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THE PATENT OFFICE LONDON

(54) DISPLAY DEVICE

(71) We, INTERNATIONAL BUSINESS MACHINES CORPORATION, a Corporation organized and existing under the laws of the State of New York in the United States of America, of Armonk, New York 10504, United States of America do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

This invention relates to a display device.

It is known that the interface between two immiscible liquids can be distorted by an applied electric field with components perpendicular to the interface. An electric field exerts an effective pressure on the interface if the two liquids have different dielectric permittivities or if they have different conductivities. The applied electric field induces an electric charge distribution on the interface between the two liquids which is subjected to a force distribution by the electric field.

Heretofore, the phenomenon of distortion of the interface between two immiscible dielectric media has been considered to be detrimental to the operation of a device in which they are present. Illustratively, contiguous oil and water layers are utilized in practice of electrophotography, as described in the following identified literature reference of background interest: IBM Journal of Research and Development, Vol. 19, Number 6, Pg. 514-522, Nov. 1975, by Y.O. Tu entitled "Theory of Liquid Ink Development in Electrophotography".

Other literature of background interest include the following identified items: S. Chandrasekhar, "Hydrodynamic and Hydromagnetic Stability", Oxford University Press, London, 1961; L.D. Landau and E.M. Lifshitz, "Electrodynamics of Continuous Media", Pergamon Press, Elmsford, New York, 1960; L.C. Landau and E.M. Lifshitz, "Fluid Mechanics", Pergamon Press, Elmsford, New York, 1959; J.R. Melcher "Field-Coupled Surface Waves", MIT Press, Cambridge, Massachusetts, 1963; and D.H. Michael, "Free Surface Instability in Electrohydrodynamics", Proc. Camb. Phil. Soc. 64, 527 (1968).

According to the invention, a display device comprises a layer of two immiscible liquids having different total dielectric properties and defining a planar interliquid boundary, electrodes arranged to supply an electric field across the boundary, the effect of the field being to distort the boundary and thereby to vary the optical characteristics of the device.

We define the total dielectric properties of a liquid as the number pair (ε, σ) where ε is the dielectric permittivity and σ is the conductivity. Two liquids have different total dielectric properties when either the ε or the σ or both differ for the respective liquid.

The two liquids are preferably immiscible e.g., oil and water. The local displacement of the interface therebetween is accomplished by the local application of an electric field which effects movement of the interface by electrohydrodynamic interaction with the dielectric media at the interface. An embodiment of the invention includes an electrode structure for applying an electric field intensity distribution so that the interface can be displaced locally and selectively and preferentially in accordance with a particular information pattern.

An electric field exerts a pressure on the interface between two immiscible liquids when the two adjacent liquids have different total dielectric properties.

The electric field induces an electric charge on the interface which is then subjected to a force due to the electric field. The electric field induced distortion, e.g., in the form of a dimple, is used to scatter light, to gate light, or to hinder total internal reflection.

Illustratively, an array of points or cells of light gates is utilized for the practice of this invention to form a two dimensional matrix addressed array optical display. The cell at a given location is turned on by applying a threshold potential between the respective electrode and the counterelectrode.

Because of the different conductivity σ and different dielectric permittivity ε of the two liquid dielectrics, the applied electric field exerts a directed pressure on the interface which is perpendicular thereto. This pressure moves the interface toward one of the electrodes, dependent upon the relative ε's and σ's of the two layers. Incident light can then be made to pass or not pass selectively and preferentially through the distorted regions of the interface.

The optical display device of this invention has an inherent memory feature due to a hysteresis in displacement of the interface between the two dielectric media. Hysteresis or memory results from an increase in the electric field in one of the liquid media caused by a distortion of the liquid-liquid interface, leading to a further increase in that distortion. A small ac or dc voltage, when left on the selected pair of electrodes after deformation of the interface produced during matrix point selection, is sufficient to maintain the deformed "ON" state.

The invention will further be explained, by way of example, with reference to the accompanying drawings, in which:

Figures 1A to *1D* are schematic drawings of an exemplary embodiment of this invention, in particular;

Figure 1A presents a cross-sectional view especially delineating the zonal boundary or interface between two layered liquid dielectric media and the change thereof obtained by particular selection of one pair of electrodes of a matrix array of electrodes;

Figure 1B presents a portion of the exemplary embodiment to delineate a selected pair of electrodes and the ac voltage and dc voltage sources for activating them;

Figure 1C presents a characterization of the exemplary embodiment especially delineating the addressable matrix electrode array structure; and

Figure 1D presents an enlarged view of a portion of Figure 1C as a basis for a descriptive characterization of illustrative materials for the exemplary embodiment.

Figures 2A to *2D* show experimental apparatus illustrating operation of the invention, in particular:

Figure 2A presents a cross-sectional view of the apparatus used for the experimental purpose and which especially delineates the geometrical relationships among the two immiscible liquid dielectric media and the electrode structure;

Figure 2B shows the quiescent state of the interface boundary between the two dielectric media for an applied voltage of O volts;

Figure 2C shows that an applied voltage of 100 volts causes a slight bending of the entire interface; and

Figure 2D shows that a voltage of 200 volts draws the interface all the way to one electrode.

Figures 3A to *3D* are line drawings which illustrate theoretical considerations, in particular;

Figure 3A shows an initial distortion of the interface region between a pair of electrodes with nomenclature useful for a theoretical exposition considering the parabolic displacement of the interface for small applied electric field;

Figure 3B shows how the interface between two electrodes changes shape as the magnitude of the applied voltage is increased;

Figure 3C shows the calculated displacement of the interface of the applied voltage for small displacements;

Figure 3D shows an estimate of the actual displacement of the interface.

In a display device according to the invention two liquid or viscous immiscible materials with different total dielectric properties, present a zonal boundary or interface therebetween and an electric field is applied with a component perpendicular to the interface in order to effect a distortion thereof. An ac or dc holding voltage may be utilized in order to maintain selected distortion. The interface need not be fully moved to an adjacent electrode cross-over point in order that there be some external manifestation of the imparted information state. The external manifestation of the information is presented by the movement of the zonal boundaries between the liquid media.

Figures 1A, 1B, 1C and 1D are schematic representations of a display device according to the invention. The device utilizes two dielectric media having different total dielectric properties and an electrode-structure by which an electric field is applied to local selected volumes of the dielectric region between the corresponding selected pairs of electrodes.

The exemplary embodiment 10 comprises electrode support plates 12 and 14, e.g., fabricated of transparent glass. The volume between the support plates 12 and 14 is filled with two liquid dielectric media 16-1 and 16-2 which are immiscible in each other and which have different total dielectric properties on either side of the interface 17 therebetween. Illustratively, liquid 16-1 which was originally adjacent to support plate 14 is toluene and liquid 16-2 which was originally adjacent to support plate 12 is water. Electrode 18-1 is shown mounted on support plate 12 and cross on electrodes 18-2 are shown mounted on support plate 14. Coverings 20-1 and 20-2 are thin films on the electrodes 18-1 and 18-2, respectively, which contact the toluene 16-1 and the water 16-2.

For optimal operational results, the contacting surface 20-1 of the support plate 12 and the electrode-structure 18-1 which is established on the interior surface thereof is treated to have a hydrophilic surface and the interior surface 20-2 of the support plate 14 and the electrode-structure 18-2 thereat is treated to have a hydrophobic surface. The art of producing hydrophilic and hydrophobic surfaces is well understood e.g., in the offset printing trade.

The opened view of Figure 1B shows two exemplary cross-over electrodes 18-1 and 18-2 in relationship of the structure of Figure 1A. An electric field is established between the named electrodes by application of a dc voltage source 21-1 via conductor 21-2 connected to electrode 18-1 and via conductor 21-3 connected to electrode 18-2. The said electric field is established between the electrodes by the closing of switch 21-4. An alternating component of electric field is applied between the respective cross-over pair of electrodes from ac voltage source 21-5 via switch 21-6 and resistor 21-7 which establishes said ac voltage component in parallel with the dc voltage source 21-1. Resistor 21-7 prevents burn-out or other deleterious effects upon dc voltage source 21-1 and ac voltage source 21-5 when both switches 21-4 and 21-6 are closed simultaneously. When the deformation of the liquid-liquid interface has been caused to move to the vicinity of one of the electrodes of the particular cross-over pair of electrodes involved, the dc switch 21-4 may be opened and the deformation then retained by the applied holding ac-voltage.

A two dimensional matrix array of addressable electrodes for the practice of this invention is presented by Figure 1C. A portion thereof is shown in Figure 1D to characterize certain details of the electrode structure. The X electrodes X1, X2, X3, X4 are established on support plate 14 and Y electrodes Y1, Y2, Y3, Y4, Y5 are established on support plate 12. Illustratively the electrodes may comprise transparent conductive tin oxide stripes. The hydrophobic coating for the X electrodes is conveniently a CuO thin film 21-8B formed by deposition and the hydrophilic coating for the Y electrodes is conveniently an Al_2O_3 thin film 21-8A, which may be been formed by anodization of a thin film of aluminum.

As illustrated in the schematic diagram of Figure 1C, by applying an operational voltage to a pair of electrodes through a matrix addressing circuit 21-9, an appropriate potential is obtained in the spacial volume characterized at the intersection between the two electrodes, e.g., the cross-over point for X3 electrode and Y3 electrode.

In the quiescent state of operation of the embodiment 10 of Figure 1, zonal boundary 17 between dielectric media 16-1 and 16-2 is essentially parallel to the glass support plates 12 and 14. When a selected pair of electrodes is activated, a directional force is applied to the interface in the area of the zonal boundary defined by the electric field pattern between the selected pair of electrodes which "pushes" or "pulls" that partial zonal boundary toward one of the electrodes of the selected pair of electrodes.

When the interface 17 has been pulled to a selected electrode by an electric field, the distorted interface manifests a modified light transmission or reflection characteristic, either because the light suffers changed internal reflection at the liquid-liquid interface or because the light is absorbed differently in one of the two layers of liquid.

The physical mechanism by which an applied electric field exerts a pressure on the interface results from the action of an electric field on two liquids with different total dielectric properties. The different total dielectric properties can be obtained either by the dielectric permittivities ε_1 and ε_2 being the same and the conductivities σ_1 and σ_2 being different or vice versa. Especially advantageous practice of this invention is obtained when both ε_1 and ε_2, and σ_1 and σ_2 are different in each of the two dielectric media.

Further, since the liquid of dielectric medium 16-1 may be moved by sequential control of the cross-over points, the configuration of Figure 1C may be utilized for manifesting a sequence of information states.

Illustratively in the case in which liquid 16-1 is toluene and liquid 16-2 is water, the electrical conductivity of the water is several orders of magnitude greater than the conductivity of the toluene. As a result, a dc voltage applied across the two liquid layers at the intersection of two liquid layers at the intersection of two electrodes, i.e. X3 and Y3, acts as if there is a relatively high electric field in the toluene and a relatively low electric field in the water after a short initial transient. The initial transient response has little influence on the liquid-liquid interface 17 because the dielectric relaxation time of the water is much shorter than the response time of the displacement of the interface. The resulting high electric field in the toluene exerts a force on the interface 17, drawing it to the electrode X3 and decreasing the thickness of the toluene layer. As the toluene layer 16-1 is decreased in thickness in the local region between electrodes X3 and Y3, the electric field therein is correspondingly increased since the applied voltage appears substantially across the toluene layer.

Accordingly, the increased electric field leads to a larger force on the interface 17 and a corresponding additional decrease in thickness of the toluene. At a sufficiently high applied voltage V_T, a threshold is reached and the deformation becomes unstable, leading to a collapse of the toluene layer in the region between the electrodes, illustratively X3 and Y3, toward electrode X3. After the collapse, only a small voltage, either ac or dc, when applied between the electrodes X3 and Y3 is sufficient to maintain the deformed interface at the electrode X3, and to maintain the thickness of the toluene layer therebetween in its collapsed condition.

In effect, the system exhibits a hysteresis or memory such that a display position, illustratively X3 and Y3, which has been selected by momentarily impressing a voltage between electrodes X3 and Y3, can be maintained by a small additional voltage applied between the electrodes X3 and Y3. This small auxiliary voltage should be insufficient to cause any display position to be selected. Thus, the small auxiliary voltage may be maintained between all of the electrodes in the X-array and all of the electrodes in the Y-array without causing any of the display points to be selected.

However, the small auxiliary voltage is established to be sufficiently large, e.g., about one-tenth of the threshold voltage, so that any point that is selected for display will be maintained even after the selecting voltage is removed. Since the operation of the device is substantially independent of the sign of the applied voltage, either ac voltage or dc voltage can be used as the small auxiliary voltage. The ac voltage is advantageous in that it minimizes the deleterious effects due to polarization bubbles which may form on the electrodes when a dc auxiliary voltage is applied for a long period of time.

The exemplary embodiment 10 operates as an optical display when the deflections of the interface 17 are used to gate or modulate light which is incident on the device. The incident light is gated by the device by a change in reflectance caused by a deflection of the interface 17 or by absorption in one of the viscous dielectric layers 16-1 or 16-2.

Illustratively, the exemplary embodiment 10 employs absorption in viscous liquid layer 16-1 which is due to an oil soluble dye in the toluene. A light output is effected at a desired point by activating by a dc voltage pulse the pair of electrodes corresponding to that point. The activation pulls the interface 17 to the electrode on support plate 14 (next to the toluene), where it is held by a small ac voltage with peak value which is from about one half to about one-tenth the peak of the dc voltage activating pulse. As a result, the thickness of the toluene layer at that point is greatly reduced, and light is able to pass through the display at the selected point.

An experimental procedure illustrating practice of this invention will be explained with reference to Figures 2A, 2B, 2C and 2D. The stable electrohydrodynamic modes of deformation of adjacent viscous dielectric media will be demonstrated for the exemplary liquids toluene and water shown in Figure 2A which is a schematic diagram of an exemplary laboratory apparatus.

A beaker 22 with lid portion 22-1 has tube 24 introduced therethrough for purpose of establishing a volume of liquid toluene "T" in the beaker 22. An additional tube 26 is established through the lid portion 22 for the purpose of introducing a volume of liquid water "W" to the lower-most portion of the beaker 22 so that the interface 28 between toluene 23-1 and water 23-2 is encompassed between the electrode structure comprised of a pair of electrodes 30 and 31, separated by about 1.5 millimetres. The water in the lower portion of the beaker 22 was established at height of approxmately 0.7 millimetres above the lower electrode structure 31. The dielectric characteristics of toluene and water are such that a potential applied across an electrode-structure per Figure 2A causes the interface to move toward the upper electrode structure 30.

The quiescent condition is shown in Figure 2B for zero applied volts so that the planar boundary 28 is parallel to the lower portion of the beaker. For an intermediate applied voltage of 100 volts, the interface boundary has not moved significantly to position 28-2. However, there is a sharp threshold in the voltage so that for an applied voltage of 200 volts the interface 28-3 is moved to a position proximate to the electrode structure 30 toward the upper boundary of the toluene. Once the threshold voltage has been exceeded and the interface 28-3 has extended to the top electrode, it can be held there with an auxiliary ac or dc voltage of about 20 volts.

An approximate theory for the operation of this invention will be presented with especial reference to Figures 3A, 3B, 3C and 3D and to the drawing of Figure 1A.

For convenience of exposition, the line drawing of Figure 3A is considered in the context of Figure 1A. Illustratively, one of the layers 16-2 has conductivity σ_1 which is many orders of magnitude greater than the conductivity σ_2 of the other layer 16-2. The respective dielectric constants have real components ε_1 and ε_2, respectively. In static equilibrium, with no voltage applied between the electrodes, the interface 17 between the immiscible liquids is a planar surface which lies a distance *d* above the electrode 18-2 on the low conductivity side. For simplicity of calculation, each of the electrodes 18-1 and 18-2 is assumed to be circular with a radius R.

As different and successively larger voltages are applied to a set of opposing electrodes 18-1 and 18-2, the interface 17 will distort as is depicted by the series 17-1, 17-2, 17-3, and 17-4 in Figure 3B. An electric field of approximately E=V/d is impressed across the low conductivity liquid 16-1 for the case of small distortion $z=Kr^2$ of the interface where K is a constant dependent on the physical parameters of the optical display and *r* is the distance from the centre of the circular electrode where the particular deformation *z* is monitored. It can be shown that displacement *z* is a function of voltage and the physical parameters of the system as given by the expression

$$\tilde{z} = \frac{d}{2} \pm \frac{d}{2} \left(1 - \frac{\varepsilon V^2 R^2{}_x}{Fd^3}\right)^{1/2}$$

The approximate solution for the displacement *z* is shown in Figure 3C.

At the critical voltage of $V_o = \sqrt{(Fd^3/\varepsilon R^2)}$, the interface is pulled completely into the electrode. In order to release the interface and return the cell to its initial condition, it is necessary to reduce the applied voltage to a small percentage, typically less than 10%, of the critical voltage. Thus, the system has hysteresis or memory;

The actual distortion of the interface in response to an applied voltage is not exactly parabolic for large distortions from the theoretical. As a result, the display device cell switches at a lower voltage than that calculated on the basis of a simple parabolic distortion. The result is a response curve such as is shown in Figure 3D.

A reference book which presents other exemplary liquids suitable for the practice of this invention in accordance with the principles thereof is: *Handbook of Chemistry and Physics*, 48 Edition, Published by the Chemical Rubber Co., Cleveland, Ohio, 1967. Data for the specific chemicals of this exemplary embodiment are listed therein: trichloromethane on p. C-407 (m306), phenyl-chloride on p. C-154 (b407).

With reference to Figure 1D, the layer 21-8B of copper oxide may desirably have thickness in the range of 10 to 1000 Angstroms; and the layer 21-8A of aluminium oxide may desirably have thickness of 10 to 100 Angstroms.

WHAT WE CLAIM IS:-

1. A display device comprising a layer of two immiscible liquids having different total dielectric properties and defining a planar interliquid boundary, electrodes arranged to supply an electric field across the boundary, the effect of the field being to distort the boundary and thereby to vary the optical characteristics of the device.
2. A device as claimed in claim 1, wherein one of the liquids is coloured.
3. A device as claimed in claim 1 or claim 2, wherein the liquids are, respectively, water and toluene.
4. A display device as described with reference to Figures 1A to 1D and 3A to 3D.

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Agent for the Applicants.

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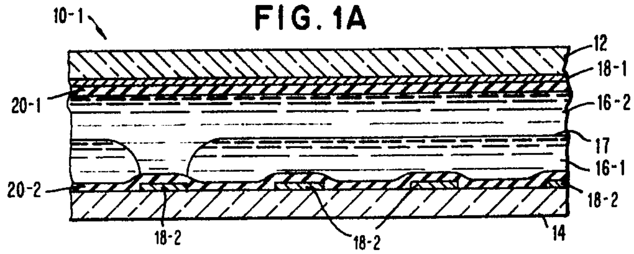
1573165 COMPLETE SPECIFICATION

4 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

FIG. 1A



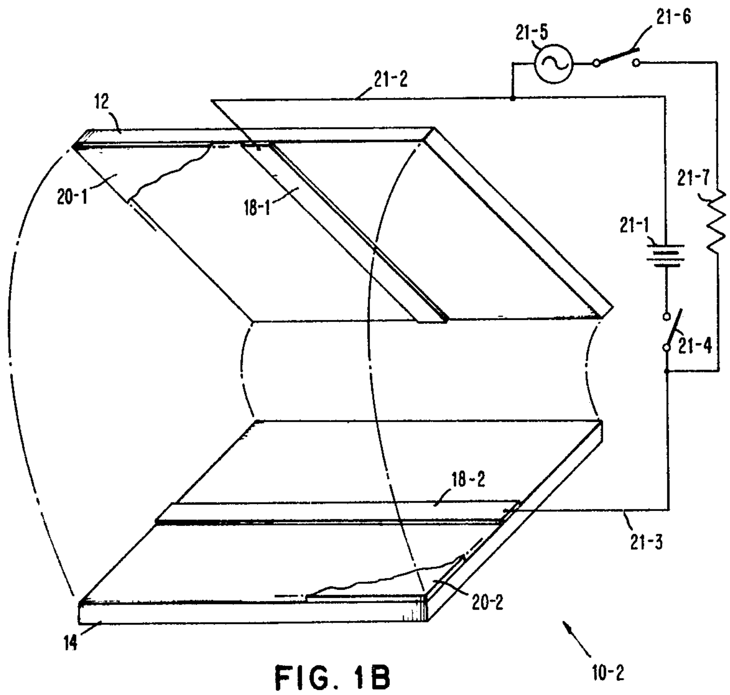


FIG. 1B

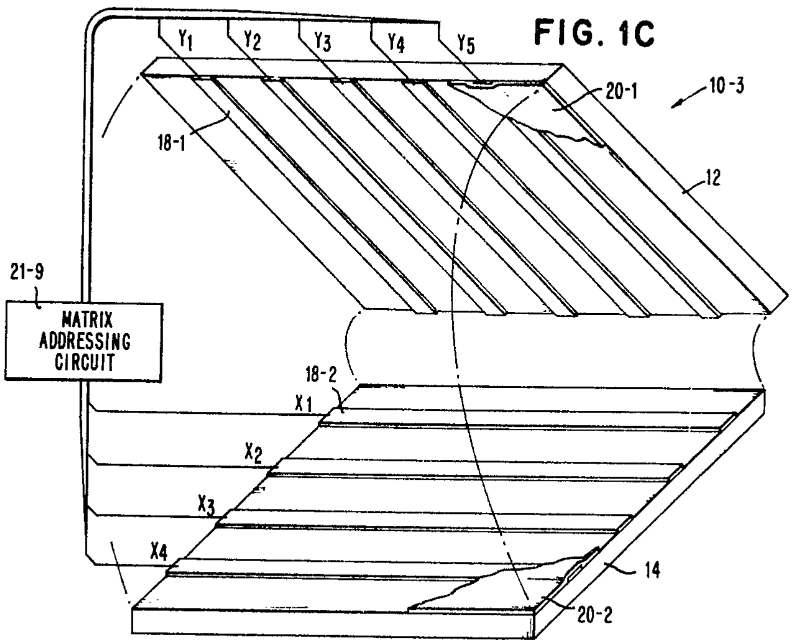

Y1
Y2
Y3
Y4
Y5
20-1
10-3
18-1
12
21-9
MATRIX ADDRESSING CIRCUIT
18-2
X1
X2
X3
X4
14
20-2

FIG. 1C

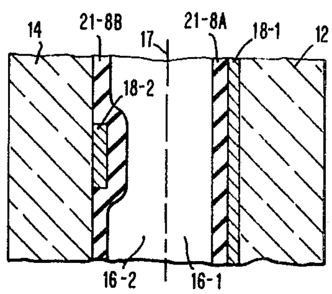
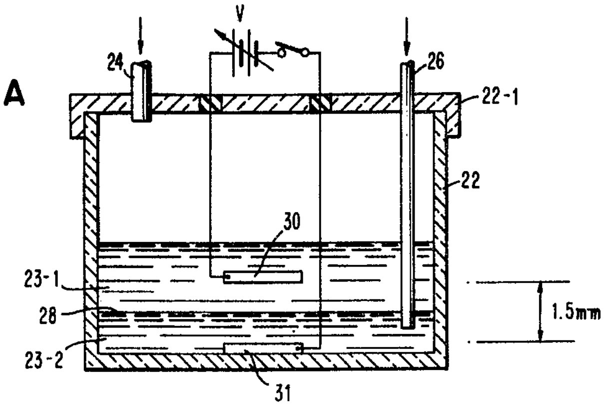

14
21-8B
17
21-8A
18-1
12
18-2
16-2
16-1

FIG. 1D

FIG. 2A



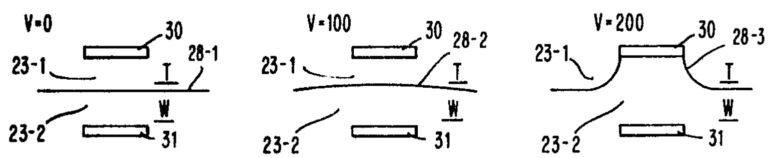


FIG. 2B FIG. 2C FIG. 2D

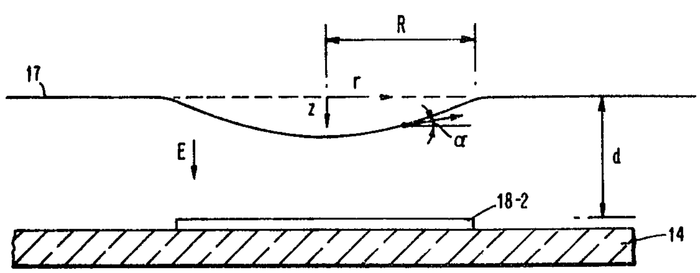
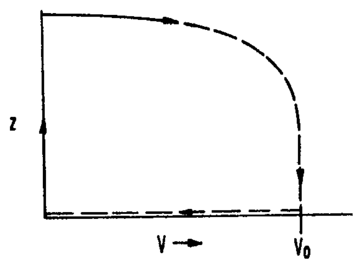


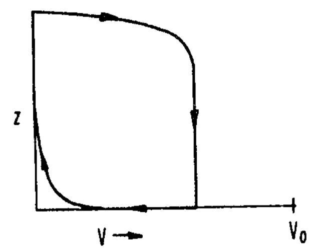
FIG. 3A

FIG. 3C



THEORETICAL

FIG. 3D



ACTUAL

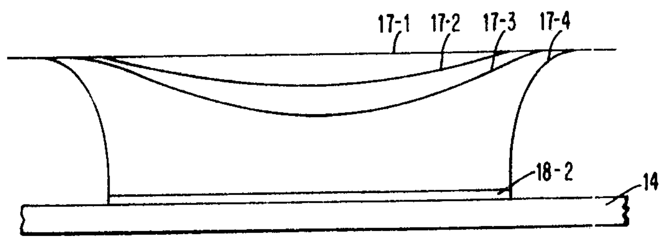


FIG. 3B