger of the two companies in 1985. In this case study, the company and its activities prior to the merger are also uniformly referred to by the name "Epson" except when Suwa Seikosha or Shinshu Seiki in particular is indicated.

[2] The term "bubble jet" is the term used by Canon, while HP calls the same method a "thermal jet method." In the following pages, both the bubble jet method and the thermal jet method will be uniformly referred to using the term "bubble jet method" except when directly indicating HP printers.

achieved the transition to ultra-high-density full-color printing dubbed as "photograph image quality," color IJ printers became synonymous with Epson. In 1997, Epson finally pulled ahead of Canon to regain the leading share of the Japanese market.

Thus the IJ printer business came to be the backbone business supporting Epson. More recently, however, price competition in the home printer market has intensified, and stable earnings into the future are by no means guaranteed. As prices for printers themselves continue to shrink, Epson has maintained its business model of ensuring earnings from consumables such as inks and recording media, but companies that have put compatible inks on the market are also active, and in overseas markets such as China in particular, establishing a business model centered on consumables has proven difficult.

Growth in the market for multifunctional devices (Multi Function Printer: MFP), which offer not just the single function of a printer but also a copy function and scanner function, has also been remarkable. Office equipment manufacturers with copiers and faxes are dominant in this MFP market.

Consequently, what is being expected at Epson is the application of IJ technology to the business market. Epson's ink-jet technology expels liquid by means of the physical deformation of the piezoelectric element. This can support the use of various liquids because, unlike a bubble jet print head that causes ink to vaporize, a load is never placed directly on the expelled liquid. Therefore Epson is attempting to apply IJ technology to various uses other than printers for home use.

In the segment for markings using expelled ink, IJ printers are making inroads for printing on cloth, rather than paper, as a medium for the ink. For applications such as printing of large-scale posters for advertising, Epson also provides OEM supply to other companies as an ink and print head package. In non-marking sectors that require ejecting liquids other than ink, IJ technology is being applied in liquid crystal display (LCD) panel manufacturing. For expelling liquids, IJ technology achieves high general-purpose functionality. For Epson's growth, identifying sectors in which this technology will be applied in the future is a critical strategic issue.

## 2. Overview of IJ Technology

The IJ technology mechanism is extremely simple: the image formation process is completed simply by ejecting ink through nozzles and onto a recording medium such as paper. Methods to eject ink are broadly divided into two types, referred to as the piezo method, which uses physical energy, and the bubble jet method (called the thermal jet method at HP), which uses thermal energy (see Figure 1).

The name "piezo method" originates from the fact a "piezoelectric element" – a ceramic piezoelectric material that expands and contracts when an electric charge is applied – is used to expel the ink. The operating principle involves the piezoelectric element, which is bonded to the external wall of ink chambers called "cavities" and causes the cavities to expand and contract, with the resulting force used to expel the ink.

In contrast to this technology, the bubble jet operating principle involves heating the ink with a heater, causing the ink to boil. This creates bubbles, and the pressure from the bubbles expels the ink. Canon's researchers stumbled onto the bubble jet mechanism in 1975 after seeing ink ejected when a soldering iron accidentally made contact with the ink-filled syringe of an injection device[3].

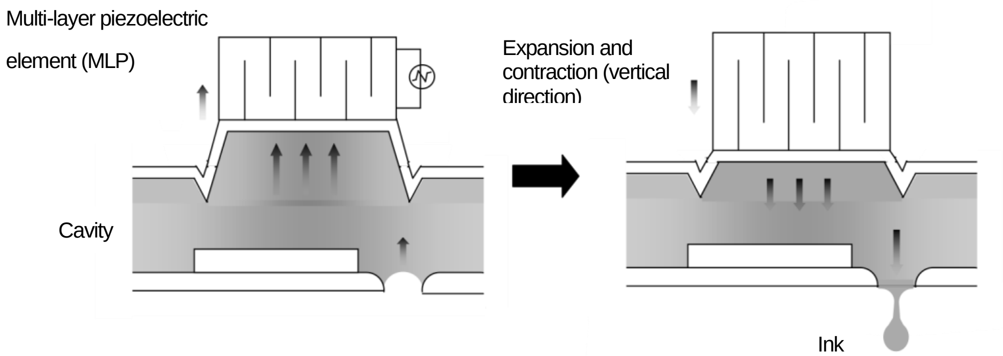
Compared with the bubble jet method, the piezo method is superior in terms of ink ejection control, ink

[3] Taken from Canon Inc.'s website.

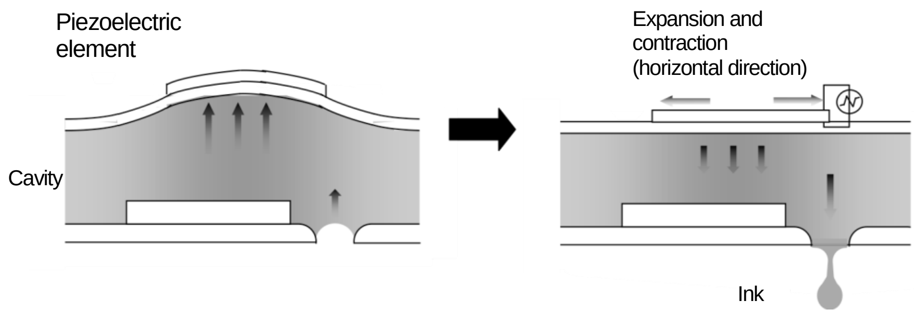
selection possibilities and print head durability. First, the ink droplet volume can be adjusted freely because droplets are controlled by physically varying the amount of voltage applied to the piezoelectric element. Second, unlike the bubble method there are few restrictions on the nature of the inks that can be used, and inks can be selected according to the use, because a load is not placed on the ink itself. Third, the print head is highly durable, because the piezoelectric element can be used semi-permanently, and the running cost is lower as a result.

Figure 1: Piezo method and bubble jet method

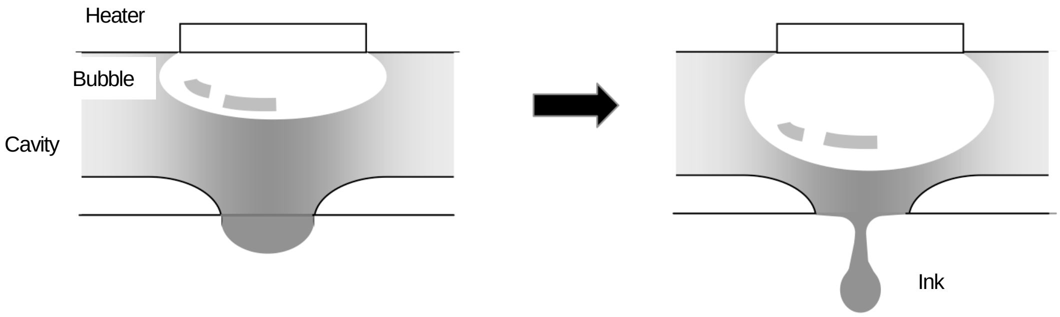
(Piezo method: MLP)




(Piezo method: ML Chips)




(Bubble jet/thermal jet method)




Source: Prepared by the authors with reference to the November 22, 2003 issue of *Nikkei Byte*

Two drawbacks to the piezo method, on the other hand, are high cost and the difficulty of miniaturization because it is not well suited to mass production. The high cost to process the piezoelectric elements and the glass that constitutes the print head, keep the price of the finished product high. Moreover, because the magnitude of displacement of the piezoelectric element is small and the size of the element is comparatively large, the difficulty of achieving a high-density nozzle arrangement is also a problem. Because the cavities depend on the size of the piezoelectric element, there is a natural limit to miniaturization of the print head and therefore ultimately to miniaturization of the printer itself.

With the bubble jet method, on the other hand, a high-density nozzle arrangement is possible because the piezoelectric elements are not needed. Mass production and miniaturization were also easier, because the printing elements are manufactured using semiconductor fabrication processes. The short head lifetime, however, was a definite problem. These advantages and disadvantages of the piezo method and bubble jet method are compared in Table 1.

Table 1: Comparison of the piezo method and bubble jet method

| | Piezo method | Bubble jet method |
|---|---|---|
| Mass production (cost) | × | △ |
| Durability | ◎ | × |
| Ejection performance | ○ | ○ |
| Increased density | × | ◎ |
| Ink selectivity | ◎ | ○ |

Source: Epson reference materials

Of these two methods, the one developed by Epson from the mid-1970s was the piezo method. Like copiers, printers originally were office equipment that required maintenance, and for office equipment durability is essential. What initially gave the company's printers a giant leap forward was the development of a small, highly durable miniprinter, which Epson created when the Epson group was selected to serve as the official timekeeper of the Tokyo Olympics. Thus the fact Epson selected the piezo method with its superb durability might be said to have been natural, despite the complexity of the configuration.

## 3. Process of IJ Technology Development at Epson

### 3.1 Progress in impact printers

Epson has been at the center of each respective chapter in the printer business, beginning with miniprinters in the 1970s, SIDM printers in the 1980s, and IJ printers since the 1990s (See Table 2 and information on the types of printers and printing methods in Appendix I at the end of this manuscript).

Epson's printer business got its start with the EP-101 miniprinter put on the market in September 1968 by Suwa Seikosha, one of the current company's forerunners. The miniprinter was designed for calculators and ECR, and printed figures and characters by stamping them out. Shinshu Seiki Co., Ltd., a subsidiary of Suwa Seikosha at that time, was responsible for the printer's mass production. Shinshu Seiki was later put in charge of the printer business and liquid crystal business, and Suwa Seikosha proceeded to diversify into the watch business, semiconductor business, crystal business and optics business. Shinshu Seiki created the "EPSON" brand in 1975. The brand name was formed by combining the initials for Electronic Printer (EP) and the word "son," meaning the future products to which the new printer would give birth. In 1982 Shinshu Seiki changed its name to Epson, and in 1985, Epson merged with Suwa Seikosha and the new entity was renamed Seiko Epson.

Research and development on printers for personal computers was begun in 1975, the same year in which the EPSON brand was launched. Epson chose the dot impact method, which breaks characters into dots that are printed by means of wire pins striking a printer ribbon according to a combination of dots. For the dot impact method, Epson adopted the SIDM method to sequentially print each character.

With the dot impact method, print quality is affected by the number of wire pins. The TP-80, the first product put on the market in 1979, had seven pins, and was followed by the launch of the nine-pin MP-80 in 1980. Epson then continued to increase the number of pins, and introduced the 24-pin UP-130K in 1983 and the 48-pin VP-4800 in 1988. Sales of SIDM method printers rose throughout the 1980s, growing in lockstep with the spread of personal computers, and in 1984 EPSON traded positions with NEC Corporation to become the leader in terms of worldwide share of SIDM method printers shipped, a position Epson has maintained to this day as the top domestic manufacturer.

In the latter half of the 1970s, however, printer manufacturers began developing printers that used non-impact methods as an alternative to the impact method in products such as miniprinters and SIDM printers. This was a period when various methods were developed, only to be quickly replaced. Epson's predecessor Shinshu Seiki also began the development of IJ technology during the second half of the 1970s. Moreover, at Shinshu Seiki this development was carried out in parallel with the development of other non-impact methods, including the electrothermal transfer printing method (video printer), the cycolor printing method (color copiers), and electrophotographic printing method.

Table 2: Summary of Epson's printer business

| | Impact printers | | Non-impact printer | |
|---|---|---|---|---|
| | Miniprinter | SIDM printers | IJ printers | Other products |
| 1960s-1970s | 1968: Suwa Seikosha introduces its first product, the EP-101<br>1975: EPSON brand established | 1975: Begins R&D<br>1979: Introduces its first product, the TP-80 | About 1975: Suwa Seikosha begins R&D<br>About 1978: Begins joint development with Shinshu Seiki. Introduces technology from U.S. corporation Kaiser | Begins R&D on products such as thermal transfer methods and electrophotographic methods from about this period. |
| 1980s | | 1980: Introduces the MP-80<br>1984: Introduces the JP-80. A nine-pin color printer<br>1988: Introduces the VP-4800, the world's first 48-pin printer | 1984: Introduces its first product, the IP-130K<br>1989: Phillips introduces multi-layer piezo for SIDM printers | 1986: Introduces the AP-80 thermal printer<br>1987: Introduces the LP-5000, the first domestic high-performance page printers<br>1988: Introduces the CV-2000 video printer and other products<br>1988: Discontinues development of video printers |
| 1990s | | | 1990: Launches urgent print head (KH) project<br>1993: Introduces the MJ-500. Equipped with a new print head. First product for personal use<br>1994: Introduces the MJ-700V2C. First full-color product. Achieves 720dpi using special paper<br>1996: Introduces the PM-700C. Realizes "photographic quality"<br>1998: Introduces the PM-9000C. LFP with dye-based ink installed<br>2000: Introduces the MC-9000. Solves pigment ink loading problem for LFPs | 1993: Introduces the LP-8000 Esper laser printer |

Source: Prepared by the authors from various materials

### 3.2 Start of IJ technology development

During the second half of the 1970s, research on various printing principles had been conducted at the experimental lab managed by the design division at Shinshu Seiki, Epson's predecessor. Despite being extremely small, a group of 4-5 individuals had conducted basic research on new printing technologies that might provide alternatives to the impact method.

Development of the IJ technology itself was begun around 1975 at Suwa Seikosha, Shinshu Seiki's parent firm. At that time, the development of various printer technologies was carried out at the order of the director in charge of technology at Suwa Seikosha. IJ technology was just one of several studied.

Some of the engineers who were involved in IJ technology development at Suwa Seikosha continued to develop the IJ printer technology after being seconded to the experimental lab at Shinshu Seiki. The feasibility of IJ technology was glimpsed when the researchers succeeded in ejecting ink and drawing a single dot for the first time in 1978, and a decision was made to return these seconded engineers to the headquarters and begin full-scale development. A decision was made to simultaneously also dispatch Shinshu Seiki engineers to Suwa Seikosha to participate in the IJ technology development. This marked the start of joint development of the IJ technology by Suwa Seikosha and Shinshu Seiki.

Akio Owatari, who would later play a role in Epson's IJ technology development, was assigned to the experimental lab when he joined the company in 1978, and afterwards moved with the development lab to Suwa Seikosha. For the project, Owatari was given responsibility for developing a new head for the IJ printer.

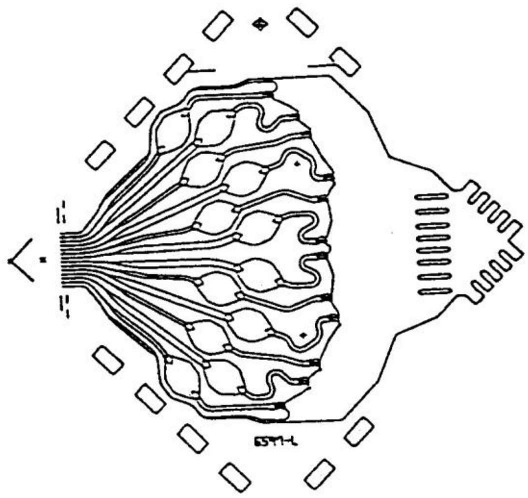
During this period a new technology, the Kaiser method, continued to spread as an IJ printer head manufacturing method. The Kaiser method was a technology that formed multiple nozzles at a time by transcribing the nozzle pattern on photosensitive glass by light exposure, then etching the pattern. Earlier technologies produced individual nozzles separately by elongating melted glass to produce a small tube, much the same way as other glassworks were made. Ink was ejected by wrapping a cylindrical piezoelectric element around the thin tube and applying voltage (this was called the "Gould" method). The Kaiser method for forming several nozzles at one time was welcomed by Shinshu Seiki's engineers as an extremely epoch-making technology because the wire dots for SIDM printers, which were the main product at that time, were also produced one by one.

When developing their new IJ printer head, Epson's engineers obtained a technology license to the Kaiser method. Epson's proprietary technology was used for the specific manufacturing process, however. The reason synthetic quartz was utilized for the material in the first print head developed, for example, was that Epson used its know-how for the manufacture of quartz oscillators for quartz timepieces. A quartz oscillator is made by placing an electrode within a crystal formed in the shape of a tuning fork that has been etched from synthetic quartz. Epson had accumulated this crystal processing technology through its internal manufacture of quartz oscillators.

Just as when producing a quartz oscillator, an IJ print head is manufactured by spreading resist on a synthetic quartz plate, transcribing a pattern from a mask by exposure and then forming the nozzles, cavities and flow channels by etching the pattern with hydrogen fluoride. The pattern of the printer head originally developed by Epson is illustrated in Figure 2. As shown in the diagram, 12 nozzles are formed with one pattern. This made it possible to create the basic structure of a head with a total of 24 nozzles by forming this pattern, staggered by one nozzle position, on both sides of synthetic quartz, sealing each surface of the synthetic quartz with a plate and then affixing a round piezoelectric element to the cavity portion. A total of 24 nozzles corresponded to the standard number of pins in SIDM printers at the time.

The new head developed using this technique was named the HG head. The first IJ printer equipped with the HG head was the IP-130K, which Epson introduced in 1984. Over the next few years, a total by six IJ printer models equipped with the HG head were put on the market, culminating with the HG-4000, which was launched in 1990.

Figure 2: Pattern of the HG head



Source: Epson materials

3.3 Problems with the HG head

Technically the IP-130K was a major achievement. Its reliability as a product was extremely low, however, and its reputation in the market was dismal. Hanaoka, who afterwards was put in charge of improving the IP-130K, commented as follows concerning the IP-130K.

> Well, it was a terrible product for us. From the moment we began selling it the nozzles clogged up and it couldn't eject the ink. It was the ink packs, of course, which had from 500cc to a liter of ink, and they would break, spilling ink inside the printer…[4]

In addition to such reliability problems, one further reason the printer did not enjoy market acceptance was its steep 500,000 yen price tag. Consequently for the HG-2500, which was introduced after the IP-130K, Epson labored to lower its costs and reduced the price to 250,000 yen. Even this was not low enough to compete with dot impact printers, however. Ultimately, Epson's engineers were unable to greatly reduce the cost of IJ printers for six years, until the launch of the HG-4000. The largest cost factor was the HG head.

The HG head manufacturing was outsourced to a group company. The initial procurement cost was about 20,000 yen. Although the cost was subsequently reduced, it fell only to 15,000 yen for 24 nozzles. In contrast to SIDM printers, which had improved their resolution from 24 pins 48 pins, the HG-4000 was able to achieve 48 nozzles only through the use of two heads of 24 nozzles each, which drove the cost of

[4] Taken from the interview with Hanaoka indicated above.

the head up to 30,000 yen.

Another problem was the high cost of the material itself, which remained expensive even after the initial crystal head material was replaced with ordinary glass. Relative to the size of the piezoelectric element, the displacement magnitude is small. Although displacement magnitude can be increased by making the crystal material thinner, a thin piezoelectric element could not be manufactured sufficiently using the technology at that time. The engineers therefore had no choice but to enlarge the cavities. This expanded the head size and drove up its cost. The complexity of the manufacturing process, in which chrome, gold and resist were deposited in order on the glass plate and then etched using hydrogen fluoride after the nozzle pattern had been exposed, was a factor behind the high cost as well.

Cost was not the only problem. The HG head faced fundamental hurdles to improving its performance. First, the nozzle cross section was not a circle but a semicircle because the HG head was formed by etching both sides of the glass. This caused a problem because the jets became plugged and the ink was not ejected cleanly in straight lies. Other recurring problems included leaking ink and paper jams, for example, which resulted from the product's imperfections. These circumstances made it necessary to provide considerable support after a sale, in order not to harm the trust that the company's printers had come to enjoy.

Moreover, to achieve both increased nozzle density and ensure cavity capacity, long flow channels had to be provided between the nozzles and cavities, as shown in Figure2. Because the components could not be arranged when the nozzles and cavities weren't separated, this resulted in a design with long channels in the shape of a peacock's tail. Because of these long channels, the inertance of the ink in the channels (inertia) increased, and the ink meniscus[5] took time to return after ink had been propelled from the nozzle. As a result, the time until the next ejection of ink increased, and ink ejection responsiveness did not improve. When the quantity of ejected ink is increased, the responsiveness falls further. Leakages of ink around the semicircular nozzles, and failure of the ink to eject at a perpendicular angle because the head was made of glass, also were problems.

These problems meant a high response frequency could not be set and placed a limit on print speed. Moreover, the low ink discharge became a problem, particularly when printing on ordinary plain paper. At the time, the assumed target for IJ printers was the SIDM printer market. The SIDM printer was predicated on its use to print on ordinary paper. Therefore during the development of the IJ printer, Epson kept in mind printing on plain paper, without the use of special papers. When printing with the HG head, however, clean characters on plain paper was difficult because of the low ink discharge quantity. The only way Epson could respond to this problem was to develop a new extremely strong alkali ink of pH13. Because plain papers at that time were acid-sized, use of a strong alkaline ink caused the paper surface to dissolve momentarily, enabling the ink to vertically soak cleanly into the paper.

As this illustrates, the HG head faced several fundamental problems. The development team was sufficiently aware of this fact as well. Because this was not a major problem when the market focus for SIDM printers was on businesses, however, no fundamental countermeasures were taken. Epson was able to ensure a certain market simply based on the product's characteristics, namely that it was somewhat faster and quieter than dot impact printers.

The introduction of the "DeskJet" printer by HP altered these circumstances completely.

3.4 The DeskJet shock

[5] The convex or concave curved surface formed on the surface of a liquid because of boundary tension.

Behind Epson's development of the HG series for business uses was the steady progress by other companies to make personal printers in step with the spread of personal computers. The appearance of bubble jet IJ printers became a particularly large threat for Epson.

The bubble jet IJ printer designed in 1975 was commercialized at nearly the same time as the introduction of the piezo method IJ printer by Epson. In 1984, HP put its ThinkJet on the market, and in 1985 Canon introduced its BJ-80. Compared with Epson's IP-130K, which cost about 500,000 yen (approximately 2,000 dollar), the ThinkJet and BJ-80 were 495 dollars and 679 dollars, respectively, making both products overwhelmingly dominant from a price perspective compared with Epson's offering. Lowering the price below the 1,000 dollar level meant the products were aimed squarely at the home use market. It was totally impossible for Epson to achieve such a price using the IJ technology at the time.

Just as the price, but even more shocking, was the disposable head concept that HP presented with the ThinkJet. A definite weak point of the bubble jet method when compared with the piezo method had been the low durability of the head. A piezoelectric element can be used almost permanently. On the other hand a bubble jet head, which applies heat using a heater, has a fundamentally short life. It had been thought that no matter how much Canon and HP pursued bubble jet development, Epson's dominance in this respect would never be shaken. If printer heads became disposable, however, durability would no longer be an issue. The appearance of the disposable head immediately placed the piezo method at a competitive disadvantage.

What further decided the bubble jet's dominance was the introduction of the DeskJet from HP in 1988. No matter how low the price was, until then the number of nozzles available with the bubble jet method was small and resolution was limited (ThinkJet was 96dpi). DeskJet, however, was put on the market at a low price of 1,200 dollars while achieving a resolution of 300dpi. In addition, in 1990 HP introduced its DeskJet500, which ensured the same resolution of 300dpi and reduced the price even further. The DeskJet500 market price dropped below the 500-dollar level in 1991 (Fujiwara, 2002). In October 1990, Canon introduced its BJ-10v, which also achieved 360dpi. With its excellent printing speed, this product overwhelmingly won support from personal computer users and became a global smash hit product (Fujiwara, 2002).

On the other hand, even though the HG-4000 put on the market by Epson during this same period only had a resolution of 360dpi it carried a price tag of about 300,000 yen. The difference with the bubble jet camp was manifest.

The debut of the bubble jet method was predicted to affect not only Epson's IJ printer but SIDM printers as well, which were the industry's top moneymaker. Fully half of Epson's earnings at the time were from SIDM printers, with Europe and the U.S. market accounting for 90-95% of sales. If the prices were equivalent, the IJ printer with its overwhelmingly better resolution and quiet operation would win out. In fact, the DeskJet rapidly eroded the market for Epson's SIDM printers, primarily in the U.S. market. Akio Owatari described the impact at the time as follows.

> The DeskJet was a real shocker. We thought that if we stayed with the HG now, well, the game would be all over. We felt a powerful threat that every printer would become a thermal jet printer, and they would capture every printer market, not just the dot (impact)[6].

In addition, electrophotographic method printers were attacking at the high-priced end of the market.

6 From the interviews with Owatari by the authors. September 20, 2007. Conducted at Epson's Hirooka Office.

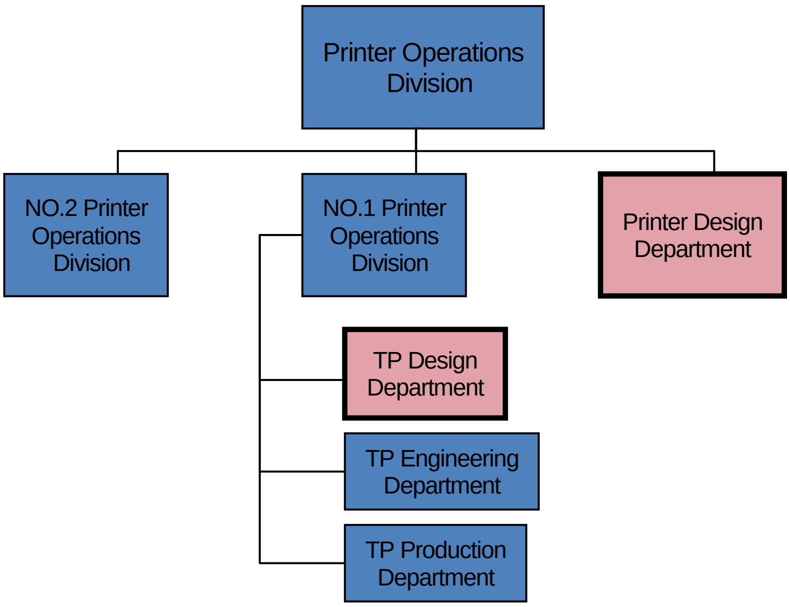
In 1984, Canon introduced the LBP-CX, which used a laser beam, and by 1986 had sold 550,000 units worldwide. For Seiko Epson this success, on top of the success of the bubble jet method, created a sense the company's very survival was at stake. Because the top price of Epson's highly profitable impact printers was for a business product selling in the 1,000-2,000 dollar range, this put it squarely in competition with laser printers.

Thus in the latter half of the 1980s, Epson found itself under attack on two fronts in the market for its mainstay SIDM printers; bubble jet IJ printers were encroaching on the low price machine segment, while laser printers had invaded the high-priced segment. Immediate action was needed.

## 4. Response to the DeskJet: Two Programs

Following the introduction of the DeskJet in 1988, the efforts at Epson to develop a new IJ printer were carried out at both the Printer Design Department and the TP Design Department (for Epson's corporate organization at that time, see Figure 3). Although both departments pursued development independently, the result was the epoch-making MACH head, which was completed by uniting the technologies developed by the Printer Design Department and the TP Design Department.

Figure 3: Overview of the Printer Business Division organization (October 1989)




Note: Printer Division II was responsible for miniprinters, and Printer Division I was in charge of terminal printers (SIDM printers and IJ printers).

Source: Prepared by excerpting from the Seiko Epson Ltd. organization chart (October 21, 1989) only the organizations related to the case described in this paper.

### 4.1 Response in the Printer Design Department

As bubble jet IJ printers and laser printers were being successively placed on the market, it became clear the HG head absolutely could not compete. Consequently, in 1987 Haruhiko Koto, who had been transferred from the Printer Design Department to the TP Design Department for commercialization of the HG series, returned to the Printer Design Department and turned his focus to development of the piezo method print head to parry the bubble jet printers (in February 1989 Koto was fully transferred to the Printer Design Department). When Koto became general manager of the Printer Design Department, the focus of development was placed on IJ technology development at the Printer Design Department, but as will be described later, development of IJ technology continued at the TP Design Department as well, mainly among the remaining engineers. Accordingly, from the closing years of the 1980s into the 1990s, IJ technology development at Epson was conducted independently in both the Printer Design Department and the TP Design Department.

The Printer Design Department initially explored a method called VIC (Vibrator in Cavity), which used a thermoplastic polymer hot melt and ejected ink by means of an oscillator moving up and down in the ink chamber. As can be understood from its adoption of a hot melt ink, the focus can be said to have been on print quality that would be able to compete with the electrophotographic method and offer the IJ printer's ease of use. The engineers were unable to develop a highly practical product with this system, however.

Consequently, in 1988 it was decided to once again concentrate development resources on IJ technology development. Traditionally in the Printer Design Department, development of video printers and laser printers was conducted in parallel with the IJ printer. The mid-1980s was a time when electronic still cameras were introduced in a rush by camera companies and electronics manufacturers. For a certain number of years during this period, video printers had also garnered attention as one type of output device.

Electronic still cameras failed to capture the market's interest, however, and similarly there was little demand for video printers. Epson was commercializing its video printer at its plant of the NO.2 Printer Operations Division in Okaya City, Nagano Prefecture, but had to withdraw from the business because of the dismal operating results. Therefore from about 1987 about 50 development team members were gradually reassigned to IJ technology development. The video printer development team was finally disbanded in October 1988, and all of the engineers were integrated into the IJ printer development team.

Here a new IJ printer development team about 100 members strong was reconstituted. Two of the individuals who were transferred from video printer development at this time and would later play a central role in Epson's IJ technology development were Haruo Nakamura and Minoru Usui.

#### 4.1.1 Development of the MLP

Usui was in charge of IJ head development. Usui initially was requested to continue the development of a print head using hot melt, but judged this avenue showed no promise and decided to design a proprietary method. Usui thought that if they could get the ink to fly freely, they would be able to achieve overwhelming performance. Usui described the situation at the time as follows.

> A head that thoroughly controls the ink ejection thoroughly controls the essence of inkjet printing and is absolutely indispensable. [...] at about the time I was a middle school student, there was a boxer named Cassius Clay (Mohammed Ali) who would say, "Float like a butterfly, sting like a bee," and that's how I imagined it would work. If we could just freely

control the ink, its flight would be absolutely true[7].

In order for the ink to fly freely, it was first necessary to ensure sufficient force to propel the ink. For that, it was necessary to master thin piezoelectric elements, which can obtain substantial deformation at a low voltage. The amount of deformation of the piezoelectric element is proportional to the "electric field strength" of the voltage divided by the thickness of the piezoelectric element. If the thickness can be reduced by half, twice the amount of deformation can be obtained.

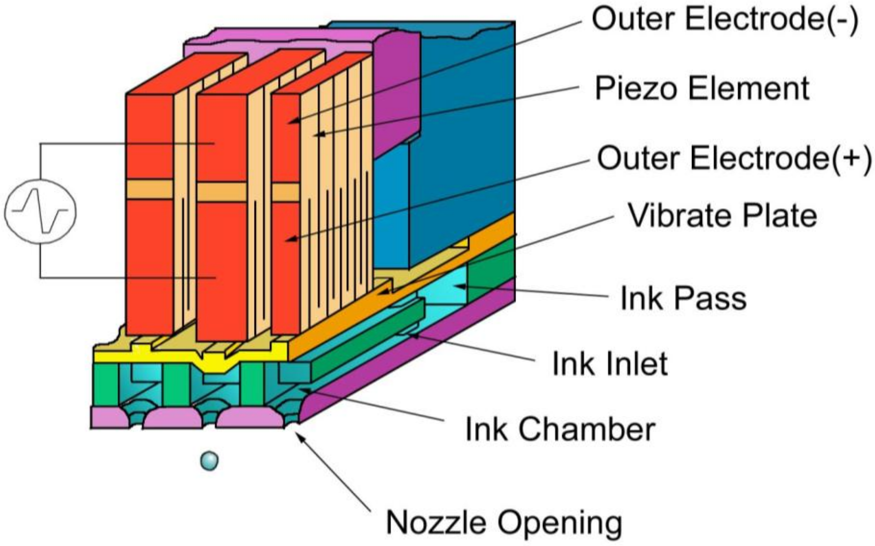
In a conventional HG head, in which a piezoelectric element of about 100μm in thickness was used, the amount of deformation even at a voltage of 100V or more was only 0.1μm. At this voltage the power supply is bulky and the manufacturing cost is high. Moreover, because the amount of deformation is small, the cavities had to be shallow and the surface area had to be enlarged, factors that prevented miniaturization. In addition, the weak force with which ink was propelled was linked to the low level of print quality. This was because the ink droplets would be ejected in a long, slender pillar shape. If the ink droplets are not spheroidal, they will not form a perfectly round dot at impact with the recording medium, and minute quantities of ink, called satellites, are scattered around the droplet.

Thin piezoelectric elements were difficult to produce because they are made of ceramic and become highly fragile when fired. Traditionally a block of piezo element material was thinly sliced, and then affixed to the cavities. With this method, thin piezo are always exceedingly difficult to handle. Therefore the procedure Usui came up with was a method to produce the piezo as part of the structure itself prior to firing. This creates a structure that layers the piezoelectric elements like strips of paper. The structure is affixed vertically to the cavities, and the ink is ejected by causing the elements to deform in a vertical direction (see Figure 4). Although this resulted in a structurally complex print head, it made it possible to achieve a thin piezo element. Moreover, because the piezoelectric elements are placed perpendicular to the cavities, the developers were able to achieve bigger displacement and increase nozzle density by extending the piezo length. Finally, the manufacturing technology was considered to be sufficiently proven because laminated ceramic capacitors had already arrived on the market, and the technical hurdle was judged to not be high.

Usui took this idea and requested production from domestic ceramic manufacturers. At this juncture, the Netherlands electronics giant Phillips brought a laminated piezo made of superimposed piezoelectric elements to Epson in October 1989 for use in the print head drive of SIDM printers. In contrast to the method of wire pins moved by electromagnets, which was the main technique at that time, Phillips proposed moving the ink with piezoelectric elements. Usui, his superior Koto and Osamu Koshiishi, the manager of SIDM head development (chief, general manager and section chief), occasionally sat in during these sales calls. Usui and the other realized they could use this product not for the SIDM printer but for their piezo method IJ printer, and when they obtained and tested a sample it was clear they could obtain a deformation of 1μm at an applied voltage of 30V with the laminated piezoelectric element. They therefore decided to develop a print head using this laminated piezoelectric element. This head was named the MLP (Multi Layer Piezo).

[7] From the interviews with Usui by the authors. March 30, 2007. Conducted at Epson's head quarter.

Figure 4: Structure of an MLP




Source: Epson resource materials

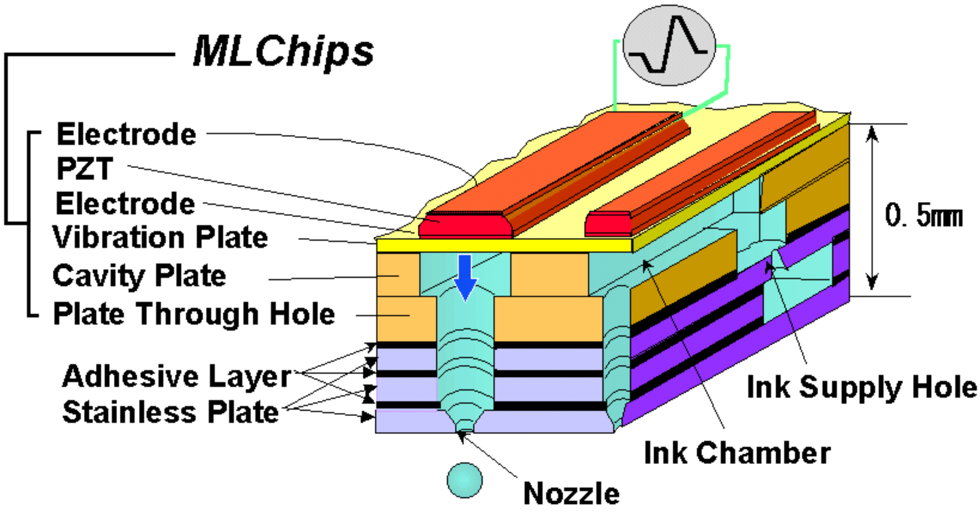
### 4.1.2 MLChips development

While these developments led the members of the Printer Design Department to focus on development of the MLP, Usui sought to develop one more head besides the MLP. Certainly from the standpoints of increasing nozzle density and obtaining displacement at low voltage, the MLP was promising. However, the MLP had a complex structure, and there was concern about whether cost reductions sufficient to compete with bubble jet printers could be achieved. Like a conventional HG head, the method of affixing a thin piezo on the cavities was superior from the standpoint of structural simplicity[8]. If the piezoelectric element could be made thinner with this system, that would yield the best result. To eject ink sufficiently, the piezoelectric element had to have a thickness of about 20μm. It was also understood, however, that this thickness was unachievable using existing technologies.

Consequently Usui decided to develop, in cooperation with an outside ceramic firm with which he had exchanged information for video printer development, a process to build the ink chambers using a ceramic laminated body, thinly apply the piezo elements using a screen printing process and then bake the entire product. If this method were successful, the piezoelectric elements would never be damaged because the product would be baked after spreading the piezo elements on a solid ceramic structure. There would be a cost advantage as well, because the entire product could be processed at one time. Although inferior in comparison with the MLP from the point of nozzle density, productivity is overwhelmingly excellent. The head produced using this system was called the MLChips (Multi Layer Ceramic Hyper Integrated Piezo Segments) (see Figure 5).

[8] This creates a bimetal structure with the vibrate plate sandwiched between the cavities and the piezoelectric element.

Figure 5: Structure of an MLChips

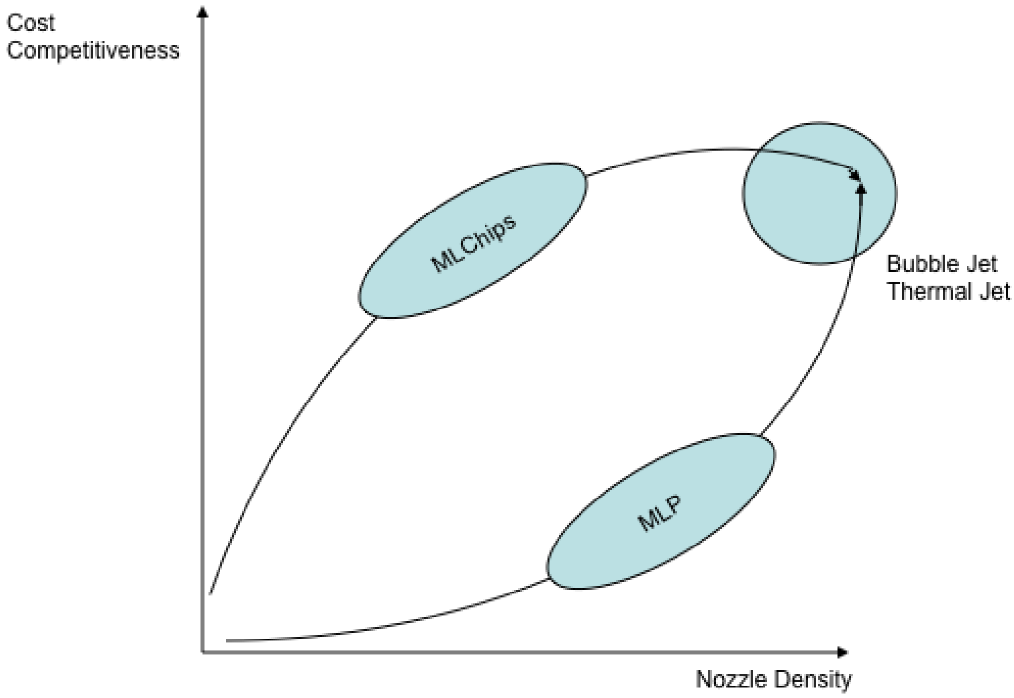



Source: Epson resource materials

Even as engineers at the Printer Design Department turned to the development of MLP for the time being, Usui laid out a road map for MLChips as the next technology to complement MLP, based on his cooperation with the outside ceramics firm.

Epson prepared both MLP and MLChips because it was contemplating the competition with bubble jet products. Usui says he thought that "with just MLP, given the complexity of its structure we'd only have limited success against bubble jets." Bubble jet heads are extremely simple structurally because they are basically just a heater attached to the ink chamber. They are also easy to mass-produce. There are no major limits on increasing nozzle density. So, both low cost and nozzle density can be achieved. With the piezo method, however, one or the other is fundamentally sacrificed. With MLP the cost rises, while with MLChips it is difficult to increase density. Usui therefore thought that by developing two types, they could go head-to-head with bubble jet printers. Usui's thinking is illustrated in Figure 6.

Figure 6: Trade-off between cost competitiveness and nozzle density




Source: Prepared by the authors based on interviews

4.1.3 A third method: Development of TFP

Attacking the bubble jet from both sides with MLP and MLChips was the immediate strategy, but in his mind Usui had already plotted an ultimate stance. Usui described this as follows.

> It had to be small and inexpensive from the get-go. That meant the piezo had to be really thin. But we hadn't found a means that would enable us to realistically do that soon. The principle was understood. But when we applied voltage, the elements failed. So we worked with the idea that ultimately wanted to replace them with something else[9].

When the problem is considered by going back to basics, with a structure like MLChips the thinnest piezoelectric element as possible is paramount. It was not thought feasible to achieve this goal with the existing technology in 1990. But it would have to be achieved in the future. Therefore in 1990, Usui requested that technology development of a head using the thinnest piezo would be conducted through the corporate R&D, not at the operating division. The technology is called TFP (Thin Film Piezo). Epson decided that, for the moment, four or five members in the corporate R&D would be assigned to this development. During this basic development, members were transferred to the operating division around 1995. Later, full-scale commercialization of TFP would begin in 2002, and would finally be achieved in the spring of 2007, 17 years after the start of development.

Usui laid out three directions for Epson's IJ technology in this manner in 1989, and then moved to put them into effect. One was MLP, which would be tackled the most emphatically at the moment. The focus was on achieving nozzle density to compete with DeskJet. The second was MLChips, which could be

[9] Taken from the interview with Usui described above.

mass produced. Because internal resources were devoted to MLP, development advanced jointly with the outside firm. And finally there was TFP. This was the ultimate technology, held close to the vest as in-house technology, but because it was not at the stage where it could be handled at the Operations Division, Epson chose the course of accumulating the technology at the corporate R&D department. Usui offered the following comment.

> We had to do both what was possible right now, and maintain its long-term competitiveness as a device[10].

4.1.4 Meniscus control

One more method Usui had considered to compete with bubble jet technology was freely controlling the ejected ink droplets. This was expressed by the Cassius Clay (Muhammad Ali) metaphor mentioned earlier. There was no question that compared to bubble jet, the piezo method fell short on the point of nozzle density. If small ink droplets could be expelled from the same nozzle, however, this would achieve the same effect as small nozzles even if the number of nozzles were fewer. Fortunately, with the piezo method it is possible control the quantity of ink expelled by varying how the voltage is applied, because the ink is ejected by the physical displacement of the piezoelectric element. Compared with the bubble jet method, this is clearly superior.

This type of ink droplet control is referred to as meniscus control. The term “meniscus” indicates the ink boundary aspect generated at the nozzle tip. The first device to achieve highly detailed color picture by means of meniscus control was the PM-700, which was introduced in 1996 as described below.

4.2 The Kinkyu Head Project (KH Project)

In 1988, the Printer Design Department’s resources were concentrated on IJ technology development, and the possibility of realizing the MLP became evident in 1989 when the developers learned of Phillips’ multi-layer piezo. Consequently, Epson decided to undertake the development of a new IJ head at the operating headquarters. Specifically, a cross-function project involving 80 individuals in total centered on the Printer Design Department was formed in June 1990. This project under the general manager’s direct control was called the “Kinkyu Head Project (KH Project).” The exigency of IJ head development was shown literally in the initials of the project’s name (“kinkyu” is Japanese for “urgent”). Various engineers from other operating headquarters’ departments and head office divisions, including engineers with knowledge and experience in optics and crystals, were assembled for the KH project.

The KH Project objective was to develop a piezo method IJ printer with quality and cost performance surpassing that available from either laser printers or bubble jet IJ printers. Specifically, the stated objectives were to further extend the piezo method’s strengths in terms of ink ejection control, ink selection possibilities and print head durability, and eliminate the piezo method’s weaknesses by reducing the cost and printer size. It was also necessary to ensure the product would be able to support the shift to color printing and greater speed in the future. The project was specifically given the goal of commercialization of the MLP.

In addition to the KH Project, two other cross-function projects were formed in the Printer Operations Division at that time (both were projects centered on the TP Design Department). One, called the “KL Project,” was a project concerning laser printer development. This was a project that sought to respond to

[10] Taken from the interview with Usui described above.

the growing laser printer market by procuring laser engines from OEM and commercializing laser printers. The second effort, dubbed the "KS Project," was aimed at shrinking the size of Epson's SIDM printers and reducing their price, in order to maintain Epson's competitiveness in the home printer market.

In other words, over the short term Epson was responding to low-price IJ printers by miniaturizing SIDM and lowering their price, and addressing the high-priced laser printer segment based on OEM. The scenario was one that sought to establish, as rapidly as possible, IJ technologies that would surpass both competing technologies. In both cases, the key would be the development of MLP that could overtake bubble jet technology.

The KH project had two major themes. One was the development of an IJ head for serial printers, and the other was the development of IJ technology for page printers. The latter was a type to use hot melt for the ink. The former targeted the bubble jet market, while the latter was aimed at the electrophotographic systems market. Ultimately it was the former type that was commercialized.

Activity under the KH Project moved forward, and the rough technological concept for the MLP was decided in April 1991. Although the project was still unable to cause ink to eject as it wanted, Usui judged the development site should be moved to design because the orientation for commercialization had been clarified, and taking several subordinates he moved to the TP Design Department, while concurrently keeping responsibility for the Printer Design Department. Usui described his decision at that time as follows.

> I thought that carrying out design would accelerate the specific commercialization process, so I moved to the TP Design Department while continuing my development duties. Because design is absolutely essential for commercialization, I thought that, rather than linking development to a shifting target, we could probably go to commercialization with what had already been decided at that point, [...] so even though we still weren't able to get everything working sufficiently, I moved to design while concurrently continuing with development[11].

Despite having moved to the TP Design Department, his group was unable to obtain sufficient cooperation for commercialization, even though it received various orders from the TP Design Department, because the head was still not sufficiently completed. For example, even though he was contemplating a resolution of 360dpi, Usui received a proposal to lower this to 300dpi because that was the resolution of HP's printers. In the end, the TP Design Department judged that conditions still did not enable MLP to be commercialized. Moreover, as described below the HG-5130, a new model equipped with a new head that was developed separately by the TP Design Department at about that time, was being readied for market introduction in the fall (October 1991 product launch; see the following section). The situation was one in which the TP Design Department wanted Usui's team to assist commercialization of the model the TP Design Department had developed itself.

Consequently in July 1991 Usui returned temporarily from the TP Design Department to the Printer Design Department to concentrate once more on perfecting the MLP. Then, in October 1991, he made another presentation to the TP Design Department because the development team had succeeded in expelling ink as intended. The TP Design Department also continued at that time with its development of a low-cost head for the next HG-5130 model, but the head's performance was inadequate, and the decision was made to go ahead with MLP mass production development.

[11] Taken from the interview with Usui described above.

The new MLP head was named a MACH print head (Multi-layer Actuator Head) (in the United States it was called the MicroPiezo). The first model equipped with the MACH head was put on early sale in the U.S. in December 1992 as the Stylus-800. The same model was afterwards introduced in Japan in March 1993 as the MJ-500. This was Epson's first product for the personal printer market and was priced at 74,800 yen. With this, a method to counterattack the bubble method was finally in place.

Further cost reductions and performance enhancements were required to fully capture the personal printer market, however. Internally, a proposal from Canon to purchase the bubble jet method head was also studied because lowering the cost of the MLP was considered impossible. In fact, at the same time the MJ-500 was introduced, the TP Design Department replaced just the MJ-500 head component with a bubble jet head purchased from Canon and introduced this product to the market as the MJ-300. The MJ-300 achieved net sales beyond Epson's forecast.

With the MJ-300 supporting the low-end of the market, downward pressure on the MJ-500 price was eased and Epson was able to successfully establish its personal printer business. This situation, however, was viewed with annoyance by Usui, who had developed the MACH head. It motivated Usui to pursue further technical development. Usui used the following words to describe the circumstances at the time.

> I mean, as business management I understood it and did it, because if we weren't able to develop the head we wouldn't be able to develop the ink jet, but it wasn't so interesting, you see. [...] but I did it because I absolutely did not want to lose...[12].

To actually achieve the MACH print head, one more critical technology in additional to the multilayered piezo was necessary. This was a metal nozzle plate. The technology was developed through the head development process undertaken at the TP Design Department.

### 4.3 Development Process in the TP Design Department

With the appearance of HP's DeskJet it became obvious, even to the development team members in the TP Design Department who had commercialized the HG series, that Epson was completely out of the running with the HG head. Epson's development of the IJ technology was put back in the hands of the Printer Design Department when Koto, who had commanded the TP Design Department, was transferred back to Printer Design Department in 1987, but even so, the TP Design Department wasn't folding its hands either. The MACH head might be able to give bubble jet a run for its money, if it could be brought to fruition. Time was limited, however. Could it really be developed on schedule? With such feelings of trepidation, even the TP Design Department decided to pursue development of a product capable of meeting the immediate market. Otawari, who as a section chief in the TP Design Department was in charge of commercialization, recalled that period with the following description.

> This (the introduction of DeskJet) was not good. The MACH jet could certainly be made denser. But new technology development usually takes time. Even when you're experienced it can't be done easily. I thought that even if new materials come along, we probably wouldn't be able to turn it into something quickly. My thinking was that if we could do (the MACH jet), we should move on to developing that next. Even so, I thought it would most likely take four or five years. It seemed to me, when I looked out five years ahead, that

[12] Taken from the interview with Usui described above.

> we'd never be able to win with HG. Whatever, we had to improve our responsiveness. Because we were no match for that (DeskJet). We had to do something, anything[13].

The HG head's weak points were clear. One was the high cost that resulted from using glass as the material and using a group company for the processing. Another was deterioration of the print quality because of the difficulty in increasing nozzle density from a design standpoint, the long path between the nozzle and cavity, which caused responsiveness and ink ejection to worsen and made miniaturization difficult, and the semicircular nozzle shape. The objective became development of a head that would be able to compete in the market for four or five years after such problems were solved.

To lower the cost, the design team decided to first switch the head material from glass to plastic that could be injection molded and to manufacture the head in-house. Hanaoka, who as design general manager at the time supervised this development, looked back on the period as follows.

> …There were those plastic cavities that I kept thinking, shouldn't we give these up already? Or should we commercialize them again? The product that we wondered if we should pick up and try the cavities was the 5130 (the HG-5130; see below), which had already thrown into the trash once[14].

Together with adopting the plastic cavities, a fundamental re-design was undertaken to shorten the distance between the nozzle and the cavity. The cross-section structure of one nozzle of this new head is shown in Figure 7. As indicated in the figure, the ink chamber is made by molding plastic from both sides, the bottom surface in the diagram is sealed with another plastic layer and the oscillation plate and piezoelectric element are attached. The ink path was made by opening a hole afterward, using an excimer laser. The SUS nozzle plate described later is then attached to the upper surface of the head. One head was formed by arranging 48 of these structures on a large plastic plate.

As shown by the cross-sectional view, a characteristic of this head is the short ink path compared with the HG head. This design resulted from seeking a responsiveness just to compete with DeskJet. Nozzle density, however, did not reach the density available with bubble jet. Therefore to achieve 360dpi, a method to improve resolution by diagonally installing the head was adopted.

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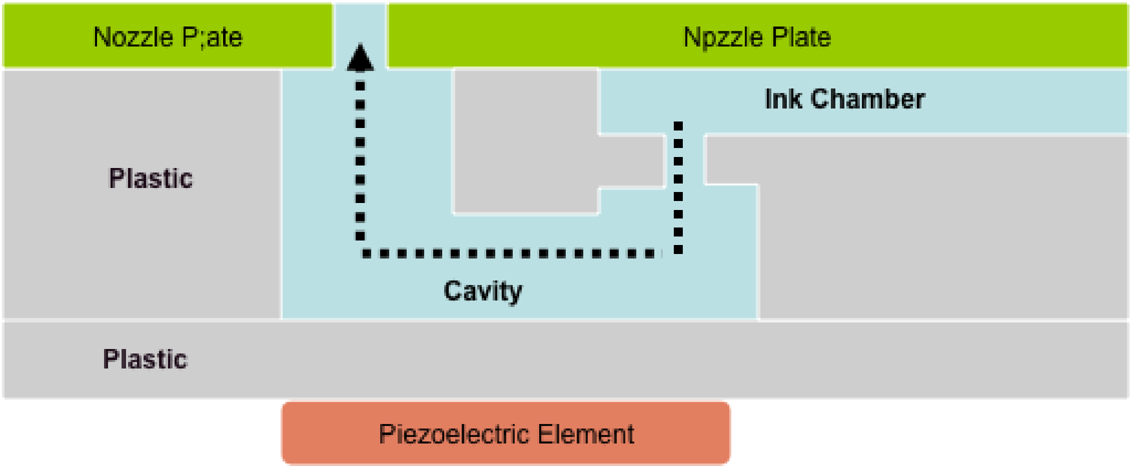
[13] Taken from the interview with Otawari described above.

[14] Taken from the interview with Hanaoka described above.

Figure 7: Structure of the head developed by the TP Design Department (cross-section)




Note: The arrow in the diagram shows the ink flow.
Source: Prepared by the authors based on interviews

4.3.1 Nozzle plate development

Using plastic for the nozzle material in this way helped to sharply lower the cost, but presented problems in terms of durability of the plastic nozzles. The design team therefore decided to make only the cavities from plastic, and then form the nozzles by opening holes in a stainless steel plate. If the shape of the nozzle tip is not close to a perfectly round circle, however, the print quality deteriorates because the ink droplets will not form a perfectly round dot when they make contact with the recording medium. Another method is to open the holes using a laser, but this leaves burn traces and the holes are not perfectly round. Consequently Epson decided on press processing. Opening minute holes in a metal plate with any thickness is not easy, however. Punching holes also produces burrs, and if this produces a stumpy, thin hole it creates increased resistance along the ink path, causing response to deteriorate. The design team thought it would be best if a taper shape like a funnel could be formed with the upper part of the hole cross section wide and the lower part narrow, but such complex processing was not considered feasible on the production technology side. Nevertheless, the production engineers led by Nagamitsu Takashima achieved this. Owatari commented on their success.

> This result surprised me as well. From (production) technology we were told, "Whatever you do, make us the best design." Anyway, maybe they thought they probably couldn't do it, but when they tried it they found out they could[15].

An extremely high level of precision processing technology developed for processing watch bearings had been accumulated at Epson. This had evolved into the component processing technology for SIDM, and was now used for the IJ head. Finally the precision press processing technology that could produce a nozzle leading-edge with a diameter of only 30μm was completed. By adopting this metal nozzle plate, print head manufacturing time and cost were reduced by two-thirds.

One more epoch-making outcome during development of the nozzle plate was the Teflon surface

[15] Taken from the interview with Otawari described above.

processing. When ink is ejected, the nozzle plate surface gets wet. If this wetness is not uniform, the remaining ink droplet obstructs the nozzle and the ink is not ejected perfectly. The design team therefore decided to put a water-repellent coating on the surface. Specifically they adopted a method of mixing nickel in Teflon powder, and then melting the mixture and plating the surface. Plating the nozzle plate after the holes had been processed to ensure the holes were not plugged required exceedingly difficult technology, but Epson was able to establish this technology as well.

4.3.2 Introduction of the HG-5130 and further problems

The HG-5130 model equipped with a print head that incorporated this metallic nozzle plate was introduced to the market in October 1991. Although priced at 226,000 yen, roughly 50,000 yen less than the previous model, it was still expensive compared with products from Canon or HP.

There remained problems with the new head. One was its cost. The head had become cheaper but still cost from 6,000 to 8,000 yen. One reason the cost did not drop was the nozzle plate’s steep price. Another problem was the difficulty of molding the plastic. Although the structure was simpler than that of the HG head, complex metal molds had to be used in order to leave the portion where the ink channel would be processed thin. The cost of this metal mold also pushed up the total cost. The depreciation and amortization expense for the excimer lasers used to open the holes for the ink channel from the rear was also high. At the time Epson had purchased three excimer laser units for 100 million yen each.

During the development of the HG-5130, Epson also developed new inks. As indicated previously, Epson envisaged acid-sized paper begin used with the HG series and decided on strong alkaline ink. When targeting household use, however, strong alkali inks could not be used. Moreover, this was a period when there was a major shift form acid-sized paper to acid-free paper, and this also meant Epson would have to change its conventional inks. Consequently the design team adopted the low penetration ink, the same type used with HP’s DeskJet. With this type of ink, however, print quality cannot be maintained unless more ink droplets are used. This made it necessary to make the displacement of the piezoelectric element even larger than in earlier print heads.

4.3.3 Development of a low-cost head

In parallel with development of the MACH head, a group working with Owatari in the TP Design Department began development of a head to succeed the head used in the HG-5130. Owatari wanted to transfer every printer to the MACH head if it could be perfected, but progress on MACH head development was unsatisfactory. In fact, although they had gotten the head out of design once, it had been returned to development because the technology was imperfect. If the MACH head wasn’t turned into a product, they would no longer be able to count on the Printer Design Department. Instructions came down from Hanaoka, the general manager, for the TP Design Department to also begin preparations immediately for the next product.

Even Owatari began to have doubts about the MACH head’s feasibility. He didn’t believe Epson could do battle with the bubble jet camp for four years using the HG-5130 head, however. Some new technology was necessary. Looking back at that period, Owatari used these words to describe the situation.

> The most troublesome component was the multi-layer piezo. Could we really make it thin like a strip of paper? There would probably be voids. Plus we’d have to overlap the

> photoresists[16]. Our concern was whether we would be able to compete with DeskJet. DeskJet is made from one layer. The MACH head configuration was complicated[17].

Owatari therefore believed they needed to fundamentally resolve the foremost problem with the HG-5130 head – its cost. Lowering the cost would require not using the expensive nozzle plate coated with Teflon and making everything, including the nozzles, from plastic. It was also necessary to rethink the complicated ink channel structure utilizing both sides of the base and the water-repellent treatment of the nozzles.

The head structure designed as a result of this study called for forming the ink chamber, ink channels and cavities on one side of the plastic substrate and sealing this component with a plastic top plate, then applying an organic water-repellent treatment to the nozzle surface (side surface) and opening the nozzle holes using the excimer laser. While the nozzle density was not increased with this structure, a substantial cost reduction effect was achieved. It also had implications in terms of the excimer laser depreciation expense. From start to finish, it was a design that emphasized cost.

The nozzles opened by application of the organic water-repellent treatment and excimer laser processing, however, had a fatal flaw – the ink did not seep from the nozzles uniformly and was not expelled straight. At about the time this problem was being studied, Usui, who had returned to the Printer Design Department and developed the MACH head, gave a presentation. If they were able to produce the MACH head, there was nothing standing in the way of adopting the head. In addition, from his communications with the production engineers and technicians, Owatari was certain the MACH head would be competitive. Furthermore, the appearance on the market in the early 1990s of resins with excellent bonding characteristics also increased the MACH head's feasibility. Owatari described the situation as follows.

> I realized we would be able to go with the MACH when I asked the manager in charge of the production technology if it was possible to make the head and he replied, "This (the MACH) is easier." When I heard this I thought, we can go. If we could really make (the (MACH head) more easily, we could achieve a positive mass production effect and our yields would go up because of the small size. Because (unlike the plastic head, the MACH) multi-work processing is doable and the heads could be made all at once[18].

As a result it was decided to halt all head development at the TP Design Department and integrate everything into development of the MACH head. Usui had led the MACH head commercialization and development at the TP Design Department. Owatari, on the other hand, was reshuffled to the Printer Design Department in place of Usui, where he succeeded to Usui's projects while simultaneously beginning work on the shift to color printers, the next big development.

[16] For the initial MACH head, the development team had adopted a complicated method to form the head by accumulating and etching layers of photosensitive resins.
[17] Taken from the interview with Otawari described above.
[18] Taken from the interview with Otawari described above.

## 5. Color Printer Development

### 5.1 The shift to color based on development of related technology

At about the time Epson put its MJ-500 on the market, HP had begun introducing color printers as its latest product. Despite the fact there was as yet no demand at that time for printing New Year's cards, let alone digital images for which color printing is a must, thermal transfer color printers had been sold as part of the personal computer craze. The shift to color IJ printers was viewed as an inevitable step. The order came down from the division manager to Owatari, who had finished development of the HG-5130 and transferred from the TP Design Department to the Printer Design Department, to put out a color printer as soon as possible.

Moving to color printers, however, was not a problem solved simply by adding colored inks. Making the transition to color, which required not only the print head but also the development and combination of related technologies such as inks and papers, picture processing algorithms and the paper feed mechanism.

First improvements in the inks were demanded. Owatari, who majored in chemistry at college, knew that color inks required characteristics different from those of monochrome inks, and had been working on the development of color inks since about 1986.

When color inks with the same characteristics as monochrome inks are adopted, the inks bleed into one another and produce mixed colors. This is because monochrome inks are low penetration inks. With low penetration ink, the water in the ink evaporates after the ink is ejected onto paper, leaving only the dye adhered to the paper. As a result a sharp, clean black character remains on the paper surface. Such ink requires about ten seconds to adhere to the paper, however. Therefore when the low penetration ink is adopted for color inks, each ink is ejected before the previously ejected ink has dried, causing the inks to bleed and produce mixed colors.

Therefore Epson first decided to switch to inks that would penetrate paper quickly. The problem with traditional inks, however, was that sharp, clean dots could not be formed because the adhered ink would flow and be absorbed horizontally along the paper fibers. Therefore the permeable constituents composing the inks were studied and “Super Penetration Ink” that enabled inks to uniformly penetrate paper was developed. Because this ink adheres to paper within several milliseconds, color mixing does not occur even if different color inks successively are adhered to the paper. With this it seemed that the shift to full-color was now possible.

Print head trouble came to light in the spring of 1993, however. As the result of an investigation it became clear this was because the cavity had not been properly polymerized. Because the super penetrating ink contains a large amount of solvent, the cavity is formed by mixing epoxy resin that can withstand the solvent with acrylic resin and placing these photoresists in layers. In conventional processing, the cavity was first hardened using ultraviolet light, and this was then heated and attached to the vibration plate under pressure. With this method, however, acrylic resin was polymerized only to about 60-70%. Therefore the ink would be absorbed into the acrylic resin, causing the cavity and vibration plate to peel away, or the cavity resin to flake, as a result. Consequently Otawari, working with the Production Engineering Department, hit upon the solution of irradiating with an electron beam during the final phase of traditional processing. The electron beam penetrated the metallic vibration plate, enabling polymerization of the resin to be increased. Thus the print head problem was eventually solved.

Yet even though the ink and print head problems were overcome, the problem of print speed – A4 size color prints took several minutes, while nearly ten minutes was required in the case of graphic printing because of the time needed for photo processing – remained unsolved. Therefore to give the product a remarkable feature that would negate the print speed issue, it was decided to boost resolution to 720dpi. Hanaoka was the administrator with responsibility for commercialization, and recalled the thinking at the time as follows.

> Monochrome printers were subject to price competition. So this situation couldn't be reversed with monochrome printers alone. If you think about it from the entire flow, the MJ-500 came out first, followed by color, 720dpi and prices under 100,000 yen. From a spec standpoint as well it was hopelessly late. The idea was to put out a product like no other in the world, even though it required a ridiculous (amount of time)[19].

To improve the resolution, the dot diameter must be reduced. Expelling extremely minute dots for a resolution of 720dpi using a print head designed for 360dpi resolution is impossible, however. Epson therefore adopted the revolutionary idea of developing paper to retain the minute ink dots and improving the print head movement and paper feed method.

The quantity of ink in a droplet at that time was 40pl. This was the appropriate quantity of ink for the ink to adhere to paper and create a dot diameter of roughly 100μm assuming plain paper printing at a resolution of 360dpi. In contrast, to support 720dpi printing the dot diameter would have to be reduced to 40-50μm. For this purpose, special paper was jointly developed with a paper manufacturer. Next, improvements were added in the form of reducing by half the horizontal traveling distance (resolution) of the print head, and the distance by which the paper is fed lengthwise into the printer.

As a result of the development of the related technologies described above the MJ-700V2C, Epson's first full-color product, was introduced in June 1994. This product, which was put on the market without a great deal of confidence in-house, was priced at 98,000 yen and supported 360dpi with plain paper and high-resolution at 720dpi with special paper, and went on to sell 360,000 units domestically and 2.4 million units in markets around the world within one year of its launch. Considering that the entire domestic printer market for all systems at that time had been in the 300,000 unit range, the explosive sales of this product are readily apparent.

### 5.2 Evolution of the MACH print head and realization of "photographic image quality"

With the launch of its MJ-700V2C, Epson successfully made the shift to color printers. Yet from the beginning Usui, who had developed the video printer, and Nakamura, who had been promoted to general manager of the Printer Design Department, had sought not merely to shift to color equipment but to print color photographs. Consequently neither of them was satisfied with the MJ-700V2C's prints, which were "pretty, but they're not photographs." To achieve "photographic image quality," further development of related technology was necessary, just as it had been to realize the transition to color printing.

First, with regard to ink it was abundantly clear that low penetration ink was capable of printing beautifully. Because high-permeation inks soak into paper too much, the colors of these inks gradually thin out. Consequently, in order to leave clear black images, in June 1995 Epson introduced to the market the MJ-800C, which returned to low penetration ink only for monochrome ink.

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[19] Taken from the interview with Hanaoka described above.

The result of this decision, however, was a greater than predicted negative market reception regarding the mixed colors. It also resulted in claims that images printed with the special paper developed a red tinge if placed near a humidifier. The reason was the color material used in the magenta ink was highly soluble, and in a high humidity environment this ink would dissolve again and the magenta dot diameter would expand, even if the special paper to constrain the dot diameter to 40-50μmI was used. Because it had conducted its endurance tests at about 85% humidity, Epson did not realize prior to putting the product on the market, that such a problem would occur when the humidity is 90% or higher. Through such twists and turns Epson, which had captured the top market share from Canon with the success of the MJ-700V2C, saw its share slip once more. Epson ultimately regained its reputation in June 1996, when it improved the magenta ink and introduced the MJ-810C, which once again used high-permeation ink for its monochrome ink.

There was still another issue that had to be conquered in order to achieve photographic image quality, however. Faithful reproduction of the colors and gradations of the original image, and elimination of the "granular quality" of the ink dots, are indispensable for high-quality pictures (for information concerning the method of reproducing the original image, see Reference II at the end of this manuscript). To achieve these Epson opted for "six color ink" and the use of "microdots" that reduced the quantity of ink in the ink droplets.

Around this time Epson increased the ink coloring materials for better permeation on plain paper and improved ink consistency. This resulted in problems when using special papers, however, giving the dots a grainy appearance. For cyan and magenta, two of the three main colors (along with yellow), the dots could be easily checked visually as grains, and Epson therefore developed inks such as light cyan and light magenta, which reduced the amount of color materials to one-quarter of that traditionally employed.

With the use of as many as six colors made from combining five color inks and monochrome ink, the picture processing algorithm also becomes more complex. When it marketed the MJ-700V2C, Epson had installed image processing software purchased from an outside firm, but later the Printer Design Department had begun development of a proprietary half-tone algorithm. Fortunately, even though the types of inks had been increased from four to six colors, very few changes to the print head mechanism were required. Therefore by putting its resources into picture processing development, Epson succeeded in proprietary development of an imaging algorithm that enabled high-speed error diffusion for six colors.

Moreover, an algorithm to adjust the voltage applied to the piezoelectric element was also developed during this period. With IJ technology, binary processing to simply eject or not eject ink was being used. In addition to this simple ink ejection-no ejection choice, a meniscus control algorithm to adjust the ink droplet volume in terms of "how much" ink to eject was developed. As a result, Epson succeeded in producing microdots that reduced the amount of ink in each ink droplet from 40pl traditionally to 13pl, making it possible to control ink droplets in three phases for large, medium and small. By increasing the number of dots per area, the achievement of microdots not only eliminated grainy appearance, it added to the number of color tones, which also proved indispensable for photographic image quality.

Furthermore, to avoid the lines and streaks known as "banding" that can appear in an image, the development team decided to adopt a method referred to as "microwaves." To achieve microwaves, the paper feed must occur in minute movements. The development team decided to install a motor to feed paper at a rate of 1/720 of an inch. When printing at a high resolution of 720dpi, however, the print speed would slow to a crawl, and printing an A4 size photograph would require as long as one hour. Despite such a sacrifice of efficiency, the development team opted to keep achievement of photographic image quality its foremost priority.

In addition to ink, Otawari was in charge of special paper development. A “photograph” is something that is printed on glossy paper. Traditional special papers were coated with silica as an ink absorbent, which gives images a white tinge. To make this transparent, the paper should be coated with alumina sol whose granules are smaller than the silica particles. Consequently Epson and another company jointly developed a coating technology using granular alumina sol, and introduced a glossy paper under the name “*Kotaku Film*” when it launched sales of the MJ-800C described above.

Through the development of these related technologies, the PM-700C was put on the market in October 1996. The letters “PM,” an abbreviation for “Photo MACH,” were adopted in the product name to link the printer in buyers’ minds to the fact the image quality equaled that of photographs. The PM-700C achieved overwhelming high-resolution at a low price of 59,800 yen. The product was highly successful, garnering a market share of about 25% within one year.

With the subsequent introduction in April 1997 of the PM-750C, which was billed as achieving a high resolution of 1,440dpi, close to the limit of visual confirmation, Epson’s printers jumped in popularity even in other countries, and Epson finally pulled ahead of Canon in terms of market share.

From this time forward Epson also continued to improve its paper, including the joint development of technology to apply silica in the same manner as photographic printing papers, in order to lower the price of its expensive, 200 yen per sheet glossy printing paper. It also negotiated with the Ministry of Posts and Telecommunications and reached an agreement on the sale of New Year’s greeting postcards for use with IJ printers[20]. As a result of developing a promotion using a pack of three New Year greeting postcards for IJ printers, awareness of the post office postcards for inkjet printer use jumped in the following year and they proved so popular they sold out. Today the 2.2 billion IJ postcards sold each year account for about 60% of all New Year greeting postcards, and producing your own color New Year’s cards has become a regular activity for IJ printer users.

## 6. Lateral Development of IJ Technology

Epson has developed its IJ technology around printers for home use. Today printers for home use remain Epson’s largest business. The market for IJ printers for home use, however, is already mature. Epson’s net sales of printers in fiscal 2007 are projected to be 778.0 billion yen, down slightly from 781.5 billion yen in fiscal 2006. With sales leveling out or declining slightly, large growth cannot be anticipated in the future.

In addition, like other home electrical appliances and electronics products, printers for home use are exposed to stiff price competition. The business model of earning profits from consumables makes it possible to lower the prices of printers themselves, but leads to a structure in which the higher the sales of printers, the greater the downward pressure on earnings. If a printer manufacturer does not increase sales of its printers, however, it will be unable to maintain its consumables business for the long term. Saddled with such a dilemma, the home printer business remains a difficult one.

In Epson’s case in particular, earnings are highly susceptible to the effects of any deterioration in sales because sales of printers for home use account for 60% of the company’s entire printer business. In

[20] Because the main devices used by individuals at the end of 1997 to produce their own color New Year’s cards were printers such as “Print Gokko”, only 10 million New Year’s greeting postcards for use with IJ printers were prepared. At the request of the Ministry of Posts and Telecommunications, the designation “inkjet” could not be used and the postcards were initially sold under the name “coated postcards.” As a result, some customers also used the postcards with laser printers, which led to claims because of problems such as the postcard coating melting and coiling around the thermal drum, causing printers to breakdown. Approval to use the designation “inkjet” was subsequently granted.

contrast, sales of business printers exceed 70% of all printer sales at rival Canon, which is believed to make it easier for Canon to manage a more stable business[21].

To address these circumstances, more recently Epson has been focusing its efforts on IJ technology for uses other than printers for home use. Such lateral development extends to three sectors: (1) business printers, (2) textile printers and (3) manufacturing devices for industrial use.

### 6.1 Sectors applying IJ technology

Business printers are technically similar to printers for household use in that they eject ink onto paper. The business models of the two businesses differ, however. In the case of printers for household use, Epson provides their final products to end customers, but in the case of printers for businesses, it frequently is in the position of supplying printer heads and inks as a materials firm. For example, Epson supplies inks and heads as a set for photo product minilab printers from Noritsu Koki Co., Ltd., sign (advertising) graphics printers from Roland DG Corporation, Mimaki Engineering Co., Ltd. and Musashi Kogyo Co., Ltd., and digital printers from Dainippon Screen Mfg. Co., Ltd.[22]. In these cases, the Epson brand is not displayed on the final product even though Epson supplies the the core technology.

In addition, from about 1996 Epson began activities to increase the awareness of applications of its IJ technology, and in September 2006 created a special website and began soliciting partner firms that would adopt Epson's IJ technology. Behind that decision is thought to be the consideration that there is a limit to how much Epson can develop on its own markets that can apply IJ technology. Moreover, because a close relationship with end customers is critical in the business market, luring customers away from existing firms is difficult. Epson therefore opted for the approach of supplying its IJ technology in the form of a core component and entrusting its customers with market cultivation.

This does not mean that Epson's activities aimed at the business market consisted only of supplying print heads and ink, however. It introduced MaxArt as a large-scale printer for posters. It also introduced CRYSATARIO as a printer for photographic minilabs, and marketed the GP-700, a printer characterized by excellent durability, for retail store back offices. In 2007 Epson also developed a printer for labels affixed to food containers and similar packaging. As this illustrates, in its printer operation for businesses, Epson targeted both the components and the end products markets.

Another sector into which Epson directed its efforts was textile printers, which eject ink onto media such as cloth rather than paper. Although Epson had been providing IJ technology for printing on fabrics since the latter half of the 1990s, this application began spreading to mass production equipment in 2003 when Epson licensed its technology to F. Lli Robustelli S.r.l., a textile printer manufacturer in Italy's Como Province. In this case as well, Epson based its business not on final products but on supply of the components. Epson supplies Robustelli with IJ heads for that company's printers. The inks developed for the specialized print heads are supplied through FOR.TEX S.r.l., which is also based in Como[23]. The Como area is Italy's pre-eminent apparel region and produces many world-famous brands. This region, which can rightly be called the supply base of Italian fashion, is brimming with textile printers that utilize Epson's IJ technology nowadays.

Besides printers for graphics such as those discussed above, IJ technology has been spread to applications in a variety of industrial uses. One use that has already been commercialized is devices for the manufacture of liquid crystal display color filters. Color filters typically are manufactured by spreading

[21] Fuji Sankei Business, January 15, 2007, page 7.
[22] The Chemical Daily, September 27, 2006, page 8.
[23] The Chemical Daily, May 28, 2003, page 10.

a color resist containing pigments on the substrate and forming the pattern using a photolithography machine. The rising cost of equipment to produce larger display sizes and the negative environmental impact of discarded materials, however, have become problems with this method. IJ technology has risen to dominance on these points in recent years. The IJ equipment that Epson developed in 2006 to support 8th-generation large-scale liquid crystal substrates is already in operation at Sharp's Kameyama Plant No. 2. Moreover, in addition to technology for color filter manufacturing, Epson has developed technology to form circuits on substrates by expelling ink containing metal micro-particles, which is expected to replace the exposure and etching process using photoresist.

Applying IJ technology to various uses such as business printers, textile printers and industry manufacturing requires the technology to propel various liquids. Therefore the development of "how will it be ejected?" is as important as development of "what will be ejected?" In Epson's IJ technology, liquids are ejected by physical deformation of the piezoelectric element. Various liquids can be ejected because a load never placed on the propelled liquid. Consequently the technology is considered to be in a more advantageous position than Bubble Jet from the standpoint of undertaking the development of various applications.

IJ technology achieves the highly general function of ejecting liquids. The question of which sectors this technology will be applied to in the future is an important strategic issue for Epson's growth. Hanaoka, who is now Epson's president, discussed the future strategic development of the IJ business as follows while employing the metaphor "from Mt. Fuji to Yatsugatake."

> Until now consumer printers have been like climbing Mt. Fuji. The market was very clear and also quite large. [...] Looking ahead, there's doubt about whether there will be another mountain as big. Rather you might say there will be several mountains, none of which is a Mt. Fuji, that we'll see based on a common technology platform in the future. I say that because, if we're talking about the IJ technology we have now, I think it's a pretty good base for making mountains like Yatsugatake. So on that point the question is how to take the business into different fields while using our current IJ technology. So Epson's stance in the future will be to establish several (businesses), because it will be OK even if they aren't that large[24].

Moreover, Epson is groping for developments that will position its IJ technology within new business models that are created as digitalization advances. For example, in January 2006 Epson developed an IJ printer in cooperation with Catalina Marketing Corporation in the United States to support point of sales systems for large-scale retail stores. This system instantaneously analyzes a product a customer has purchased and prints a discount coupon corresponding to it, so that a customer who bought Coca-Cola, for example, is provided with a discount coupon for Pepsi Cola, and has been installed in about 12,000 stores in the United States[25]. Hanaoka spoke about this approach as follows.

> [...] It's very interesting how a certain business model and our technology in our printers can be joined. [...] Replacing a traditional business model with technology isn't interesting, but here the business model itself was changed through the addition of our products. If our product isn't added there, it's not interesting. [...] Take the example of textile printing – when

[24] Taken from the interview with Hanaoka described above.
[25] Management Newsline (Seiko Epson), No. 15, April 2007.

> this becomes a business model where the middleman isn't needed as long as there is a designer and shops, that's a completely different business model, you see. So we'll put our products into such business models. This is the type of approach we'll take.

## 7. Conclusion

Although there is an IJ printer business today that supports Epson, it was certainly not the case that such growth had been envisaged from the start of development. When Epson began its development, IJ technology was just one among several technologies. Since the 1970s, Epson has been involved in the development of every printer technology. This includes technologies that were commercialized but did not achieve successful results from a business standpoint. It also includes technologies that were not commercialized. Through such trial and error, the superiority of IJ technology was gradually clarified.

IJ technology was also turned gradually to practical applications through patient trial and error. The first printer had frequent problems. The HG head cost was difficult to reduce. Realization of the MACH head looked questionable. And surpassing the bubble jet in terms of nozzle density and cost was not easy. By sketching out a future ideal, however, and working toward it by solving problems gradually, based on the piezo method's fundamental advantages in propelling ink by physical deformation and the belief that cost and performance could both be achieved if a thin piezo element could be created, Epson's current IJ technology was established. Hanaoka put it this way.

> When design engineers make a difficult request, it's really a matter of approaching the ideal gradually [...] over some period of time. That's apart from the question whether it can be done today, or whether it will be possible to do tomorrow. So of course, how to make [...] something that's difficult might very well be hard, yet once you've been able to do it, the product's appeal increases tremendously. Well, that's the benefit of continuing to plug away at something, I suppose, and I think that maybe, since that time, everyone has eventually come to see it that way.

## Appendix I : Types of Printers[26]

Printers are classified into several types depending on the volume printed at one time and the printing method.

Based on volume printed at one time, devices are classified into three types: page printers, line printers and serial printers.

Page printers use a method of printing an entire page, at one time by summarizing the print data for one page, consisting of the characters and images, and calculating where to arrange the data on the page. While this method is often adopted for printers that utilize the electrophotographic method described below, it is sometimes also adopted for inkjet (IJ) printers and thermal transfer method printers. In contrast to this method, line printers and serial printers use a method of sequentially printing each individual line or each individual character.

Based on the printing method, printers can also be classified into impact method and non-impact method printers.

The impact method refers to a method of printing by having the print head strike (impact) a recording medium such as paper; this method can be further divided between typing methods that print characters by typing them on paper, and the dot impact method, which breaks down characters into dots within a square-shape and prints them using wire pins that strike a ribbon according to the combination of dots that form the character's shape. Both methods are indispensable as business office equipment because they can be used with plain paper and can be used especially for printing multi-sheet pay slips that use carbon paper. They are quite loud when printing, on the other hand, and therefore inferior in terms of operating noise.

Non-impact methods include, in addition to the IJ method, methods such as thermal printing and electrophotographic printing. The two thermal methods are thermal transfer printing and direct thermal printing. Of these, the thermal transfer method transfers images to the recording medium by heating, with the thermal print head, dry ink that liquefies or sublimates under heat; these are referred to as the hot melt thermal transfer method and the dye-sublimation thermal transfer method, respectively. The direct thermal method, on the other hand, uses special paper with a coloring layer, and forms images by directly heating the paper using the thermal print head to cause the paper to produce colors. The electrophotographic method is a printing method used in plain paper copiers. Printing is accomplished by applying light to a drum using a laser or LED (light emitting diode) to make a latent image using the charge and causing powdered toner to be absorbed by the charged area, then transferring the toner to paper.

[26] The descriptions in this section are based on the August 30, 1993 issue of Nikkei Personal Computing, the August 22, 1994 issue of Nikkei Electronics and the December 8, 1997 issue of Nikkei Computer.

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