The National Cash Register High-Speed Magnetic Printer

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I. INTRODUCTION

THE magnetic printer is designed to operate in conjunction with an electronic data processing system. It operates on the principle of recording a latent magnetic image on a special paper, which is essentially magnetic tape with a white topcoat. The image is in the form of an alphanumeric (or other) character which is subsequently made visible by exposure to a ferromagnetic powder attracted to the magnetized portions of the paper. The powder is coated with a thermoplastic resin and requires a heating operation to fix it to the paper. An example of the print is illustrated in Fig. 1.

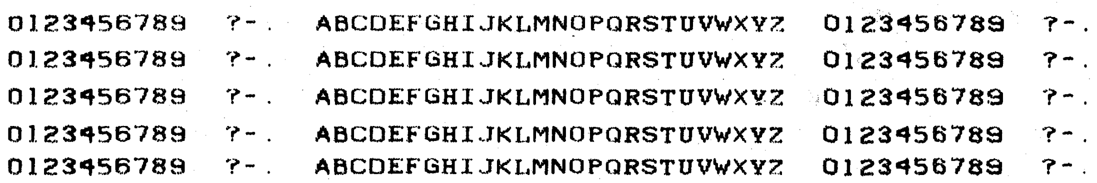

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Fig. 1—Sample of print.

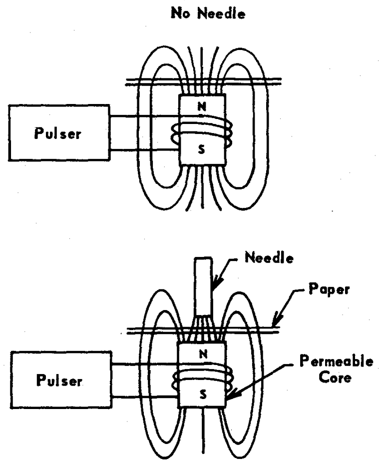

Fig. 2—Effect of permeable needle on field strength.

II. PRINCIPLES OF OPERATION

Printing is accomplished by utilizing the fact that a weak diffuse field will not magnetize the paper while a strong concentrated one will. Field concentration is obtained, as illustrated in Fig. 2, by placing a permeable needle directly above the area which is to be printed. Print may then be made visible by exposing the area to a black permeable powder.

Dynamic operation of the printer is illustrated in Fig. 3. The magnetic field is established by a coil wound around a permeable bar. It is energized with pulses of a length directly proportional to the length of vertical scan to be recorded. Illustrated is a three-by (three vertical needle sweeps per letter) format where the letter T is formed by pulsing the bar when needle 1 passes over the top area, while needle 2 is traversing the entire bar, and when needle 3 passes over the top area. The needles are arranged in the form of a helix on a drum rotating over the bar and are spaced so that only one needle is within the field of the bar at any one time.

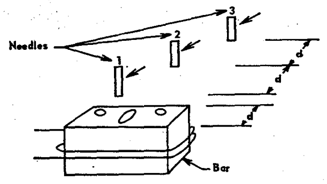

Fig. 3—Three-by system.

A completed breadboard of the magnetic printer (Figs. 4-6) consists of a spiral track of needles arranged around the surface of a drum. Directly over the drum supported by a fixture, is a permeable bar. The magnetic field which places the latent image on the paper is established between the needle points and the bar. During the time that a particular needle point is passing under the bar, a magnetic flux path is established between the needle and bar only when the coil is energized. Seven vertical scans are allotted for each character (seven-by system). The scan (bar) is energized for the full height of a given character (width of bar) if a full vertical line is to be recorded for that portion of the character, or the scan is energized for only a portion of the time as needed.

As an example, consider the formation of the letter L.

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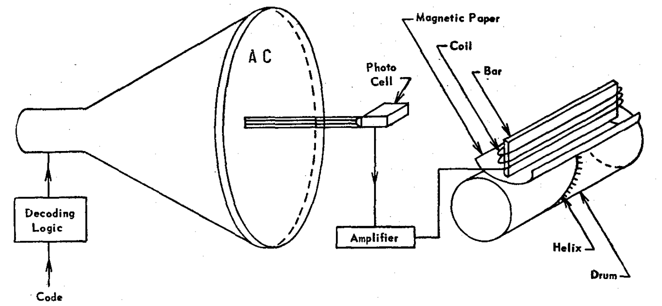

Fig. 4—Block diagram of magnetic printer system.

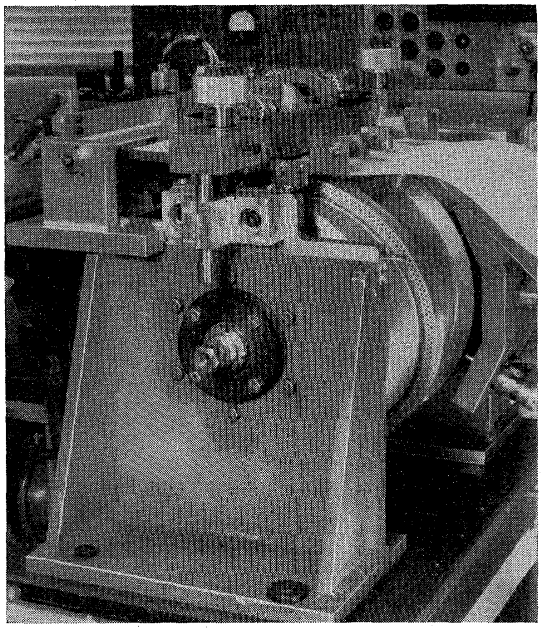

Fig. 5—Close-up view of the drum, bar, and paper.

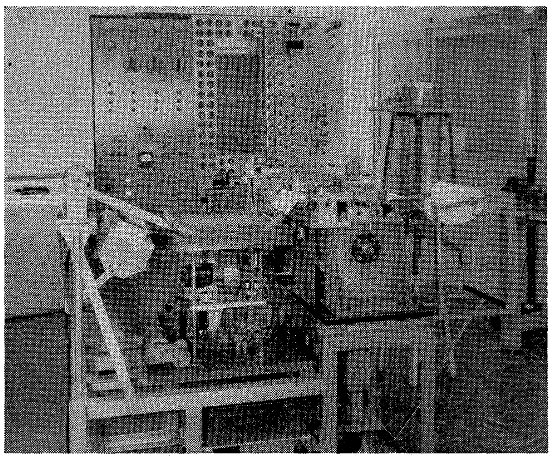

Fig. 6—Breadboard model of magnetic printer.

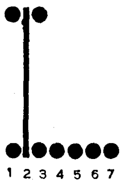

Fig. 7—The letter L.

The second scan is a full height scan, whereas the other six are energized for only portions of each pass over the bar. The resulting image appears in Fig. 7.

The encoder which has been utilized in conjunction with the printer is a cathode-ray-tube device. Over the face of the CRT is placed a photonegative mask which has on it all of the characters which are to be used in the printer (60 or more). The mask is easily replaceable with other sets of characters or symbols. In back of the mask is a photocell which converts the light energy from the phosphor on the face of the CRT to electrical pulses. When a character is to be printed,[1] the binary coded representation of the character enters the electronic input circuitry of the printer. A decoding matrix then directs the horizontal and vertical deflection plates of the CRT to a certain portion of the face of the tube, this point being at one corner of the character (on the mask) which is to be scanned. The CRT beam then scans the character in seven sequential vertical sweeps in synchronism with the passage of the seven needles past the bar in the printer. The photocell senses the beam when it illuminates the transparent portions of the mask. In like manner, when the light energy is interrupted by the opaque portions of the mask, the photocell lies dormant. The electrical signals from the photocell are amplified and converted into current pulses for the coil and magnetic field pulses from the bar. This CRT encoder has been utilized for some time and has proven very reliable. Various other types of encoders, such as a magnetic core matrix are feasible and would probably be less expensive.

As the drum rotates over the bar, a full line of characters can be printed. Since the width of the helix depends upon the diameter of the drum for a given letter size, one can design either a large drum to scan 120 characters per revolution or a smaller drum to scan 40 characters per revolution with three spirals (each with an independently pulsed bar) wound on its surface. To achieve equal speeds, the smaller drum would have to rotate three times as fast. The present system scans 40 characters per revolution and 80 characters per line at a speed of 1200 characters per second or 15 lines per second. Higher speeds than this have not been attained with the present breadboard due to mechanical vibrations set up upon rotating the drum at high speeds. There is no reason to assume that increases in speed by at least a factor of ten cannot be attained with better drum design.

The paper that is used is formed by a series of layers:

1) Base kraft paper.

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[1] Along the edge of the drum is placed a magnetic layer. On this layer are placed pulses in line with the first needle for a revolution, each needle beginning a character, and each needle on the drum. Three separate reading heads are utilized. Thus the printer can "signal" the encoder or paper feed when a line begins, when a character begins, or when the needle begins scanning the bar.

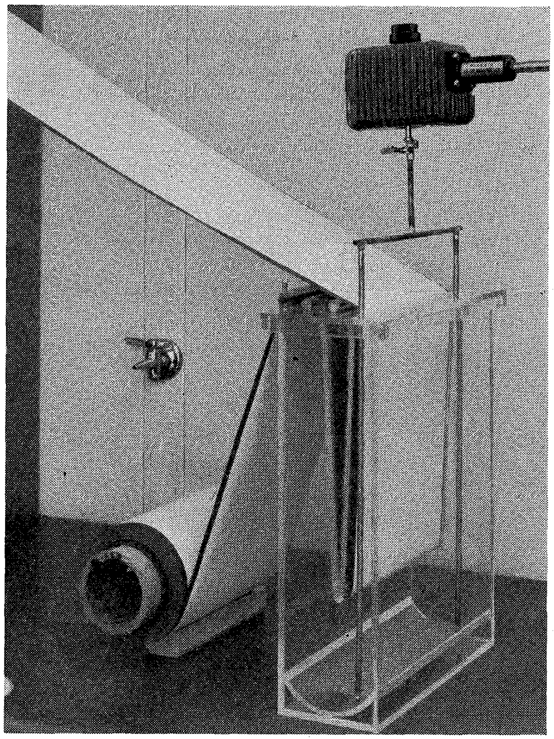


Fig. 8—Experimental working model of a liquid inking chamber.

2) Magnetic oxide layer (can be permanently magnetized).
3) White topcoat.
   a) Forms a contrasting surface for the black ink.
   b) Forms a multilith surface.

The printer produces only one copy at the time of printing. However, since the paper contains a multilith topcoat, it can be utilized to make any number of copies at a later time by a simple multilith operation.

Inking is accomplished by passing the paper through a liquid (Freon-113) suspension of iron particles (mapico black coated with resin) which is in a state of rapid agitation. This operation can be accomplished with the apparatus illustrated in Fig. 8 at speeds greater than 15 lines per second. For off-line operation a continuous feedthrough would be utilized. For on-line operation, since it is not desirable that the paper stop for any length of time in the inking solution (overinking would occur), a take-up reel would be utilized so that the paper would be passed through the inker in long passes (10 feet or more). As soon as a pass through the inker was completed the paper would stop, the agitation would stop, and therefore further inking would cease. When another ten feet of paper built up, the printer would signal the agitator to begin again and another ten feet of paper would be inked.

III. Design Parameters and Experimental Results

A. Needles

1. Needle Permeability: The flux density, B_n, concentrated in the needle is a measure of the print quality that can be obtained since it is directly proportional to the field magnetizing the paper. A certain minimum B_n is necessary as a print threshold, and as high a value as possible should be obtained consistent with the other variables. Since $B_n \approx \mu_n$ (needle permeability) H_B (field due to bar), it can be seen that keeping all other parameters constant, the higher μ_n is, the higher B_n will be. The effective permeability μ', is not only a function of the material utilized but also of the length to diameter ratio of the needle. The graph in Fig. 9 illustrates how important this ratio is.[2]

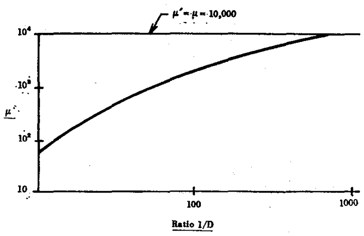


Fig. 9—Effect of length to diameter ratio of needle on effective permeability.

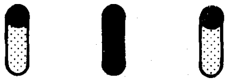


Fig. 10—Needle retentivity and trailing.

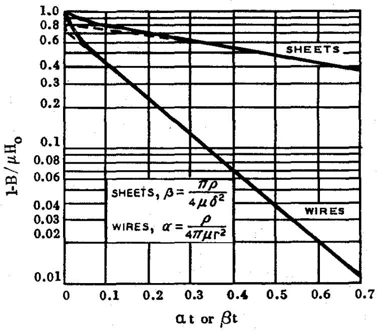


Fig. 11—Build-up of flux in wires and sheets subjected to sudden constant field.

If the needle utilized has "hard" magnetic characteristics (permanent magnet properties), and retains part of its field after being pulsed, it will continue to print in a weaker fashion if this field is above the threshold value of B_n. To eliminate this "trailing" effect, "soft" magnetic materials should be used. For example, if trailing occurs, the letter T would look as shown in Fig. 10.

2. Needle Response Time: In te megacycle region, the needle response time will be primarily dependent upon eddy current effects. These effects are in turn functions of permeability, resistivity, and geometry. The graph[3] in Fig. 11 illustrates the effects of these variables for wires (needles).

[2] R. M. Bozorth, "Ferromagnetism," D. Van Nostrand Co., Inc., New York, N.Y., p. 848; 1951.
[3] *Ibid.*, p. 784.

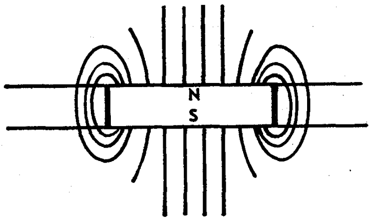


Fig. 12—Field distribution for magnetized paper area.

The larger the resistivity, and the smaller the diameter and permeability, the quicker will be the rise time of the needle. The same general argument will apply to the decay of the fields. An example follows:

$$H = 0, \qquad t = 0$$

$$H = H_n, \qquad t \geqq 0$$

Needle — mu-metal ($\mu \approx 4 \times 10^4$).

Let $1 - \dfrac{B_n}{\mu H_B} = 0.1$ (*i.e.*, 90 per cent of rise is attained)

$$\alpha t = 0.35.$$

Case I:

$$r = 0.005 \text{ inch}$$

$$t = 0.44\ \mu\text{sec.}$$

Case II:

$$r = 0.060 \text{ inch}$$

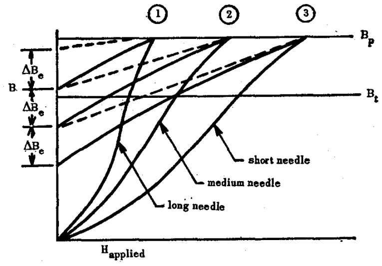
$$t = 66\ \mu\text{sec.}$$

If the needle response time is too slow, a transient "trailing" effect analogous to permanent retentivity will be present.

3. Needle Shape: Fig. 12 is a lateral view of a piece of magnetic paper containing a pulsed portion. The area which will most attract the permeable powder is that portion exhibiting maximum field strength. It is apparent that this will occur not at the center of a pulse, but at the edges, where a short return path for the magnetic flux is available. Print density from a large needle will suffer by having central unprinted areas, while a very small needle will have lesser area coverage on the paper. The effect of powder diameter should be appreciable as the particle size approaches printed area dimensions.

4. Effect of Needle Length: Curves 1, 2, and 3 of Fig. 13 illustrate the general behavior to be expected of the hysteresis curves as needle length is shortened while diameter is kept constant. The heavy lines depict the static magnetization-demagnetization curve while the dotted line indicates the mode of demagnetization in a dynamic (high frequency) case. After a short period of time, B will drop to the normal static case.

a) The needle of Curve 1 will exhibit strong "transient retentivity and also permanent retentivity which will cause light print to appear on the paper even if the bar is not being pulsed.
b) Needle 2 will exhibit weak "transient" trailing and no permanent retentivity.
c) Needle 3 should show no "transient" trailing or permanent retentivity.



B_t = Threshold flux density at which print just becomes visible on paper.
B_p = Flux density needed for dense printing.
ΔB_e = Transient flux density remaining after each pulse due to eddy currents.

Fig. 13—Effect of nedle length on hysterisis characteristics.

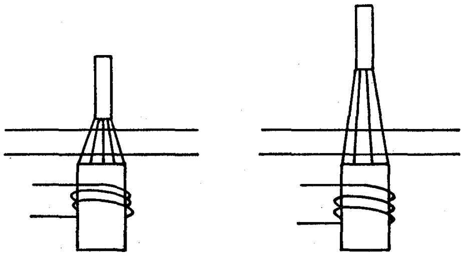


Fig. 14—Paper field definition and concentration as a function of paper-needle distance.

These effects were all demonstrated by experiment, and strong printing with no trailing was obtained with soft iron, piano wire, and mu-metal of 0.10 and 0.05 inch in length.

5. Needle Distance from Paper: As the needle is moved away from the paper surface, a marked diminishing of field strength and definition is apparent (see Fig. 14). Thus, optimum printing conditions will be present when the needle is as close as possible to the paper surface.

6. Overlap of Needle Fields: In a three or multiple-by system depicted in Fig. 3, it is possible for the fields of successive needles to cancel each other if they overlap. Fig. 15 shows what proper and improper needle spacing can do in a two-by system.

7. Needle Pulsing: Six mu-metal needles were wound with twenty-five turns of wire each and connected in series through a commutator so that the pulses received were the same that were ordinarily fed to the bar (see Fig. 16). Experiments were conducted to determine the effect of:

a) Needle pulsing alone.
b) Needle and bar pulsing with same and opposite polarities.

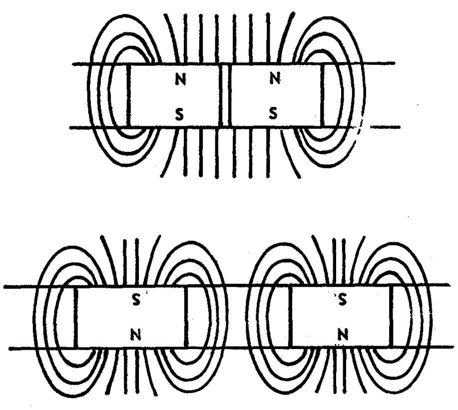


Fig. 15—Paper field patterns as affected by needle overlap. (a) Improper. (b) Proper.

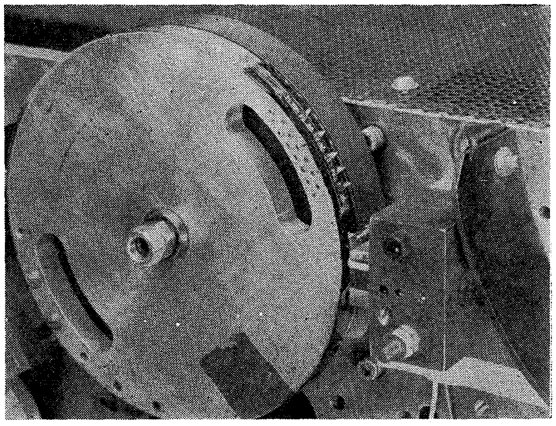


Fig. 16—Close-up of needle pulsing equipment.

c) Needle pulsing in the presence of a nonmagnetic (lucite) bar.

All results were positive but it was felt that the slight improvement in print quality did not warrant the extra trouble inherent in mechanizing the commutator system.

The purpose of this experiment was to determine whether the directed field emanating from the needle point itself, instead of the bar, would improve definition of print. Very little improvement resulted.

8. Needle Materials Tested: The following materials (available in needle form) were tested to determine optimum results with respect to permeability, retentivity, and response time:

a) Welding rod (commercial grade)
b) Piano wire
c) Phonograph needles
d) Ferrite
e) Mu-metal
f) Laminated mu-metal
g) Pure iron wire (reagent grade)
h) Pressed powered carbonyl iron (GQ-4).

The best over-all characteristics were obtained with mu-metal which exhibits high permeability (response at low field strengths), low permanent retentivity (no permanent trailing), and fair eddy current lowering (slight "transient" trailing found at high field strengths). Transient trailing (eddy current effects) is apparent with all needles at high field strengths, but decreasing the length to diameter ratio of the needle almost completely eliminates this effect.

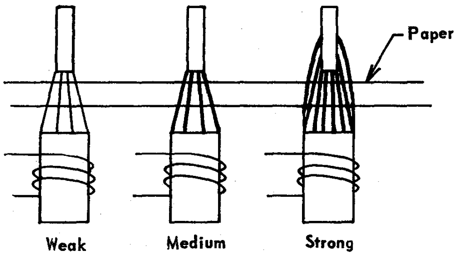


Fig. 17—Effect of bar field on paper field concentration and definition.

As a result of these experiments and analysis of design parameters, the needles utilized in the printer were fabricated of short (50-mil length, 7-mil diameter) pieces of mu-metal wire. The wire was then mounted in nonmagnetic stainless steel cylinders (60-mil outside diameters with a 7-mil hole drilled down the center) to give rigidity and to keep the wires away from the surface of the aluminum drum. The cylinders had no noticeable effect upon the print quality.

B. Bar

1. Field Strength of Bar: Weak bar fields will cause no print at all until the threshold of B_n is exceeded. Very strong fields will cause printing over a wide area with loss of definition, even though field strength is increased. An optimum field strength exists (see Fig. 17).

The effect of varying the current through the bar from 0.5 amp to 3.0 amp is illustrated by Fig. 18, next page.

2. Effect of Stray Field from the Bar: Because of stray field from the bar, weak print may appear both above and below the desired line unless special precautions are taken. This effect was substantially decreased by winding the bar up to its very tip, thus effectively directing the field in the desired direction. Fig. 19 illustrates the two cases.

3. Bar Distance from Paper: Since $B_n \approx \mu H_B$, and since H_B does not vary much with small distances from the bar, one would expect approximately the same definition of field in the two cases. Gradual diminishing of field strength as the bar is moved from the paper should also occur (see Fig. 20).

4. Electronic Response Time and Bar Permeability: The rise time of the electronic circuitry pulsing the bar should be kept to a minimum. Besides being a function of various circuit parameters, the electronic rise time is markedly affected by the L/R ratio of the pulsing coil. The number

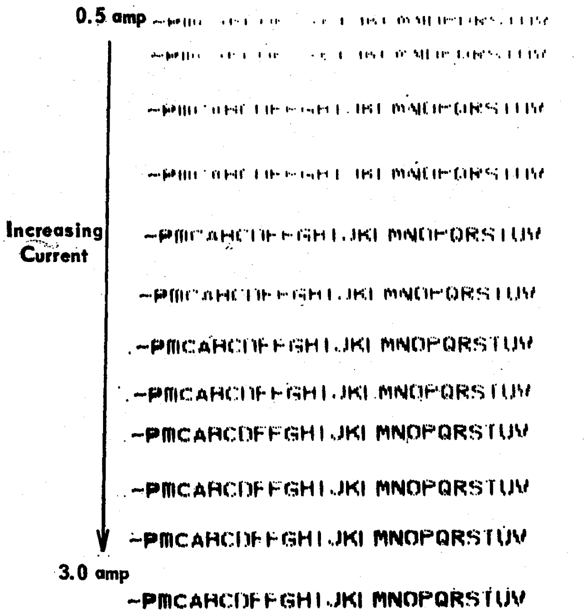


Fig. 18—Effect of bar current.

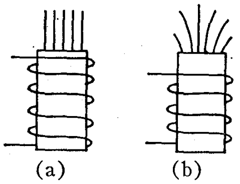


Fig. 19—Bar field. (a) Properly wound. (b) Improperly wound.

of turns about the bar should be made an optimum with respect to print quality, since not only rise time but H_B is a direct function of the inductance of the coil. To obtain a given H_B, (or a given number of ampere-turns) the current should be maximized consistent with other variables and the number of turns held to a minimum. Bar permeability should be as large as possible to minimize number of ampere turns necessary.

5. Bar Response Time: The magnetic response time of the bar lags behind the pure electronic response, and, if too slow, may cause transient "trailing" of the same type as in Section III-A, 2 (needle eddy-currents).

6. Bar Retentivity: As long as the retentivity $(H_B)_{\text{ret}}$ is below the threshold value for printing, this may aid somewhat in acting as a "bias." Instead of pulsing the bar from $H_B = 0$ to $H_B > (H_B)_{\text{threshold}}$, one may decrease the eddy currents by pulsing from $(H_B)_{\text{ret}}$ to $H_B > (H_B)_{\text{threshold}}$. The same type of analysis would apply to needle retentivity.

7. Bar Material: Bars constructed of the following materials were tested:

a) Ferrite
b) Mu-metal
c) Laminated mu-metal

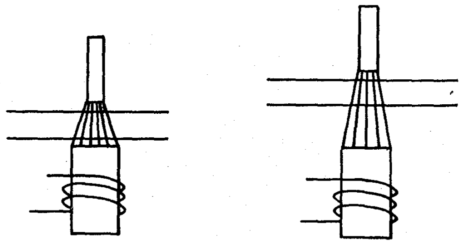


Fig. 20—Paper field concentration as a function of paper-bar distance.

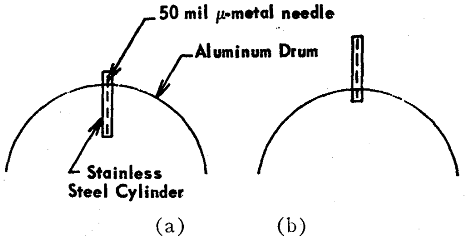


Fig. 21—Effect of drum mass. (a) Poor print. (b) Good print.

d) Pressed carbonyl iron (all types)
e) Cold rolled steel.

Good print was attained with all bars tested, but ferrite gave consistently better results. At present speeds, ferrite gives acceptable results (as do the others). At higher speeds, on the order of 10,000 characters per second, further experimentation may be necessary to provide a high enough response time.

The final bar utilized in the printer was 0.1 inch wide, 0.875 inch high, and 8 inches long. 100 turns of wire were wound in four layers of 25 turns each, concentrated on the upper 3/8 inch of the bar (to keep the field well defined). Continuous runs were not made, but it is anticipated that heat effects with concomitant insulation breakdown of the wire will occur under these conditions if precautions are not taken. Magnet wire with high temperature characteristics will be necessary.

C. Drum

The large mass and high electrical conductivity of the aluminum drum used in the prototype magnetic printer are the cause of *large* eddy current effects, so that it has been found necessary to mount the mu-metal needles as far from the drum surface as possible with present equipment. No print at all was obtained when the needles were at the surface of the drum, while marked improvement was obtained by moving the needles away from the drum surface as indicated in Fig. 21.

Other approaches which would eliminate this effect are:

1) Fabrication of a nonconductive drum.
2) Coating the aluminum drum with a nonconductive layer at least two inches thick.

D. Aluminum Paper Guides

Fig. 22 illustrates the geometrical configuration of paper guides, bar, needles, and paper; Fig. 23, the print obtained from this system.

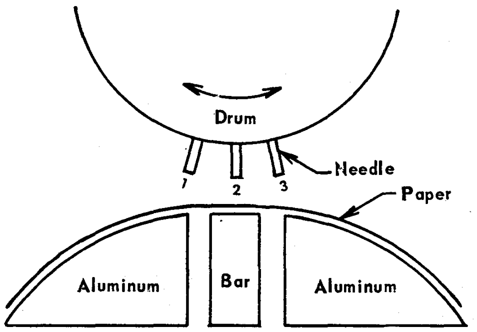


Fig. 22—Effect of paper guides.

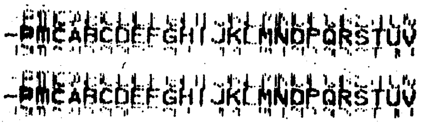


Fig. 23—Print with paper guides.

While needle 2 of Fig. 22 is pulsing, needles 1 and 3 are so close to the paper surface that the stray field from the bar causes weak print to appear both above and below the desired line. Letters below are displaced one needle to the left and those above, one needle to the right.

For example, while needle 2 is tracing out the center scan of the letter T, needle 1, which is displaced to the left and which is beneath the line, is tracing the same scan. Needle 3 is doing the same thing above the line and displaced one to the right.

A slight amount of retentivity is also apparent. This is attributed to the presence of the high conductivity aluminum guides with consequent eddy currents. These two effects were eliminated by utilizing the following system illustrated in Figs. 24 and 25.

By causing the paper to be bent sharply over the end of the bar, it is possible to eliminate the effect of the adjacent needles, since print threshold is very sensitive to distance of the needles from the paper. The lines seen above and below the print are due to an "edge effect" of the bar. Extra strong lines of force emanate from this region and the effect was easily eliminated by placing a 5-mil mylar shim over the bar surface. This sufficiently lowered the field of the edge to a value below the print threshold but did not substantially lower the over-all field strength.

E. Paper

1. Paper Response Time: Since the magnetic layer in the paper is composed of finely powdered ferrite particles, with consequent minor eddy-current problems, it is probable that the paper response time is appreciably faster than that of the bar and needles.

2. Paper Magnetic Fields: In order to most strongly attract the printing ink (fine magnetic powders), the magnetic particles in the paper should have characteristics of maximum retentivity.

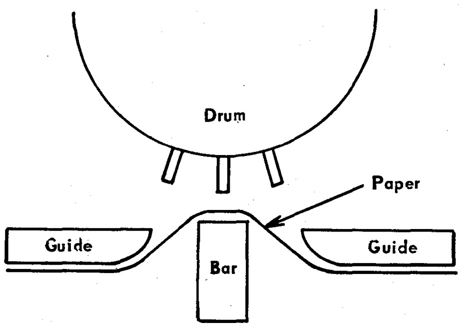


Fig. 24—New guide system.

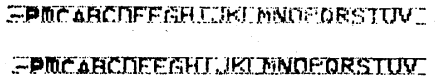


Fig. 25—Print with new guide system.

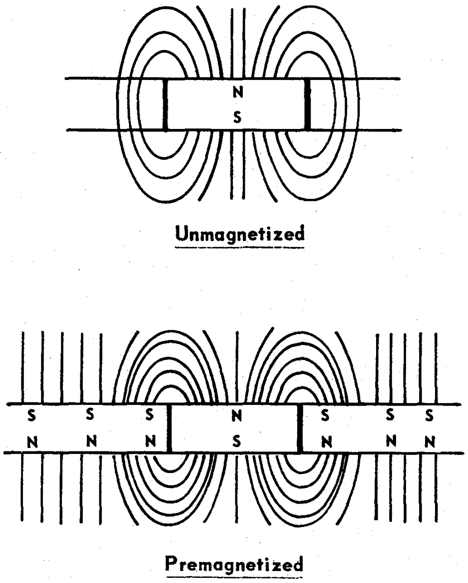


Fig. 26—Paper field patterns as affected by premagnetization.

3. Paper Orientation and Magnetization: Since the ferrite particles in the magnetic layer are asymmetric, they should be oriented during manufacture so that the axis of maximum permeability lies in the direction of the field which is to be applied (*i.e.,* perpendicular to the plane of the paper).

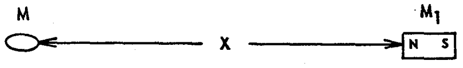
Premagnetizing the paper in a direction opposite to that of the applied field should enhance printing density by shortening the flux return path (see Fig. 26).

F. Inking

1. Liquid Inking: Investigations determined that inking in a liquid medium did not have to be conducted under static conditions. Agitation by a Fisher Vibrastirrer yields greatly improved results. Movement of paper through the liquid medium does not cause smearing or other deleterious effects on print quality. An experimental inking chamber is illustrated in Fig. 8.

2. Gas Phase (Dust) Inking: All experimentation in this area yielded poor results with a large amount of background inking. There is also a serious danger of explosion when utilizing small iron particles in a system where static charges can be built up.

3. Inks and Field Attraction: If an unmagnetized particle is brought into the field of a permanent magnet, the force of attraction is as follows.[4] (See Fig. 27.)



$$F(\text{attraction}) = \frac{6MM_1}{X^4}$$

where
M = induced magnetic
M_1 = permanent magnet

Fig. 27—Attraction of permeable particle by a magnetic field.

The larger the permeability of the particle, the larger are M and the attractive force. At the same time it is desired to minimize the X^4 term by using fine particles to allow a minimum distance of approach. Thus, since fine particles have lowered permeabilities,[5] an optimum ink particle size must be experimentally determined in order to maximize (F/mass) of the particle.

Particle shapes and interactions with surrounding fluids will influence the rate and density of deposition upon a magnetized paper surface. Maximum covering power per particle is also desirable for best printing contrast.

4. Solvents: Freon-113 is an excellent dispersing agent because it has the following properties:

a) Volatile
b) Nontoxic
c) Noninflammable
d) Nonviscous.

IV. PRESENT CHARACTERISTICS AND FUTURE CAPABILITIES

The present characteristics and future capabilities are listed below.

1) Speed—1-2000 characters per second at present: 20-50,000 characters per second ultimately.
2) Type face—External and replaceable fonts of 64 or more characters each; unlimited number and kind of characters are available with the restriction that they must fall within the space usually reserved for capital letters.
3) Legibility—Comparable to typewriter print.
4) Noiseless—Except for paper feed.
5) Low maintenance—No mechanical moving parts except rotating drum. No breakdown due to solenoids and moving hammers, no wear of type face, no ribbon debris.
6) Serial operation—No line buffer necessarily needed. Continuous (nonintermittent) off-line paper feed possible.
7) Copies—Unlimited number available from a multilith master which is printed directly. Only one copy immediately available unless printing is conducted in tandem.
8) Immediate visibility—Not available: lag of ten feet of paper if used for on-line operation with take-up reel; about two feet for off-line operation with steady travel through inker.
9) Character size—Present machine has ten characters per inch, each 0.1 inch high, width of printing line 80 characters. All of these parameters can be easily varied.

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[4] *Ibid.*, p. 729.
[5] *Ibid.*, p. 45.