High-speed thermal printing

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INTRODUCTION

Thermal Printing is a unique new concept in non-impact printing, whereby electrical signals are directly converted to heat to produce a printed output. This paper covers a program to build an advanced development model of a High-Speed Thermal Teleprinter, utilizing the Thermal Printing technique, for the U. S. Army Electronics Command. The teleprinter, which prints at 240 characters per second, was the result of the development.

History

The concept of Thermal Printing was developed to meet a requirement for a low-cost, quiet, high-speed computer print out device. At the time that the contract was awarded to NCR (June 1964), however, the most advanced Thermal Printer was a keyboard operated, strip printer, which had a maximum operating speed of 15 characters per second, and made only a single copy.

Viewed against this background, a 2 year program to develop a Teleprinter which printed across a full page at 60, 120, and 240 characters per second and made from three to six copies certainly appeared to be a very energetic undertaking. However, from the Government's point of view, the features of thermal printing made the potential gains commensurate with the risks.

Features of thermal printing

In addition to being non-impact, Thermal Printing has the following salient features which make it attractive for both military and industrial applications:

- **Reliability**—Inherent high reliability due to the absence of moving parts.
- **Low RFI**—The absence of high voltages and solenoids allows even the rigid requirements of FED-STD-222 to be met.
- **Silent**—The printing process itself is completely quiet; the only sound is that of moving the paper.
- **Low power**—Due to high efficiency of direct electrical to thermal energy conversion.
- **Speed**—Absence of moving parts and their associated inertias allows high speed operation.
- **Clean**—No inks, powders, or fixing actions are required.
- **Multiple copies**—Most non-impact printers do not have this capability.

Thermal technology

To achieve Thermal Printing, two novel components are utilized. The first, a print head, is an array of resistors selectively heated electrically to generate a thermal image. The second is a thermal sensitive paper which is held in contact with the print head to provide a printed record of the thermal image.

Numerous approaches have been tried in fabricating print heads, and several promising new approaches[1] are still being developed. However, the print head configuration described herein has been used in all Thermal Printers built to date.

Each individual printing element consists of a tin oxide resistor deposited on the edge of a ceramic substrate (Figure 1a). Electrical connection to the printing element is made through the copper leads on the top and bottom surfaces of the substrate. Fifty print elements are fabricated on a single substrate to form a

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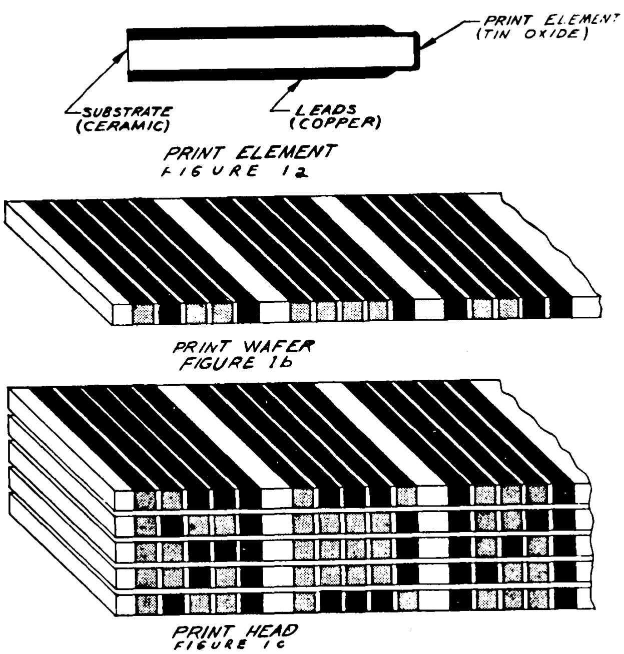

Figure 1a—Print element
Figure 1b—Print wafer
Figure 1c—Print head

print wafer (Figure 1b). They are arranged in 10 groups of 5 with a space in between each group.

Five wafers are mounted together to form a print head (Figure 1c). Each print head contains ten 5×5 matrices; each matrix is capable of printing one character. Eight print heads are mounted side by side in the printer to achieve the 80 character line.

By applying power to combinations of print elements in a matrix, the thermal image of the desired character can be formed in the appropriate position on the print line. The Thermal Printer has the capability of printing any one of 64 alphanumeric characters or symbols in any position on the print line.

A 5×5 matrix was chosen over the more widely used 5×7 matrix for the following reasons:

1. Choosing the 5×7 matrix font would increase the number of print head wafers and driver circuits by exactly 40% plus increase the complexity of the selection logic by approximately 40%.
2. The intelligibility of the printed characters employing the 5×5 font rather than the 5×7 font was not significantly reduced.

High-speed thermal teleprinter

The High-Speed Thermal Teleprinter was developed to print at speeds of 60, 120, and 240 characters per second, print 64 Alphanumeric Characters using the serial input mode, provide a MIL-STD-188B interface, and produce multiple copies.

Let us now discuss what problems were encountered along the way, what significant advances were made, and how this printer operates.

When this thermal printing contract was initiated, there were some major areas where either ideas had not been proven or no firm ideas existed at all. Major problem areas were known to be the print wafers and a multi-copy process.

Print wafer problems

There were four basic problems in the print wafers alone. They were abrasions, interconnections, alignment, and burnout.

The abrasion problem was due to the print heads rubbing against the paper while printing. At the time of the contract award print head life was about 15,000,000 lines of print. Through tests of various resistor materials and overcoats, and continued plated mechanism development, the life of the print head was extended to 50,000,000 lines of print, which is equivalent to operations at the 240 characters per second speed with a 25% duty cycle for 2 years. The total printed output would be equivalent to that of an existing 10 characters per second, Standard A, Military Teleprinter operating at a 25% duty cycle for 48 years.

The next problem area was interconnections. For a full 80 character line, there are over 2,000 printing elements lined up in 5 rows. The print line is 0.1 inch high and 8 inches wide. This means that over 2,000 connections had to be made to the wafers through a cross sectional area of only 0.8 square inches. To do this a technique was developed to connect high density, copper clad, mylar cable conductors to the matching conductor pattern on the wafers. The conductors are on 0.028 inch centers—0.018 inch conductors with 0.010 inch spaces. There are several standard ways that the cables could be fastened to the print wafers. The connections could be bonded with a conductive epoxy, soldered, or welded. All of these processes, however, require very precise registration and would need to be performed in a clean room as foreign particles could short out adjacent conductors. In addition, the soldering and welding both damage the copper clad mylar cables, and the problems of registering a conductive epoxy pattern would be difficult. To overcome these problems, the process that was used for this development was first to apply a very thin coat of non-conductive epoxy on one side of the wafer, then lay the cable on the wafer and align the conductor patterns visually. Next, the cable and the wafer are clamped together

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with a plastic clamp that permits visual verification of the alignment while the epoxy is drying. After the epoxy dries, we have not only a permanent, rugged, mechanical bond between the wafer and the cable but also a good electrical connection between each conductor on the wafer and its corresponding conductor on the cable. The mechanical bond is, of course, formed by the epoxy. The electrical connection is not so easily explained, since this epoxy is a good electrical insulator.

The key to understanding the electrical contact is that the conductor surfaces are not microscopically smooth but composed of tiny hills and valleys. When bonding is performed, the pressure forces the epoxy into the valleys and causes the hills to make contact. After the epoxy is dried and the clamp removed, the epoxy still holds the conductor surfaces in contact. Typical resistance is 0.1 ohm with a maximum resistance of 0.25 ohm. Connections of this type have been tested successfully at temperatures as high as 1000° F, at which point the mylar cable failed (not the electrical connection). Over 100 cables, having 30 conductors each, have been bonded to date, and only two defects have been found. This would indicate a 98% yield which is better than previous experience with a dip solder technique for this application. This process may find other uses. In general it could be considered whenever a permanent connection is desired between multiplicities of conductors and space is at a premium.

The next problem area is alignment. If all the printing elements are not located in the same plane thermal transfer to the paper will be poor, resulting in poor quality printing. Tests have shown that the allowable deviation from the printing plane is around ±0.0002 inch. Since the print head plane is composed of five discrete wafers, the required alignment is not easily maintained. In previous work this had not been considered a major problem because only single character printers had been built. In these instances the area of the printing plane and the cost of the wafers were both relatively small. This led to hand tailored wafers and assembly procedures which could not easily be expanded to adequately meet our problem. Although maintaining the flatness of the printing surface on the wafer to these dimensions was no problem, the tolerance on the dimension which located the printing plane could not be held closer than ±0.0005 inch.

Consequently, the procedure adopted was to measure and divide them into groups of five, such that each group was within the required tolerance. Each group of five would then be used in one print head assembly. The print head assemblies were then made so that they could be adjusted to overcome the alignment problem between adjacent print head assemblies. Although this approach has produced a functioning printer, it is felt that the problem has only been eluded rather than solved. However, there are other techniques currently under development for producing print heads that would not have an alignment problem.

This brings us to the remaining problem area—burnout, where the most significant contribution was made. When this program started, the state-of-the-art thermal print heads were satisfactory for 15 cycles per second operation, consisting of a 10 millisecond print pulse followed by a 57 millisecond cooling period. However, in this application, under worst case conditions, we had a 4 millisecond print pulse followed by 21 milliseconds of cooling time. The only easily measured parameters which were useful in this area of development are energy required per pulse to achieve printing, and energy required to cause failure (burnout) at a given duty cycle. In this design a 10 mws pulse of energy is used to print and, at the maximum duty cycle of 16.7%, 15 mws of energy per pulse would be required to cause an element to fail.

It is interesting to note that unlike most other printing systems, thermal printing does not require more energy to go faster. This is because the inertias associated with mechanical printers have no thermal counterparts. The term "thermal inertia" is a widely used misnomer which can lead to faulty conclusions about heat flow. Printing has been achieved with pulse times as short as 150 microseconds.

The limiting factor in high speed operation is not therefore the energy required, but the maximum temperature which the elements can withstand. With constant energy required, shorter pulse time causes the input power (rate of energy) to be increased causing the maximum temperature to increase.

Since a thermal print element is composed of layers of different materials in a three dimensional configuration, an accurate mathematical model is difficult to construct. However, a simplified mathematical model has been constructed from the equations for the temperature of a semi-infinite solid with a single heat pulse applied at the surface and parallel heat flow, perpendicular to the heated surface.[2] A number of assumptions (which are now known to be not precisely correct) must be made to apply to these equations to simplify them; the resulting curve approximates the shape of the measured Temperature versus Time curve for a printing element (Figure 2). The model consists of two equations, one for the time while the print element is heating and one for the time while it is cooling.

$$T_H = \frac{CP\sqrt{t}}{A} \qquad (1)$$

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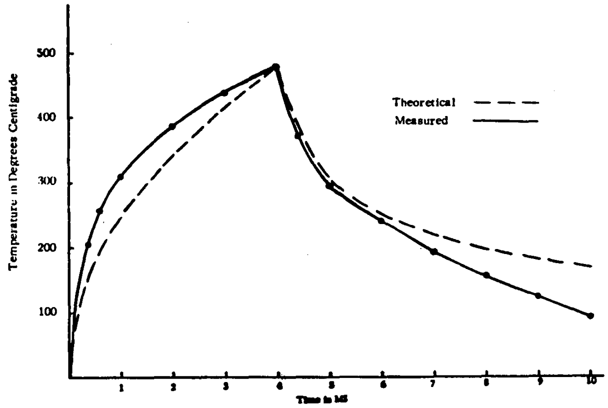

Figure 2—Thermal printing process

$$T_C = \frac{CP}{A} (\sqrt{t} - \sqrt{t - t_p}) \quad (2)$$

where T_H = Temperature while heating
P = Input Power
A = Area of Printing Surface
t = Time
C = Empirical constant
T_C = Temperature while cooling
t_p = Time of printing pulse

The vertical tangent at $t = 0$, in both the theoretical and measured time-temperature curves, graphically emphasizes that the previously discussed "thermal inertia" does not exist. In can also be seen from equation (2) that the rate of cooling is a function of the rate of heating. This feature, which has been confirmed experimentally, means that for high-speed applications where a short heating pulse is applied, cooling also occurs more rapidly.

Since the energy required for thermal printing remains nearly constant regardless of pulse width, this application was more severe in two respects. First, applying the same energy in a shorter time causes the element to be driven to a higher maximum temperature. Second, since the applied energy is the same but the cooling period is shorter, the energy must be carried away faster. The graph, referenced in Figure 3, shows the performance of the elements on a print wafer that was available when this program started. The "y" axis represents energy and the "x" axis represents the print elements. For each print element there is a circle representing the print energy and a triangle indicating the burnout energy. Three important aspects of the print elements should be observed on this graph. The first is that the variation of both the print and

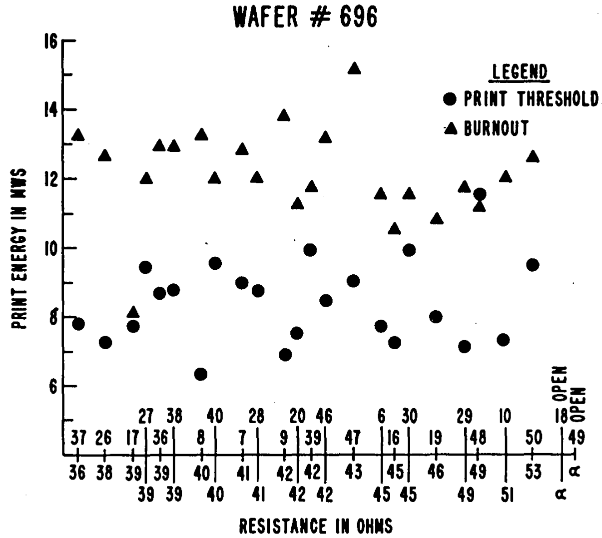

Figure 3—Print element temperatures vs time

the burnout energies are large. The second is that some of the print levels are higher than some burnout levels, indicating inadequate performance. The third is that some elements show adequate margin of safety between the print and burnout energies. Many changes in the print element were tried in an attempt to obtain a consistent, adequate margin of safety between the print and burnout energies. Finally a real breakthrough came. It was found that the thickness of the copper conductors on the wafers was a very important factor in obtaining high performance print elements. This makes sense since the copper conductors would be a major thermal conductor also. Using this knowledge it was also found that the dimension from the printing surface to the copper termination was also an important factor. By controlling and optimizing both these parameters it was possible to both reduce the variation in print and burnout energies and maintain a consistent high performance level. This is shown in Figure 4. Wafers having thse characteristics were used in the printer.

Although successful Thermal Printers have been produced, much work in the basic research areas needs to be done if the full potential of Thermal Printing is to be realized. Two of the more promising areas are:

(1) Refining the mathematical model to include the effects of paper and the copper leads; both of these are known to cause gross effects. Extend the model to handle the case where multiple heat pulses are applied.
(2) Testing thermal sensitive papers down to millisecond response time range to determine the limitations which the papers themselves may impose on the process.

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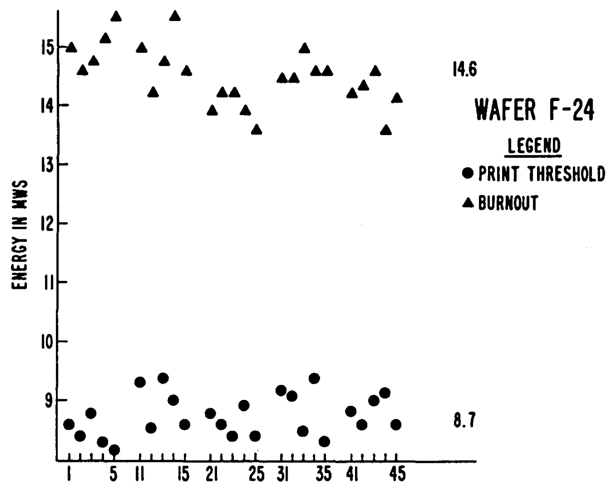

Figure 4—Early print wafer

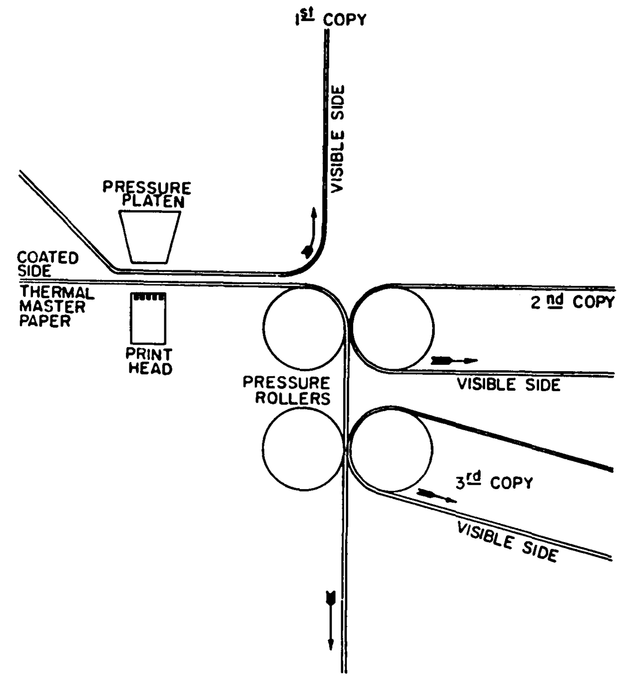

Figure 5—Improved print wafer

Multiple copy problem

The other major problem area was in making multiple copies. All previous thermal printers made only a single copy by contact with a heat-sensitive paper which changed color when and where it was heated. Therefore, a paper was used which had the particular property that it is sensitized by heat and makes copies by transfer under pressure. When the paper is heated by the print heads the back coating becomes tacky — not tacky to the touch but tackiness that will cause colored material to be transferred to plain paper when it is subjected to the fairly high pressures of the pressure platen and pressure rolls as shown in Figure 5. There are 300 to 400 pounds of pressure on these rolls in order to insure good copy. The tackiness remains for approximately 15 minutes so copies can be made during this time period. The paper must also retain enough of the colored material so that it will not all be released initially but can make a number of copies. A very desirable feature of this copy process is that only plain paper is needed to make copies thus reducing the operating cost. Three copies can be made in the printer and three more by a copy roll box which was also delivered with the printer.

Papers capable of producing up to 20 legible copies have been tested. Copies made in this manner will not smear with handling or fade due to time or temperature.

Although the single copy and multiple copy papers are functionally different, they can both be used on the High-Speed Thermal Teleprinter. Threshold temperature for both types can be altered to fit different applications. Normal threshold temperatures range from 125° F to 200° F.

Printer logic

This printer uses the thermal print heads to give a 5×5 matrix font in a full 80 character line arrangement as described previously.

Now that we have the print heads, let us discuss how the printer operates electronically to cause thermal printing. The block diagram shown in Figure 6 will aid us in this discussion. The printer receives the incoming data in serial form — a start bit, 7 bits in ASCII* format, a parity bit, and then a stop bit. This represents one character. In the Input Section, the digitizer converts the data to logic voltage levels and stores this information in parallel form in the receive register. It also checks the data bits to be sure that they are of odd parity and checks the stop bit to make sure that synchronization has been maintained over the character interval. After the stop pulse has been received, the contents of the receive register are loaded into the intermediate register to make room for the reception of another character. Next, the Control Section will shift the contents of the intermediate register into the print register. The contents of the print register are then decoded to determine the proper character to be printed. This character information is then sent

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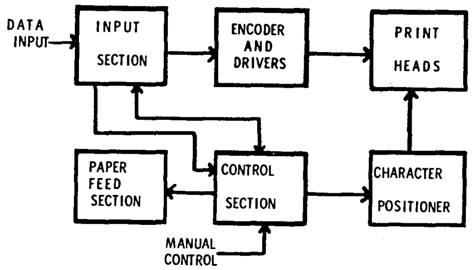

Figure 6—Printer block diagram

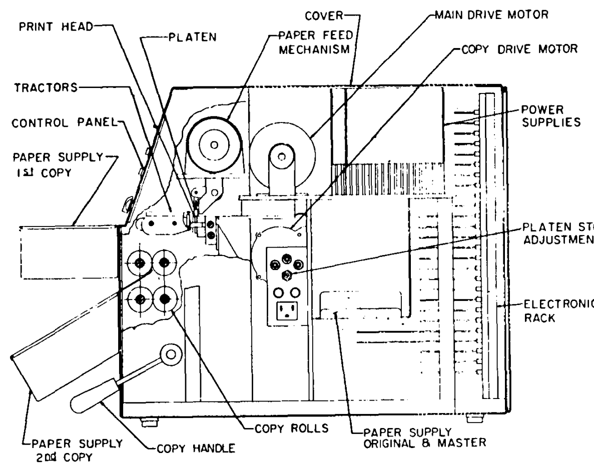

Figure 7—Printer layout

to the Encoder and Driver Section where encoding into the 5 × 5 font code is performed and the appropriate bit drivers are turned on so that the desired character will be printed. The position in which the character is printed is determined by the Character Positioner.

When the character has been printed, the character position counter in the Character Positioner will be upcounted. The outputs of the position counter are next fed into the character decoder which in turn selects the character driver which determines the position in which the character is to be printed. If the character received is a carriage return or line feed symbol, a line feed operation will be performed by cycling the clutch and brake circuit in the Paper Feed Section, and a carriage return operation will be performed by merely resetting the character position counter to zeros. Notice that no mechanical action is involved for a carriage return operation.

After several line feeds have been performed the copy paper tension switches in the Paper Feed Section will sense the slack in the paper and activate the copy roll gear motor which will drive the copy section.

Hardware

Now that we have discussed the operations of the printer, let us look at how the hardware for this printer fits together. A side view of the printer is shown in Figure 7. The location of the electronic circuits, power supplies, paper supply, paper feed mechanism, printing head, platen, copy section, and control panel is shown in this layout. It should be pointed out that all the logic in the machine is integrated circuits even though the design was started in 1964.

The way that the media is handled in this printer may copy roll gearmotor which will drive the copy section.

paper are stored together in a 2-ply fan-folded format with the folds on 5½ inch perforations. This media is sprocket fed one line at a time. As this media comes under the print head the master paper is on the bottom. To effect printing the platen is operated towards the media in order to obtain a firm contact between the print head and the media. This platen remains operated until a line feed character is received, then the platen is moved away from the media and the media is stepped one line to prepare for the next line of print. As a message is printed, the original copy moves up the front of the printer and this copy can be viewed through a window. The master copy goes down into the copy section where two more copies are made. If only the original copy is desired, the master copy can be routed directly out of the machine after producing the original copy. Then, if desired, the master paper can be used off-line with a copy roll box to make at least five more copies. A photograph of this printer is shown in Figure 8.

Other developments in thermal printing

Let us now talk briefly about other developments in thermal printing and possible applications.

Contrary to what many people think, the speed of thermal printing is relatively fast. A 150 microsecond current pulse has been found to cause printing although this speed of printing has not been thoroughly tested to date. But even forgetting about this 150 usec rate and taking the 4 msec rate of printing used in the High-Speed Thermal Teleprinter, we can show that thermal printing compares in speed with high-speed line printers .The present High-Speed Thermal Teleprinter prints serially by character so with the addition of multiple electronic circuits, this thermal printing technique

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Figure 8—High-speed thermal teleprinter

could be incorporated into a line printer configuration —printing each line of characters simultaneously. The speed calculation for such a printer is as follows:

Assuming a 4 msec print time and a 21 msec line feed time (which is within the state-of-the-art for line feed techniques and will also be equal to the cool down time for the print head) we have 4 msec + 21 msec = 25 msec per line. Therefore

$$\frac{1}{25\,\frac{\text{msec}}{\text{line}}} \times \frac{\text{msec}}{10^{-3}\text{sec}} \times \frac{60\text{sec}}{1\ \text{min}} = \frac{2400\ \text{lines}}{\text{minute}}$$

which is comparable with the speed of other type line printers of this size.

USAECOM has also sponsored a development of Miniaturized Techniques for Printing (MINIPRINT) with NCR. This is an exploratory development printer which prints at 15 characters/second, can be operated from a keyboard, and was developed for potential use as a self-contained, battery operated, tactical teleprinter. The package size of the present model (cigar-box size) may also contain all the required electronics. The printing is immediately visible on new thermal sensitive master paper. The master and first copy are made simultaneously in this printer and at least ten legible copies can be obtained using the master copy and plain paper in an off-line pressure device.

CONCLUSION

The Thermal Printer can print data received at any mixed rate of input — including input from a keyboard. The rate of input has been tried and tested at rates as high as 240 characters/sec which is certainly not the upper limit. Since we also get an electronic, non-impact printer which appears to be very reliable and can produce multiple copies on plain paper, thermal printing may have potential application in many systems — both communications systems and automatic data processing systems.

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