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MAGNETIC PARTICLES DISPLAY MATRIX-ADDRESS DEMONSTRATOR.(U)
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MAGNETIC PARTICLES DISPLAY
MATRIX-ADDRESS DEMONSTRATOR

CONTRACT #06951

PURCHASE #N62269-76-M-4305

REPORT #NADC-76278-30

JANUARY 7, 1977

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LAWRENCE L. LEE

MAGNAVOX GOVERNMENT AND INDUSTRICAL ELECTRONICS COMPANY

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A flat panel display has been fabricated using spherical magnetic particles sandwiched between two transparent glass plates. The particles are each half white and half black corresponding to opposite magnetic poles. A 10 by 15 electromagnetic element matrix has been fabricated to address the display. After uniform magnetization of the matrix elements, the polarity of elements is reversed with current supplied through microswitches closed by a punched card. The display plate placed over the matrix will display alpha-numerics in

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20. ABSTRACT (Continued)

accordance with the program punched into the card. The alpha-numerics can be displayed either as white on a black background or a black on a white background.

The purpose of this research is to demonstrate the matrix-addressability of the magnetic particles display. The idea for the magnetic particles display was introduced in an earlier publication (1). The method suggested in (1) for matrix-addressing makes use of a threshold in the demagnetization of ferromagnetic materials with hysteresis. The display's memory is made of such a material. When magnetized in one direction, the memory can resist demagnetization by magnetic fields below a certain threshold. Stronger fields may cause the direction of magnetization to be reversed. The currents through the addressing wires is designed to generate a reverse magnetic field below the threshold everywhere except at the intersection where the combined field strength would exceed the threshold and the magnetization locally reversed. There the display will show a light spot against a dark background (or vice-versa).

Considering the low sensitivity of the magnetic particles currently available, fairly strong magnets are needed for the memory. "Cunife" happens to be one of the materials with remanent magnetization in approximately the right range. A 10 x 15 matrix is constructed. The addressing wires are wound around each row and each column 5½ times so that lower currents may be used. For simplicity in construction, a bank of microswitches is used to control the addressing. And for convenience in demonstrating the display, program cards are used to control the microswitches.

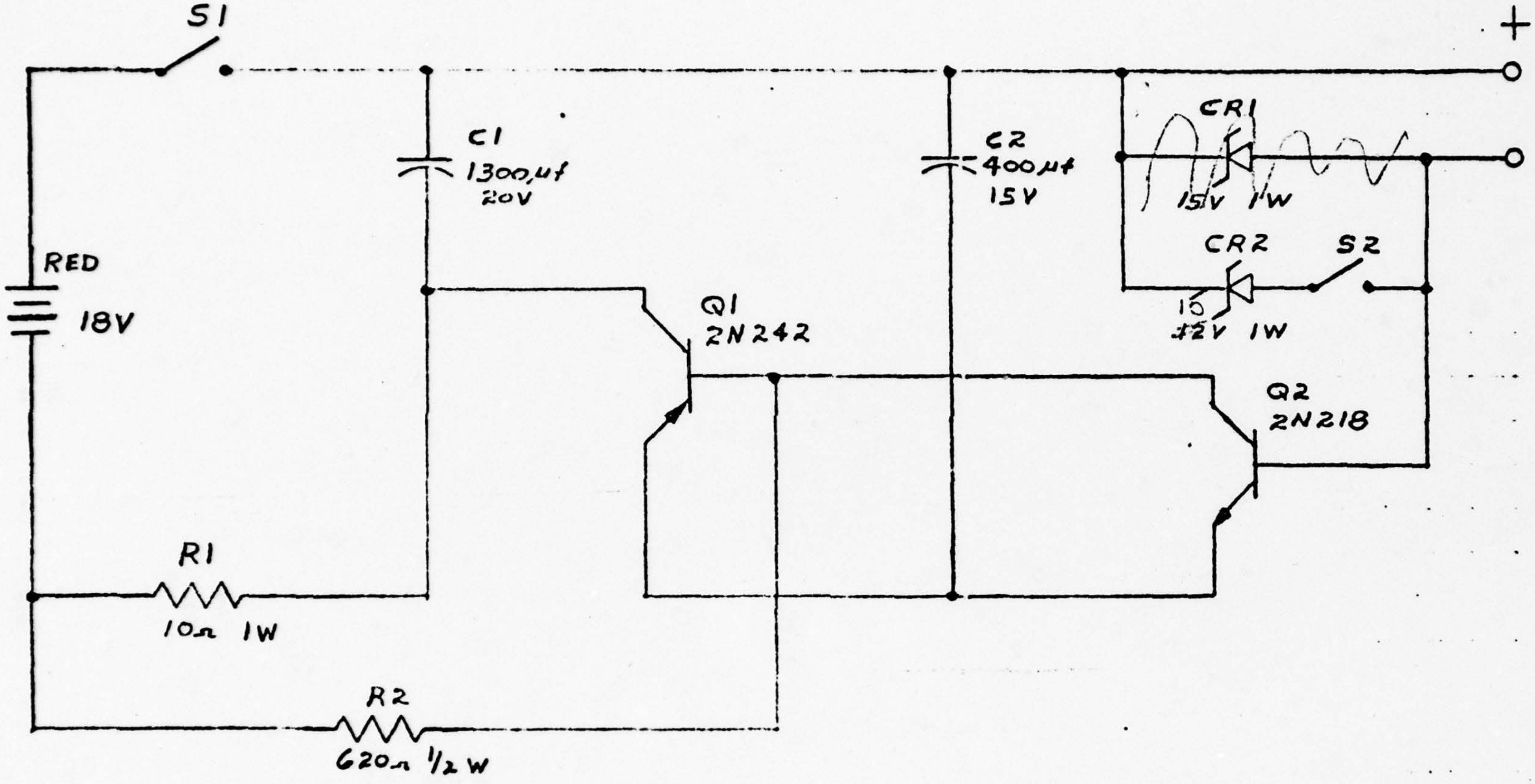
The memory is prepared for matrix-addressing by first being magnetized uniformly in one direction. This is accomplished by passing the "eraser" magnet over the display's surface. Then the program card is slid over the bank of microswitches. Each row of holes in the program card addresses a spot on the display be sending a pulse of current through the loops around the row and column corresponding to the addressed spot. Any pattern can be written into the display by using the appropriate program card; and the spots can be entered in any desired order. The display can be disconnected from the control unit to demonstrate the nonvolatility of the memory.

(1) A Magnetic Particles Display

by

Lawrence L. Lee

The Magnavox Co.
Fort Wayne, IN.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C2
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CR2
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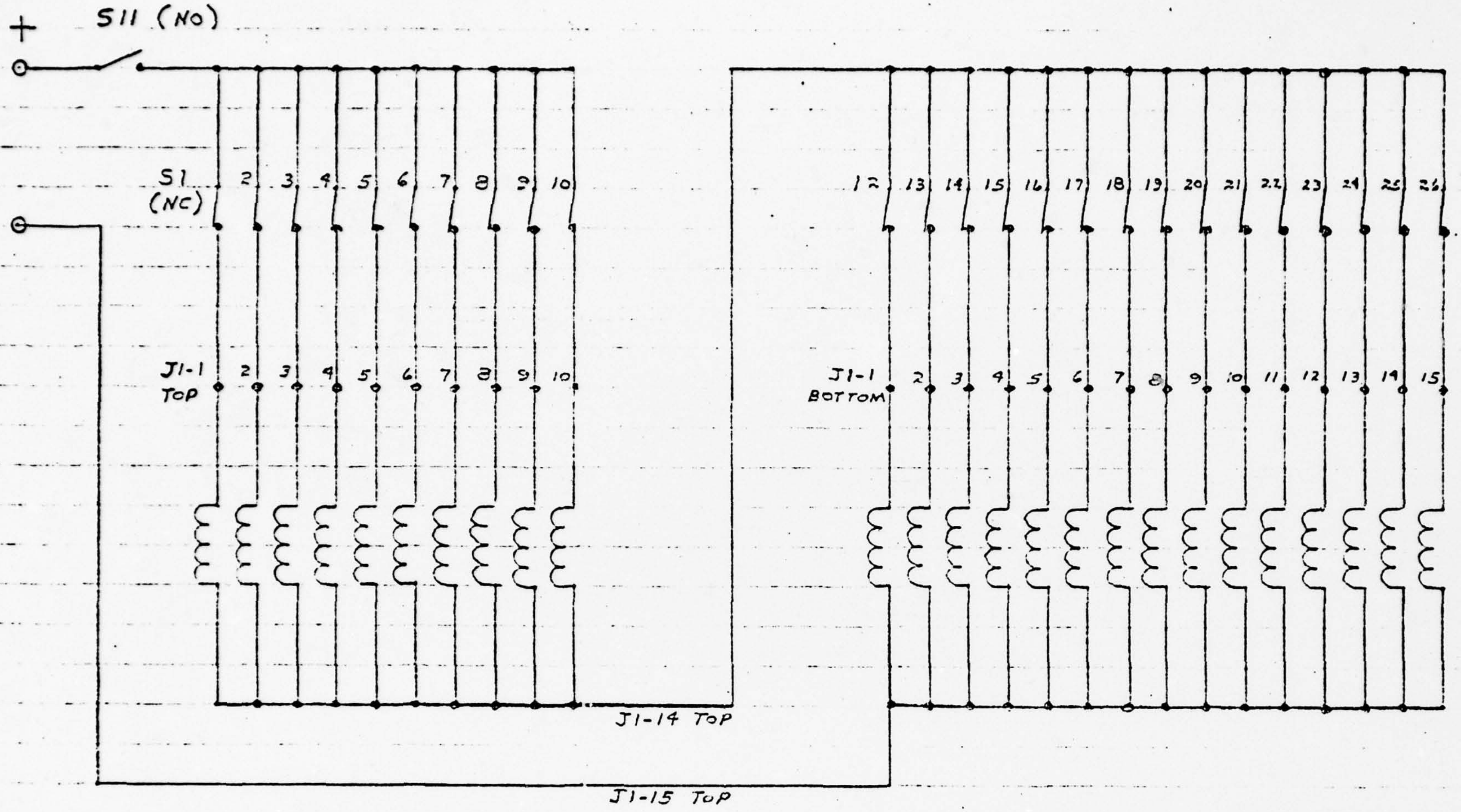
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J1-1
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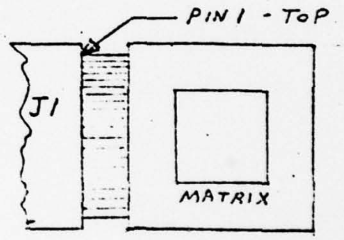
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MATRIX

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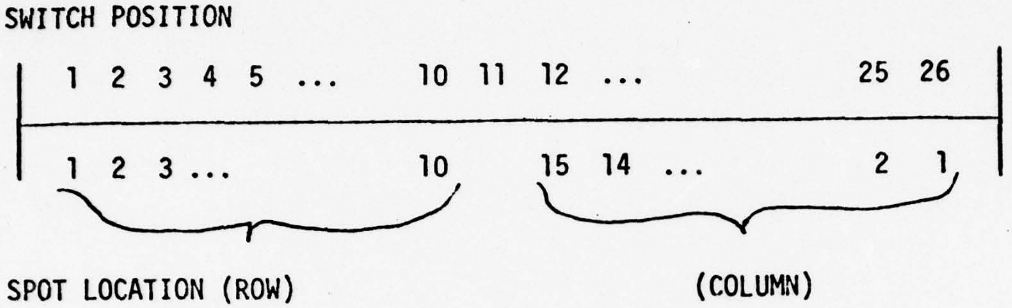
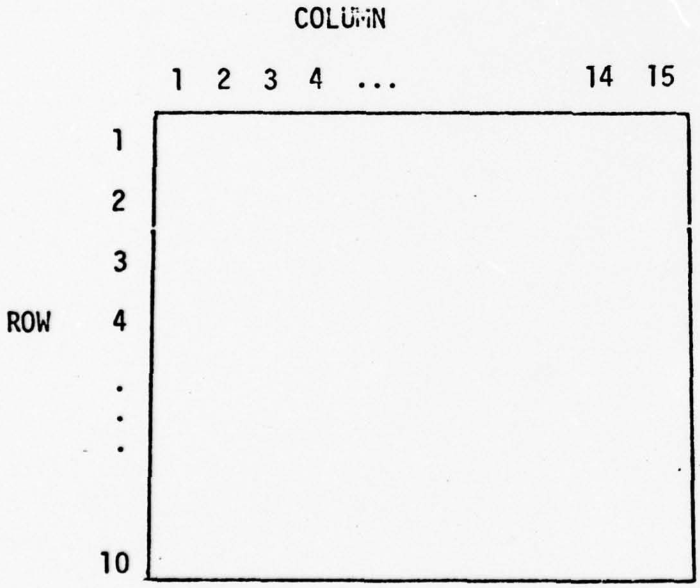
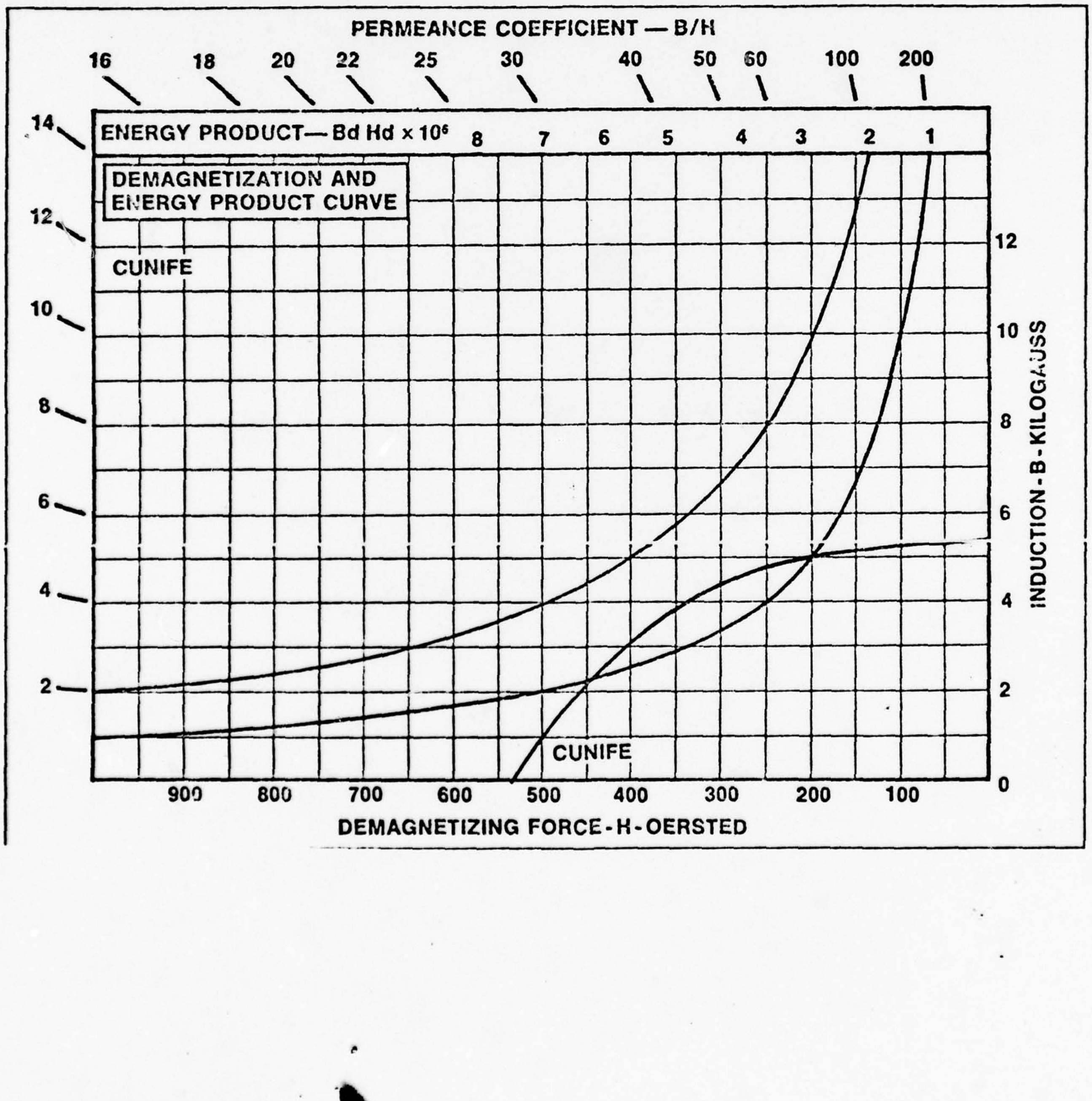




Demagnetization Curves for CUNIFE

cunife



A Magnetic Particles Display

by

Lawrence L. Lee

The Magnavox Co.
Fort Wayne, IN.

Abstract

A new type of flat-panel ambient-illuminated display is described. Images in this display are formed by magnetically controlling the orientations of small spherical multicolored magnetic particles. A demonstration model is shown and the possibility for application to television is studied. It is estimated that for a 9 cm by 12 cm black-and-white screen with built-in magnetic memory and 500 by 500 sequential matrix addressing, the display panel can be driven at TV rates with an average current of 0.27 A and dissipation of 0.26 watt. Contrast ratios up to 40:1 seem achievable with continuously variable greys. The display also features a nonvolatile memory which can be very desirable for some applications. Methods for fabricating this display are also discussed.

Introduction

There has been much recent interest in flat-panel displays. Several varieties are in existence. (1) Some have found applications as read-outs for watches, calculators, and other electronic instruments. The prospect for extending their applications to widespread display of higher resolution images is greatly improved by the success of miniaturized electronic components which provide the necessary addressing capability. But flat-panel displays are by no means yet ready to replace the CRT in many of its applications. Take television, for example; none of the existing flat-panel displays has the right combination of brightness, contrast, resolution, and response speed to produce a satisfactory TV image, and furthermore, they are more costly. Consequently, it seems rather unlikely that flat-panel displays would be able to compete successfully with the CRT in these areas for many more years to come.

Instead of competing with the CRT in applications where it performs well, new displays might do better if concentration was made in areas of the CRT's weaknesses. In television applications, opportunity exists for the introduction of new flat-panel displays in small portable sets. There the CRT's bulk, fragile glass envelope, poor image quality under bright lights, high voltage, and high power requirements are serious disadvantages. Introduction of flat-panel, ambient-illuminated displays to this area of application would be welcome in the TV market.

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(1) "Special Issue on New Materials for Display Devices ", Proc. IEEE, 61, 7, pp 801-1056, (1973)

The display described in this paper is of the flat-panel, ambient-illuminated type and is referred to as the Magnetic Particles Display. The image in this display is formed by controlling the orientation of many tiny magnetic particles. The particles are black on one side and white on the other so that their orientations with respect to the viewer convey optical images by scattering of the ambient light. A study of the display's potential application to television is presented, and this study suggests that the display may be used in small portable TV's. Methods for fabricating the display are also investigated. No exotic material is needed and technology exists for manufacturing the components, so the display should be inexpensive to produce when manufactured in large quantities.

An advantage of the magnetic particles display over other flat-panel ambient-illuminated displays such as liquid crystals and electrophoretic cells is the possibility for direct utilization of magnetic memories. It is well-known that ambient-illuminated displays in TV applications need one unit cell of memory at every image spot. Magnetic memories are often simpler and more reliable than electronic memories, especially when large numbers of them are used in limited spaces. The magnetic memories also make possible the use of relatively slow display materials (response time of the order of 30 ms). For applications other than TV, the non-volatility of the display's memory can be a very desirable feature since it provides a possibility for displaying stationary images with zero power consumption.

Operating Principle and the Demonstration Model

A demonstration model of the magnetic particles display was constructed as shown in Fig. 1 to illustrate the operating principle (cf. ref. 2). Each particle in this model is a plastic magnet about 0.8 mm in diameter, black in one hemisphere and silvered in the other, magnetized so the silvered side is north, and encapsulated in a cavity in the transparent panel. Individual encapsulation of every particle was necessary to prevent the particles from clustering. Images are formed by subjecting the display to appropiately configured magnetic fields; e.g. by placing the display panel against patterns cut from a sheet of rubber magnet (Magnetized through its thickness). Some of these images are shown in Fig. 2.

Much smaller particles would be used in practical displays of this type. The particles would have to be fabricated by efficient processes such as those suggested in a later section of this paper, and the magnetic field would be controlled electronically through an addressing system containing grids of electrical conductors.

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(2) S. Sherr, " Fundamentals of Display System Design", Wiley Interscience, (N. Y.) pp 180-182 (1970).

An Application to Television

The magnetic particles display offers wide ranges of design parameters from which desirable combinations may be chosen to suit specific applications. It would be impractical to investigate in this paper the display's performances under all combinations of operating conditions. Therefore further studies on the display will be directed towards a specific application; that of small portable television. Many of the display's features will be revealed by this study.

Consider a black-and-white small portable TV with a 9 cm by 12 cm magnetic particles display for a screen. Construction of the display is shown schematically in Fig. 3. The top layer contains the image-producing particles which are about 10 micrometers (μm) in diameter, black-and-white, and magnetized as described previously. The particles are individually encapsulated with small amounts of clear liquid in transparent spherical shells of inner diameter about 15 μm and wall thickness up to 2.5 μm. The shells are cemented onto the panel; but the particles, which are free to rotate, will orient themselves to align their magnetic moments with the local magnetic field.

The magnetic field at the particles' position is the resultant of 1) the internal field of the particles' dipole moments and 2) magnetization of the memory. The latter is controlled by electric currents through the conductors in the horizontal and vertical grids. There are 500 conductors in each grid,and a display element (spot) is an area bounded by two intersecting pairs of adjacent conductors (fig. 4). At every spot, there is one unit memory to control the orientation of many particles (see expanded view in Fig. 3).

The selection of these design parameters is based on practical considerations such as limitations of the particles' fabrication and encapsulation processes, the properties of available magnetic materials, capabilities of inexpensive current sources, etc. Results of the following study will show that the choice has been reasonable.

Further details about the addressing system are given for the calculation of non-uniformities and other effects. It will be assumed that the memory assembly is composed of many tiny buttons of "square-loop" memory material, each $108\,\mu m$ by $144\,\mu m$, $80\,\mu m$ thick, and is fabricated on a flat substrate of high magnetic permeability. The conductors are round copper wires $40\,\mu m$ in diameter, and positioned at the centers of the grooves in the memory assembly.

The Necessity and Advantages of the Memory

Television images are formed by addressing spots sequentially, and since there are 250,000 spots, each is addressed for only 1/250,000 of the frame time. Cathode-ray tubes with high peak brightness can perform well with this mode of addressing. Sufficiently high peak brightness cannot be achieved in ambient-illuminated displays, so the image must be retained for a longer time to be seen. This requires the use of a unit memory at every picture spot.

For the magnetic particles display, the memory is just a magnet. Once magnetized by the control currents through the addressing wires, it will turn and hold the particles in the desired orientations.

At the TV rate of addressing, each spot is addressed for about 0.12 microseconds. During this time, the memory will be magnetized; but the particles need not have rotated as yet, because the magnetization will persist until the same spot is addressed again in the next frame. The memory allows the particles more time to respond; in this case, the time is extended by a factor 250,000. In a display equipped with memory, the particles' response speed need not be much faster than the frame rate (30 per second).

The Addressing System

A picture spot is addressed by currents through the four nearest conductors (Fig. 4). Because of the close proximity of these conductors to other parts of the picture, there arises the problem of discrimination, i.e., the ability to address a chosen spot without disturbing the rest of the picture. An addressing system with good discrimination should produce no significant disturbance anywhere along the four wires except at the intersection. Discrimination is usually provided by a threshold behavior in the display's response to activation. It will be demonstrated how the demagnetization characteristics of stabilized magnets can be used in an addressing system to provide both discrimination and memory.

The magnetic field that controls the particles' orientations are due to 1) interactions among the particles and 2) magnetization of the memory. Other effects such as geomagnetism and the direct influence of the addressing currents are neglected (the latter because of its very short duration). Interactions among the particles cause the dipoles to align parallel to the plane of the display panel. In these positions, the particles appear grey (half-black and half-white). To make them appear lighter or darker, an external torque must be applied. This torque is $\underset{\sim}{m} \times \underset{\sim}{B}$ ($\underset{\sim}{m}$ is the magnetic dipole moment of the particle and $\underset{\sim}{B}$ is magnetic flux density caused by the magnetization of the memory). Near the center of the spot, $\underset{\sim}{B}$ is in the direction of the normal and is fairly uniform. The presence of permeable material in the particles would tend to concentrate the flux and increase the torque. But this effect can cause $\underset{\sim}{B}$ to increase by at most a factor three (for a sphere of infinite permeability in an otherwise uniform magnetic field),so it is neglected in this order-of magnitude analysis. The normal component of $\underset{\sim}{B}$ is continuous across the surface of the memory because div $\underset{\sim}{B} = 0$. Therefore the central brightness of the spot is a function of the normal component of $\underset{\sim}{B}$ *inside* the memory, which in turn is related to the magnetic field $\underset{\sim}{H}_a$ generated by the addressing currents. Inside the memory material, the relation between $\underset{\sim}{B}$ and $\underset{\sim}{H}$ is studied with the help of a hysteresis plot.

A hysteresis plot of the normal component of the magnetization $\underset{\sim}{M}$ vs the normal component of the magnetic field $\underset{\sim}{H}$ is shown in Fig. 5.

For the study of the demagnetization and stabilization processes, the intrinsic plot (M vs H) is preferred over the normal plot (B vs H) because the external field can be more easily isolated. The total magnetic field H is the sum of the external field H_a (generated by the addressing currents) and an internal field H_m (due to the magnetization M of the material). The hysteresis curve is a relation between M and H . It is determined by the material properties of the memory. The internal field H_m is a result of the magnetization and is linearly proportional to M. This proportionality is determined mostly by the geometric configuration of the memory and surrounding materials of high magnetic permeability. It is assumed to be constant. (The small fluctuations caused by the particles' motions are neglected for simplicity.) Therefore the relationship between M and H_m is represented in Fig. 5 by straight lines of constant slope (M/H_m). Some of these lines are shown in the figure. The line through the origin is the load line. It shows the absence of external magnetic field. The other lines are displaced horizontally by an amount equal to the external field. The magnetic induction (or flux density) B can be obtained from this plot by using the realtion $B = \mu_0 (M + H)$. For simplicity in the explanations given in this section, the memory material is assumed to be isotropic so the normal component of M is a function of the normal component of H only; and the fields are assumed to be uniform throughout the entire spot. Effects of non-uniformity will be considered in a later section.

Suppose that initially, a magnetizing field H_i is applied, causing the unit-memory to operate at the point A (Fig. 5). When this field is switched off, the unit-memory will operate at the point C on the load line. Suppose that a reversing field H_s is now applied. It will cause the unit-memory to operate at D; and upon removal of H_s the state of magnetization will be represented by the point E, also on the load line. The return path DE is approximately parallel to the tangent of AC at the M axis. The state represented by E is said to be stabilized because further applications of external demagnetizing fields of strengths H_d or weaker will cause only reversible changes represented by minor loops such as E-D'-E. Stronger demagnetizing fields will cause the operating point to move farther down the hysteresis curve towards F. These represent irreversible changes, because upon removal of the field, the operating point will return to other points on the load line. For example, the field $2H_d$ will cause the unit-memory to operate at F; and when it is switched off, operation will return to G.

An addressing system with good sensitivity and discrimination can be obtained by using E (Fig. 5) as the initial state of magnetization for the memory and also as the state of minimum reflectivity (black) ; G as the state of maximum reflectivity (white), a fixed current through the vertical conductors (Fig. 4) to generate a magnetic field of strength $-H_d$, and a variable video current through the horizontal conductors such that black corresponds to zero video current and white to a video current that generates a field $-H_d$. This arrangement assures that no demagnetizing field stronger than H_d will exist anywhere outside the addressed spot; and at the addressed spot, the field ranges between $-H_d$ and $-2H_d$. The unwanted disturbances will all be reversible, and they produce little visible effect because of their short duration.

Returning the memory to the initial state E can be done with a line-at-a-time erasure. This calls for a pulse of "erase" current through the horizontal conductors to magnetize an entire line to the state A (Fig. 5) followed by a stabilizing pulse of strength $-H_s$. These pulses may be applied during the time allowed for the return of the horizontal sweep. The magnetic field generated by the erase pulses are stronger than the ordinary addressing fields. So special precautions are taken to assure that they do not generate unwanted disturbances in the areas above the erased line; disturbances below can be tolerated because the downward motion of the vertical sweep assures that these disturbances be erased within a fraction of a millisecond. Taking advantage of this assymetry, a strong erase pulse (up to 4 times the magnetic field strength used for normal addressing) can be confined to the erased line and below by passing more (about three times as much) current through the lower conductor than the upper one.

The Effects of Non-uniformities

Two kinds of non-uniformities are discussed here: 1) The magnetic field diminishes as the inverse distance from a current-carrying conductor, and 2) The memory material does not occupy all the area inside the spot.

The inverse-distance effect can cause loss of discrimination. The field strengths at various position within the memory material have been calculated. In these calculations, the usual formula for magnetic fields around long cylindrical conductors are used. The flat substrate behind the memories is supposed to be highly permeable, so images are used in order to satisfy boundary conditions at the interface. The permeability everywhere else is assumed to be μ_0. (The effects of higher permeability for the memory and particle materials would greatly increase the complexity of the calculations, but it would enhance both the magnitude and the uniformity of the magnetic field.) The magnetic field within the memory is found to vary by as much as 24%. To make sure that areas of particularly strong field do not generate unwanted disturbances, the memory must be initially stabilized against the maximum unwanted demagnetizing field. This can be done by using stronger stabilizing currents and a wider range for the addressing field. The addressing current would be increased by about 48% .

Because the memory unit does not occupy the entire area of a spot, the magnetic field at the edges would not be the same as that at the center. The image contrast would be reduced if some of the particles (for example, those directly in front of the addressing conductors) were not fully activated. This would be especially noticeable in areas of the image where many adjacent spots are all black (or all white). Fortunately, this effect can also be overcome by using stronger magnetic fields: Consider an area of the picture encompassing many adjacent spots designated to be all black (or all white). The memory's magnetic field at a short distance (say 20 μm, about equal to the thickness of a layer of encapsulated particles) in front of the memory assembly would be almost uniformly in the direction of the normal, so all the particles can be fully activated if they were at this position and the field were sufficiently strong. Calculations show that the field strength required would be about three times as much as that needed to fully-modulate only the central portions of the spot.

Resolution, Contrast and Grey-tones

The particles in this display are so small that they cannot be resolved by the unaided eye; but the resolution of the display is limited by the spot size, in this case, about 200 μm. There are several advantages in having many particles per spot: 1) The effects of defective particles or encapsulations become less noticible. 2) The positions of the particles with respect to the addressing system are not critical, so they may be placed at random to simplify assembly of the display. 3) Each layer of particles would be so thin that multiple layers may be used to increase contrast: In a single layer of encapsulated particles, the maximum geometric cross-section of the particles is only 0.45 times the total area. If the particles are viewed against a dark background, the image reflectivity will be limited to the range from 0 to about 0.45. By using multiple layers, the geometric cross-section can be extended. For a double layer, the maximum geometric cross-section is 0.85 times the total area. Imperfections and shadows will probably reduce the effectiveness of the increased cross-section, so it seems reasonable to expect an achievable reflectivity range between 0.015 and 0.60 . This would give a maximum contrast ratio of 40. The particles can be oriented so that the visible hemisphere is partly black and partly white, so continuously variable grey tones are obtained with this display by controlling the video current. The picture in Fig. 6 was made by deliberately degrading a photographic image so that its reflectivity ranges approximately from 0.015 to 0.60 . It is shown here to illustrate the expected appearance of images formed by the magnetic particles display.

Speed and Sensitivity

Response speed of the magnetic particle is a function of its inertia, the drag due to viscosity, and the applied and restoring torques. The following analysis shows that inertia plays a much lesser role than drag. In a steady-state rotation at angular velocity Ω of a sphere of radius R_1 immersed in a liquid of viscosity η inside a stationary concentric spherical shell of inner radius R_2, the drag is

$$D = 8\pi\Omega\eta \frac{R_1^3 R_2^3}{R_2^3 - R_1^3} \tag{1}$$

Using numerical values $\Omega = \frac{\pi}{2} \times 30$ rad/sec, $R_1 = 5\ \mu m$, $R_2 = 7.5\ \mu m$, and $\eta = 10^{-3}$ Kg/m-sec, we find $D = 2.1 \times 10^{-16}$ newton-meters. The moment of inertia I of a particle of radius R_1 and density ρ is

$$I = \frac{8}{15} \pi R_1^5 \rho \quad . \tag{2}$$

Assuming $\rho = 3 \times 10^3$ Kg/m^3 and $R_1 = 5\ \mu m$, we find $I = 1.6 \times 10^{-23}$ Kg-m^2.

A torque of magnitude D will accelerate the particle to the steady-state angular velocity Ω in 3.5×10^{-6} second. It is therefore evident that the effect of inertia is quite negligible. Consideration of the conservation of angular momentum assures that the time required to establish the steady-state flow must also be of the same order of magnitude as the particle acceleration time. The steady-state solution is a good approximation even when the torque is not constant; as long as its variation is slow enough for inertia to remain negligible. The rotation is then " quasi-steady". The torques are calculated in the following paragraph, and they satisfy the "quasi-steady" conditions.

The torque that causes the particles' rotation is the resultant of 1) mutual interactions among the particles and 2) action of the addressing system. Interactions among the particles create a restoring torque to align the dipoles parallel to the display panel. This torque can be calculated using the formula for dipole-dipole interactions: In this calculation, the encapsulated particles are assumed to form a planar array of maximum packing density, so each capsule is in contact with six nearest neighbors. The particles are assumed to be positioned at the centers of the spherical capsules, to behave like dipoles, and to all be pointed in the same direction. This direction is described by a polar angle θ to the normal and azimuthally towards one of the neighboring particles. Then the torque due to a particle's interactions with its six nearest neighbors is $\left|T_i'\right| = \frac{\mu_0 m^2}{4\pi r^3}\left[2 + \sqrt{1 - \frac{1}{4}\sin^2\theta}\,\right]\sin\theta\cos\theta$, turning the dipole away from the normal. Here m is the dipole moment and r the distance between dipoles. Interactions with all other particles would increase this torque by about 30% , but it cannot be expressed in terms of any simple analytical expression. So the approximate expression

$$|T_i| = \frac{\mu_0 m^2}{\pi r^3}\left[2 + \sqrt{1-\tfrac{1}{4}\sin^2\theta}\ \right] \sin\theta \ \cos\theta \qquad (3)$$

will be used for the total torque on the particle due to mutual interactions. The external magnetic field near the center of the spot is in the direction of the normal, it exerts a torque

$$T_x = m B \sin\theta \qquad (4)$$

on the particle. At the equilibrium position, θ would be such that $T_x = - T_i$. In a quasi-steady rotation,

$$T_x + T_i = D \qquad (5)$$

The particle will rotate to full blackness if $T_x \geq T_i$ for all θ ; similarly, they will rotate to full whiteness if $T_x \leq -|T_i|$ for all θ . This determines the range of B from full blackness to full whiteness. Using numerical values in equations 3 and 4 , the range is calculated :

$$|B| \leq (1.5 \times 10^8)\ m \qquad (6)$$

The particles' dipole moments should be chosen small in order to minimize the addressing current, but large enough to provide adequate response speed. For $m = 2 \times 10^{-12}$ Amp-m^2, B would have a maximum value 3×10^{-4} weber/m^2 (in cgs units, m divided by the particle's volume is 48 oersteds and $B \leq 3$ gauss). This combination would provide enough response speed to change the brightness by a factor 2 (from 25% to 50%) within 15 milliseconds, and would require an addressing current of about 60 mA in each wire (assuming a square hysteresis loop and a permeance coefficient $B/\mu_0 H$ near unity). However, up to 4.5 times as much current (270 mA) may have to be used in order to overcome the undesirable effects of non-uniformity.

Power Consumption

Currents up to 0.27 amps may be used in each conductor for addressing. But the average current in the horizontal conductors is only half its peak value. Resistance of 40 μm diameter copper wire is about 15 ohms/meter, causing an average resistive dissipation of 0.26 watts. Other losses, such as magnetic hysteresis, liquid viscosity, radiation, and eddy currents are estimated to be substantially smaller and are therefore neglected.

The inductance and capacitance of each pair of vertical addressing conductor are 0.08 microhenries and 2.6 picofarads respectively; for the horizontal wires, they are 0.11 microhenries and 2.9 picofarads per pair. With all wires connected in series, an impedance-matched driver should supply 2 volts. The rise-time would be 2.5×10^{-8} second.

Fabrication of the Display

Inexpensive methods are available for production of the magnetic particles display. The particles may be made of fine "hard" ferrite powder held together by a suitable binder. The mixture in liquid state would be forced through vibrating nozzles to form uniform spherical droplets which would solidify in-flight into black, unfinished particles.

Ten micron particles are known to be producible by this method .(3) The particles can then be coated white or silvered in one hemisphere and magnetized. Perfect alignment between coloration and magnetic dipole moment can be assured by cementing the particles in place or holding them with a magnet during these operations.

The particles may be microencapsulated in a liquid phase coacervation process which has been used for encapsulation of many different materials.(4) The final products would be tiny transparent hollow spheres each with a magnetic particle and a small amount of inert fluid inside. These encapsulated particles can then be cemented onto a suitable substrate to form the display panel.

The memory can be constructed from a variety of materials. For maximum ruggedness and economy, ferrite powder imbedded in an impact-resistant plastic might be used. The waffle-iron shaped surface may be molded. The memory structure would lend mechanical support to the conductor grids which may either be ordinary magnet-wires, or metallic lines. The latter may be screen-printed, electroplated, or formed by photo-etching.

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(3) C. D. Hendricks and S. Babil, " Generation of Uniform 0.5-10 μm solid particles", J. of Physics E: Scientific Instruments, <u>5</u> , pp 905-910, (1972).

(4) J. A. Herbig, " Microencapsulation", Encyclopedia of Chemical Technology, Interscience, John Wiley, N. Y., (1963-72).

The matrix-addressing control circuits consist of solid-state switches. They should be placed directly onto the periphery of the display panel, eliminating the need for a large number of external connections. The magnetic particles display can be addressed either one-spot-at-a-time or one-line-at-a-time. The former method of addressing is assumed in this study, it is compatible with the standard TV video outputs and does not require additional memory, So further complication of the addressing circuitry is avoided.

Additional Features

In addition to the many potential advantages already revealed by the preceding study, the magnetic particles display has other salient features: 1) The memory is non-volatile. Once the image is formed, it remains stored until it is erased. No power is needed to display a stationary image. For applications such as information read-outs where the image is changed only occasionally, the use of this non-volatile memory may result in a substantial reduction of energy consumption. 2) Grey tones can be stored in the memory. 3) Very high data rates can be attained by using one-line-at-a-time addressing. 4) It is conceivable to obtain a display for multicolored images using the basic magnetic-particles principle. It can be implemented by using five-colored particles similar to that shown in Fig. 7. By orienting the proper hemisphere towards the observer, most shades of colors can be displayed (neutral greys are exceptions, they can only be displayed as a mixture of other colors, if there are many particles per spot). The orientation of the particle must be controlled about two axes of rotation. This might be done by using particles with higher magnetic moments in an inhomogeneous control field. 5) The display can be modified to include feed-back sensors for applications such as communication between computers and users. Inputs into the memory can be made manually with a magnetic pen.

Some of the prominent features of the magnetic particles display are listed in table 1 as a convenient reference.

Conclusions

A new idea for a flat-panel ambient-illuminated display has been presented and it has been investigated for its possible application to television. Exploiting the hysteresis properties of magnetic materials, an addressing system with memory can be made to serve the triple purpose of 1) retaining the image long enough for the eye to see, 2) achieving discrimination in the addressing system, and 3) reducing the requirements for the particles' response speed: The allowed response-time has been extended (by a factor 250,000) to about 30 milliseconds which is reasonably easy to achieve. It was furthermore observed that the display's sensitivity and response speed are dependent upon the choice of the particles' dipole strength. The power consumption of a 9 cm by 12 cm display panel would be about 0.26 watts, excluding that dissipated in the addressing circuitry.

No exotic material or unknown technology is needed for the fabrication of the magnetic particles display, so it should be possible to develop a low-cost mass-producible display in a reasonably short period of time.

Table 1. Some Features of the Magnetic Particles Display

ITEM	CHARACTERISTICS
Flat panel	Less than 5 mm thick
Matrix address	Good discrimination with memory*
Resolution	200 μm spot size* 250.000 spots* (sequential addressing 30 frames per second) Higher resolution with one-line-at-a-time
Contrast ratio	Up to 40:1 by reflection of ambient light
Grey scale	Continuous
Multicolor	Possible in principle
Speed	0.1 microsecond (memory write-in)* 30 milliseconds (particle response)*
Current	0.27 amp * (30 ms response, 200 um spots)*
Voltage	2 volts *
Power Consumption	0.26 Watts* No power needed for stationary images
Memory	Non-volatile (needs no sustaining power) Compatible with grey-scale
Operation under adverse conditions	Mechanically rugged, can be made flexible Can be made to operate over wide temperature range
Cost	Potentially low (need no exotic material, and technology is available)
Life	No data on particle capsules, Addressing system should last indefinitely Particles panel can be changed easily if necessary

* These figures are taken from the study on application to TV. They may be used as typical values.

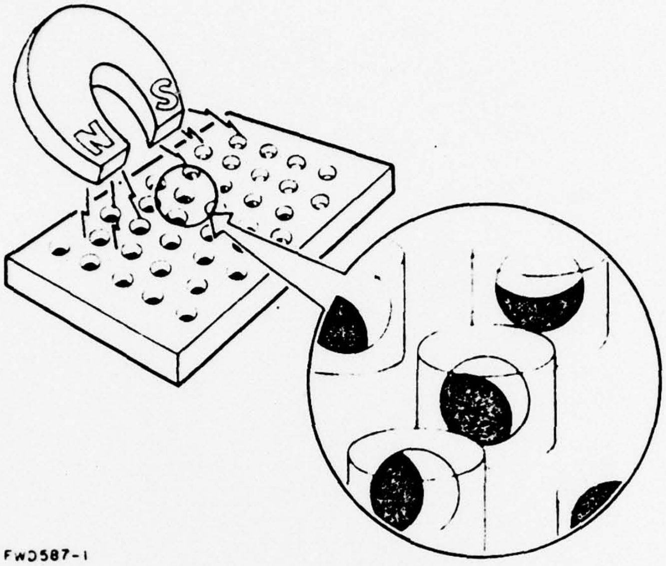

Figure 1. Schematic of Demonstration Model Illustrating Working Principles of Magnetic Particles Display

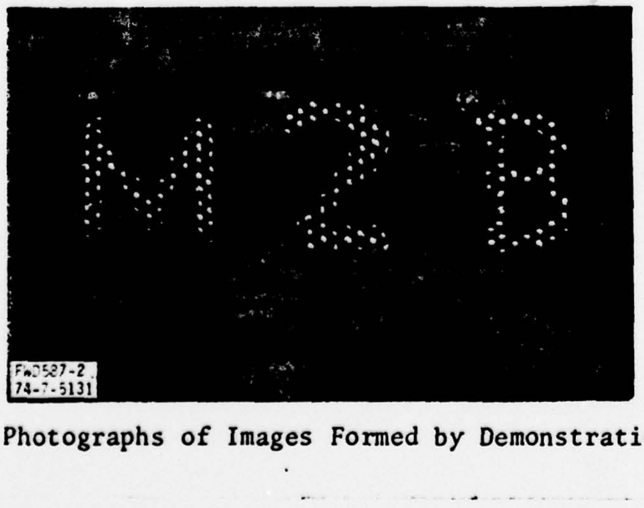

Figure 2. Photographs of Images Formed by Demonstration Model

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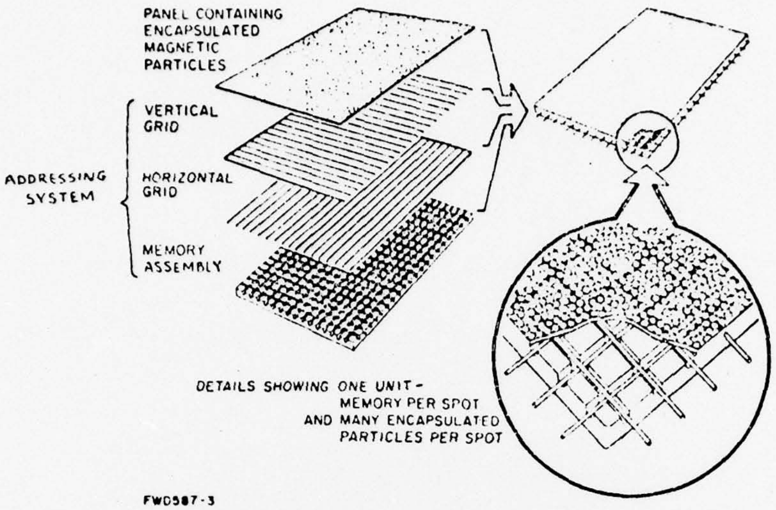

Figure 3. Schematic of the Construction of the Magnetic Particles Display

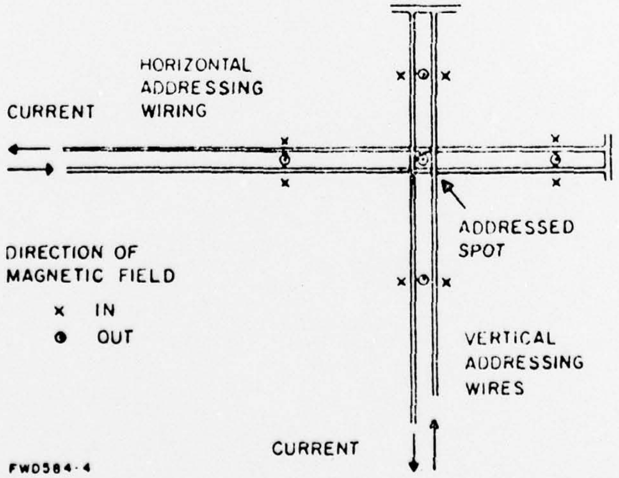

Figure 4. Addressing a Spot by Currents Through Four Conductors.

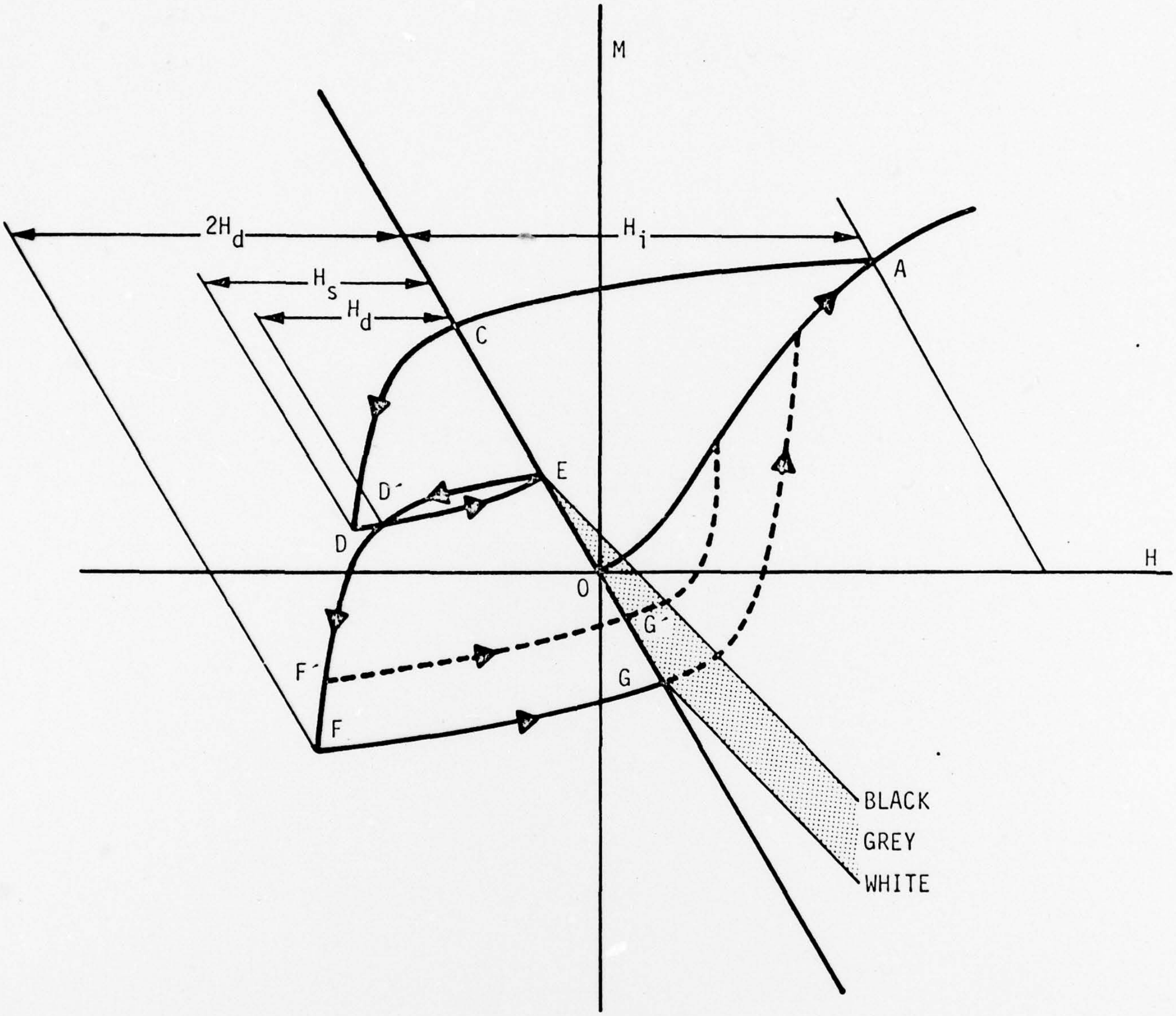

Figure 5. Hysteresis Plot of the Addressing System

Figure 6. Example of Relfected-Light Image having Reflecting Range of 0.015 to 0.60

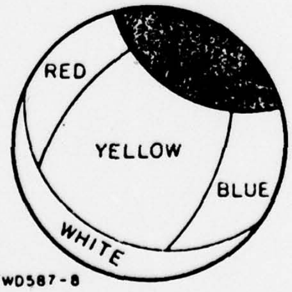

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Figure 7. Five-Colored Sphere for use in Multi-Color Magnetic Particles Display

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