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DEVELOPMENT OF VISUAL-DISPLAY
AID TO AIR NAVIGATION

Final Report

NASA Grant NGR 39-004-038

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DEVELOPMENT OF VISUAL-DISPLAY AID TO AIR NAVIGATION

Final Report

NASA Grant NGR 39-004-038

1 January 1972 to 31 March 1973

Submitted by

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Submitted April 1973

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SECTION 1

INTRODUCTION

This report is the final report on the work performed on NASA Grant NGR 39-004-038 at Drexel University during the period 1 January 1972 to 31 March 1973. The objective of the program was to design, develop and fabricate a liquid-crystal, visual-display aid to air navigation. The display was to be used to locate an aircraft on a standard navigational chart when activated by two independent VOR signals. A prime consideration was to make the display sufficiently inexpensive to encourage its widespread use in private as well as commercial aircraft. This work is a continuation of a program started in January 1971.

1.1 Scope of Program

The scope of the program described in this report includes the design and fabrication of the liquid crystal display, the design and fabrication of the electronic interface between the VOR system and the display and a study of the stability of the liquid crystals under operating conditions. Demonstration models were to be fabricated from available liquid crystal materials; no attempt was to be made to synthesize liquid crystals, but techniques were to be developed to purify commercially available materials.

1.2 Program Organization

The work described in this report was performed at Drexel University in the graduate research laboratories of the Physics and Electrical Engineering Departments including: Professor Lord's laboratory in Disque Hall; and Professor Matcovich's microelectronics laboratory in Stratton Hall. Three faculty members and three students were engaged in this work.

1.3 Summary

A ten-by-ten inch display panel was designed and fabricated. Panels made from aluminum-Mylar laminates were not satisfactory due to peeling and poor line definition. Panels made from copper-Kapton laminates in the parallel line configuration geometry were not satisfactory due to Kapton residue left in the Kapton channels. Panels made from copper-Kapton laminates in the perpendicular line configuration geometry were satisfactory and were used extensively in this report period.

Lifetime studies on liquid crystals were continued and extended to include newly available liquid crystals and testing in controlled ambients. These tests indicate that lifetimes in excess of one year are possible. A method for purifying liquid crystals and improved quality control techniques were developed.

Voltage sensitive cells were made and tested, but they do not appear to be practical for the present application.

The electronic system was designed and fabricated. A practical phase detector and encoder was fabricated and tested. An integrated circuit driver was designed and fabricated, but severe problems developed when it was used to drive display cells; the cells failed after short periods of operation. Extensive effort was made to solve this problem, but it was not fully resolved even at the end of the program. Tests made near the end of the program indicated that DC operation may be practical. A simple decoder-driver was designed based on DC operation.

A paper, "A Large, Flexible, Liquid Crystal Display Cell" was presented at the IEEE Conference on Display Devices held on October 11, 12, 1972 in

New York City. A paper, "Variation of DC Domain Threshold in Nematic Liquid Crystal under Continual Dynamic Scattering" was published in the Journal of Applied Physics, Vol. 44, No. 1, January 1973. Both papers are based on work performed under this program during the current report period.

SECTION 2

SYSTEM CONCEPT

2.1 Description

The navigational aid comprises two, ten-by-ten inch, transparent, flexible, display panels and interface electronics for converting VOR data to directional data for the displays. A display panel, shown in Figure 1.1, comprises a radial pattern of electrically conductive line pairs, liquid crystal material contained between the line pairs, and addressing and activating electronics. The interface electronics comprises a phase detector, encoder, register, decoder and driver.

2.2 Operation

In operation two displays would be placed on a standard navigational chart and centered on appropriate VOR station locations. The directional data from each station would be detected and encoded and sent to the display panels. The panel electronics would decode the signal and activate the radial line most closely approximating the aircraft direction from the VOR station. The activated line would turn a "milky-white" and would be clearly distinguishable from unselected lines. The intersection of the selected lines on the two panels would indicate tha aircraft's location on the chart.

2.3 Design Criteria

A prime objective of the program was to make the navigational aid sufficiently inexpensive to encourage its use in private as well as commercial aircraft. Consequently standard integrated circuits were to be used; the display was to be integrated circuit compatible and the display itself was to be inexpensive. As reported in the first annual report, the intra-electrode spacing required in a parallel configuration cell is 12μ. Maintaining this spacing over a ten-by-ten inch square would be very difficult if rigid electrodes were used. Consequently, only flexible electrode materials were considered for the displays.

Since many lines were to be used on the display, the connector was potentially a high cost component. To reduce the number of pins required, the line selection data is transmitted in coded form. This procedure requires additional electronics, but the circuits in integrated form are relatively inexpensive.

2.4 Basic Display Cell Configurations

The two basic configurations for the liquid crystal cells are described in Sections 2.4.1 and 2.4.2. In both cases the liquid crystal is contained between conductive electrodes and the electric field, E, due to the applied voltage is perpendicular to the electrodes. In both configurations the resistivity of the liquid crystal cell is very high ($\sim 10^9$ ohm-cm) and only small currents flow when the voltage is applied. Although small, this current is essential to the operation of the cell and the physical design must reflect this requirement. The operational characteristics of these cells were determined in the first phase of this program and are reported in the first annual report. A voltage sensitive cell was evaluated in this phase of the program and the results are presented in Section 2.4.3.

2.4.1 Parallel Configuration

In the parallel configuration shown in Figure 2.1a the direction of the incident light is essentially parallel to the electric field. At least one of the conductive electrodes used in this configuration must be transparent. If the dynamic scattering phenomenon is to be observed by reflected light, the back electrode should be highly reflective. If the phenomenon is to be observed by transmitted light both electrodes must be transparent. The optical path length, d, is related to the electric field, E, through the relationship: $E = V/d$ where V is the applied voltage.

2.4.2 Perpendicular Configuration

In the perpendicular configuration shown in Figure 2.1b the direction of the incident light is essentially perpendicular to the electric field. In this configuration transparent electrodes are not required and the optical path length is independent of the electrode spacing. A highly reflecting surface must be placed in the light beam if scattering is to be observed by reflected light.

2.4.3 Voltage Sensitive Cells

Investigations were made into utilizing a recently reported electro-optic effect in nematic liquid crystals possessing positive dielectric anisotropy. This effect makes use of a twisted nematic structure to provide a 90° phase rotation of light passing through a thin cell. The twisted structure is achieved by rubbing the transparent electrodes so that the nematic molecules align along the electrodes in the direction of rubbing. The cell is made by orienting electrodes with their alignment directions perpendicular. The directrix of the medium then continuously rotates 90° from one electrode to the other. If the cell is placed between aligned polarizers such that one of the polarizers is oriented at 90° to the molecular direction of its adjacent electrode, the cell then appears dark in transmitted light. If a voltage is applied to the electrodes, the molecules align parallel to the field, that is in the direction of light propagation. The light in the cell now travels along the optic axis of the medium and experiences no optical rotation; hence, the light is freely transmitted by the aligned polarizers. This effect requires a lower voltage than dynamic scattering. In the several 12μ thick cells made, a voltage of 5 volts AC or DC provided a striking physiological contrast ratio. It was noted, however, that this effect was very sensitive to the surface preparation of the Nesa electrodes and it was difficult to get a uniform orientation over the entire electrode. Cells made from mylar electrodes with an evaporated metallic coating were not as functional as the mylar substrate is itself optically active, and interferes with the operation of the cell. While this effect provides good light valve operation at low voltages, the difficulties involved in treating the flexible electrodes and maintaining the proper orientation precludes its use in the present application.

SECTION 3

LIQUID CRYSTAL MATERIALS

3.1 Available Materials

Nematic type liquid crystals were used in this program. These materials, which are normally transparent, become milky-white when a field is applied due to the "dynamic scattering" of the incident light. Several companies supply nematic liquid crystals on a commercial basis. Most available nematics are in the liquid crystal state at temperatures above the normal ambient; however, several are available which function at room temperature. These are listed together with the suppliers in Appendix A.

3.2 Quality Control

The quality of the liquid crystal is significantly affected by absorbed water and gases and by exposure to ultraviolet radiation. The effect is due to decomposition of the liquid crystal and can occur in storage or operation. Most commercial materails are reasonably pure when received, but quickly absorb water and gases.

The nematic-isotropic transition temperature is a convenient and accurate measure of crystal quality. Decomposition products and dissolved gases lower the degree of nematic order and so the transition temperature. Test results on fabricated cells indicate that the liquid crystal transition temperature must be within a few degrees of its theoretical value to achieve satisfactory device operation.

Two procedures were initiated during this phase of the program to improve the quality of the liquid crystals. They are described in the following sections.

3.2.1 Storage

In the initial phase of the contract the liquid crystal materials were stored at room temperature. When the transition temperature measurement was introduced as a quality control measure, the transition temperatures of all the materials in stock were found to be at least 6°C below the manufacturers' specification. Subsequently, all materials were stored in the dark and under refrigeration. This procedure was intended to minimize degradation due to decomposition of the liquid crystal.

3.2.2 Purification

Experimental data indicated that the transition temperature of the degraded liquid crystal could be raised by use of the following procedure: the crystal was placed in a vacuum desiccator and held at a temperature above its transition temperature for a period of several hours. During the process, bubbles of escaping gases, presumably water and volatile decomposition products, were observed. By use of this process the transition temperatures of the liquid crystals could be raised to within 2°C of the manufacturers specification.

3.3 Stability Tests

The stability tests initiated in the first phase of the program were continued. Two new liquid crystal materials, Merck Licristal V and Eastman Nematic Mixture 11643, and two new electrode materials, silver and nickel, were added to the test. The same test procedures were continued; the cells were in the parallel configuration, the spacing was 50.8μ and the excitation was 40 volts at 60 Hz except as noted. These data are presented in Appendix B.

3.3.1 Lifetime

3.3.1.1 Standard Cells

The longest-lived crystal was Merck Licristal IV; the longest-lived electrodes were Nesa and Nesatron glass. The most stable metal film electrodes were those made from aluminum; cell lifetimes were comparable to those made from Nesa and Nesatron glass. Several cells have exceeded 589 days of continuous AC operation.

3.3.1.2 Controlled Ambient

Since liquid crystals are known to degrade when exposed to normal ambients and ultraviolet light, lifetime tests were made on samples held in dry nitrogen atmospheres and shielded from light. The dry nitrogen atmosphere can be approximated in displays by hermetically sealing the cell and the light shield can be approximated by use of ultraviolet filters. Since long lifetimes were expected, the cells were operated with DC excitation. Previous tests indicate that failure under DC operation is much more rapid than under AC operation. Test cells were made from Varilight 1047 liquid crystal and Nesa glass in the standard configuration. Cells placed in the protected ambient continued to operate after 34 weeks of continuous DC excitation. Similar cells in the normal laboratory ambient failed after one week of continuous DC excitation.

3.3.2 Failure Analysis

Cells made with evaporated thin metal films had a large number of electrode failures. Lifetimes of these cells did not appear to be a measure of liquid crystal stability but rather a measure of the stability of the thin films. The copper electrodes used in the tests made since January 1972 were evaporated on glass over a thin layer of chrominum to improve continuity and adhesion. Half of the failures in copper-electrode cells occurred in the area where the electrode was exposed to the air.

A distinct interaction was observed between Eastman Mixture No. 11643 liquid crystal and copper and aluminum electrodes. All failures in nickel cells occurred in the region exposed to air. Half of the electrode failures in silver cells occurred in the part exposed to air. Failure in cells with gold electrodes all occurred through the liquid crystal with subsequent burning of the material; the apparent cause was local peeling of the gold.

3.4 Basic Properties

3.4.1 Birefringence

The contrast ratio obtainable in a nematic liquid crystal device is primarily dependent on the optical anisotropy of the liquid crystal. The best measurement of this anisotropy is the birefringence of the crystal; consequently, the study of birefringence iniciated in the first phase of this program was continued in the second phase.

The birefringence was measured by use of a wedge interference technique. The wedge was placed in an electrically heated oven to provide temperature control and the entire assembly was placed on a microscope stage. The wedge was illuminated by a 0.5 mw He-Ne laser polarized at an angle of 45° to the optic axis (molecular direction) of the nematic medium so that the components of the beam perpendicular and parallel to the optic axis are of equal amplitude. As each of these components travels through the medium with a different index of refraction, for certain path lengths in the wedge, destructive interference will occur between the two component waves and a series of equally spaced dark fringes is seen in the wedge. An eyepiece is used to measure fringe spacing as a function of temperature. The birefringence, $n_e - n_0$, can be computed through the relation:

$$n_e - n_0 = \frac{\lambda}{\Delta x} \cot\alpha$$

where λ is the wavelength of the illumination, Δx, the fringe spacing and α, the apex angle of the wedge. Figure 3.1 gives the birefringence as a function of temperature for all the commercially available room temperature nematic materials.

Although liquid crystals are birefringent, their uniaxial nature makes it possible to measure the ordinary index of refraction, n_0, of an unoriented sample by using a standard Abbe refractometer. The refractometer used had provisions for altering the temperature. Thus n_0 was measured as a function of temperature, in the same temperature interval as $n_e - n_0$. Hence the values of both n_0 and n_e as a function of temperature have been obtained. A subsequent analysis of these data (along with the density measurements reported in 3.4.2) will be made to test a recently proposed model[1] for the interaction of nematogenic molecules.

3.4.2 Density

A basic factor involved in the interactions that cause the orienting of nematic molecules is the density of the material. Also, the discontinuity in

[1]"Theory of Birefringence of Nematic Liquid Crystals," S. Chandrasekhar, D. Kirshnamurti and N.V. Madhusudana, Molecular Crystals and Liquid Crystals, 8, 45-49 (1969).

the expansion of a sample of liquid crystal undergoing a phase transition is a fundamental quantity which must be accounted for by the various theoretical models for nematic ordering. As many of the room temperature liquid crystals in this project were synthesized only recently, there was a need for basic data to be reported for these materials.

To measure the density of a material, a known weight was used to fill a dilatometer, an instrument consisting of a volumetric flask with a graduated capillary. The dilatometer volume was previously calibrated against several known liquids. The instrument was then immersed in an insulated bath which was slowly heated. As the material expanded with temperature, the volume was noted and the density of the material calculated. The data are presented in Figure 3.2 and clearly show the discontinuity in volume at the transition to the isotropic state.

These data, along with the indices of refraction are presently being analyzed after the model proposed by Chandrasekhar, et al, to determine the relative contributions of various intermolecular interactions to nematic ordering.

SECTION 4

DISPLAY DESIGN AND FABRICATION

4.1 Display Design

The layout of the display, shown in Figure 4.1, has not changed appreciably from that described in the 1971 annual report. The active area of the display is nine inches in diameter and contains 36 lines spaced 10° apart. Attempts were made to fabricate each of the basic cell configurations described in Section 2.4; the perpendicular configuration proved to be more practical, but neither was fully satisfactory.

4.1.1 Design Considerations

The design criteria to insure visibility were established in the first phase and presented in the first annual report. The lines were to be 30 to 40 mils wide and opaque. These lines were wide enough to be visible when activated yet not so wide as to obscure information on the chart. The selected line was to be pulsed to improve visibility and a reflective line backing was to be used to improve contrast.

To insure reasonable lifetime, the liquid crystal cell should be hermetically sealed and should not come in contact with the sealants or other adhesives. Excitation should be AC although recent data suggest DC can be used (Section 3.3.1.2) if a protective ambient is provided. First phase data indicate operation should be in the 0 to 60 Hz range and 60 Hz was chosen for convenience.

4.1.2 Line Designs

The preferred perpendicular line design is shown in Figure 4.2. The base is Mylar coated on both sides with aluminum. The back side aluminum is etched to the overall line width to provide a reflective backing and the front side aluminum is etched into the line pattern shown in the Figure. Aluminum metallization is preferred because of its stability in contact with the liquid crystal (Section 3.3.1.1) and because it is a good reflector. Mylar is preferred because of its transparency and color (water-white). The mylar cover is coated to minimize reflections. The aluminum spacer is intended to keep the cover out of contact with the liquid crystal. The cover would be sealed along the outer edge only, to prevent contact of the liquid crystal with the sealant.

The preferred parallel line design is shown in Figure 4.3. The use of copper and Kapton reflects fabrication problems. The substrate must be etched and techniques for etching Kapton were available. Although mylar etching processes were reported, the processing procedure could not be determined.

4.1.3 Materials

4.1.3.1 Substrates and Conductors

Metal-plastic laminates can be made in a large variety of materials and thicknesses. Unfortunately procuring these materials in reasonable quantities was very difficult. Of the many materials sought, the following were the only materials received:

1. Kapton substrate two mils thick, coated with ½ oz. copper from the Fortlin Company.

2. Mylar substrate two mils thick, coated on one side with ½ oz. copper and the other with ½ mil thick aluminum from TME Company.

3. Mylar substrate two mils thick, coated on one side with ½ mil thick aluminum and on the other with two mil thick aluminum from TME Company.

4. Transparent gold-coated, flexible plastic from Liberty Glass Company.

5. Transparent silver-coated, flexible plastic from DuFont.

The Kapton laminate was made without adhesive between the copper and the Kapton. The Kapton was transparent, but had a distinct yellow color. The Mylar laminates were made with a Mylar type adhesive between the layers. This adhesive should have no more effect on the liquid crystal than the Mylar substrate. The Mylar was transparent and water-white.

4.1.3.2 Covers and Sealants

An antireflection coated flexible, transparent palastic material was obtained from Optical Coating Laboratory, Inc. for use as a cover material for the perpendicular cell displays. Two sealing materials, RTV 732 and RTV738 were obtained from Dow Corning Company for use in sealing the covers over the liquid crystal cells.

4.2 Fabrication

The display panels were fabricated by Towne Laboratories of Somerville, New Jersey. Etching techniques were developed and evaluated at Drexel (see first annual report); however, the display panels were too large to be fabricated in the equipment available at Drexel.

4.2.1 Process Limitations

All attempts to fabricate display panels with aluminum electrodes failed. The samples obtained had poor line definition and poor adhesion of conductor to substrate. The etching of fine line patterns of the required dimensions in aluminum is within the state-of-the-art; however, the starting materials must be smooth, uniform and strongly adherent. Suitable materials could not be obtained from the suppliers since the quantities involved were small and projected use uncertain. Delivery times on laminates averaged well over two months.

Good quality perpendicular geometry displays made from copper-Kapton laminates were obtained and used to fabricate models. The parallel geometry displays made from the copper-Kapton laminates had good line definition, but were defective in that considerable Kapton residue was left in the bottom of the Kapton channels.

4.2.2 Perpendicular Configuration Displays

The perpendicular line configuration is shown in Figure 4.2. Because of the long narrow geometry the liquid crystal was inserted in the line before the cover was attached. The total volume to be filled is less than one microliter. Care was taken to keep the liquid crystal from the seal area or a good seal could not be made. To accomplish the filling, a five microliter capacity syringe was used. The syringe had a Teflon plunger, a hollow platinum needle and a final Teflon filter. The syringe was mounted on a projection microscope equipped with a 40 power lens. The microscope was enclosed in a clean hood. The lines were filled by use of the syringe while they were observed on the projection screen. The liquid crystal was purified and its transition temperature was measured prior to use. No difficulty was experienced in filling the lines or keeping the seal area clean. The covers in the original models were attached by use of double sided masking tape.

Because of the difficulties with the electronics (section 5.3) only a few samples were made which were sealed with RTV compound.

4.2.3 Parallel Configuration Displays

The parallel configuration cell is shown in Figure 4.3. The cover of the parallel cell must be electrically conductive and transparent and its conductive side must come in contact with the liquid crystal. Two cover materials were obtained; a gold coated plastic from Liberty Glass and a silver coated plastic from DuPont.

Two problems are encountered in fabricating this cell. One was removing the Kapton from the channel; the other was sealing the cell. Since the channel is four inches long, 0.015 inch wide and only 0.0005 inch in depth, filling the channel after capping was impractical. On the other hand when the cover was placed over the channel after it was filled, the liquid crystal was drawn into the cover seal area by capillary action and the cover could not be sealed. To eliminate this problem, a cooling plate was built so that the liquid crystal could be frozen while the cover was installed. The cooling plate was placed in a dry nitrogen box to prevent condensation of water vapor when the sample was cooled. Several cells were fabricated and mechanically strong seals were made. However, the cells were either inoperative or operated over small areas only. Examination showed that the channels had Kapton residues at the bottom of the channels and that the conductors on the plastic peeled. Attempts to clear the bottom of the channel were unsuccessful and no other transparent conductive plastics were available. Because of these difficulties use of this configuration was discontinued.

SECTION 5

ELECTRONICS

5.1 Electronic System Design

The electronic system was designed to accept the VOR signals and drive the appropriate line on the liquid crystal display. A block diagram of the system is shown in Figure 5.1.

The input is obtained from a VOR bearing indicator and is assumed to comprise two 30 Hz square wave signals which represent the 30 Hz reference signal (f_1) and the 30 Hz bearing signal (f_2). The signal goes through a phase comparator whose output is a pulse of length proportional to the phase difference. The pulse length is measured electronically by having the comparator output pulse gate a 10.8 KC signal through the encoder. The output pulse contains one cycle of the 10.8 KC signal per degree of phase difference. These pulses are counted and the directional data stored in the register. These data are sent to the display where the input is decoded and the appropriate line driven to the "on" state.

5.2 Phase Detector and Register

The detailed circuitry of the digital phase detector is shown in Figure 5.2. The phase difference between f_1 and f_2 is determined by the phase comparator consisting of the binary flip-flops FF_1 and FF_2, and the EXCLUSIVE-OR gate consisting of AND gates G_1 and G_2, and NOR gate G_3. The initial states of flip-flops FF_1 and FF_2 are unknown, but regardless of their initial states, a negative going edge of f_1 will transfer the state of flip-flop FF_1 into that of flip-flop FF_2. Similarly a negative going edge of f_2 causes flip-flops FF_1 and FF_2 to assume opposite logical states. The output G_3 of the NOR gate will be a logical zero in that case; if the two flip-flops are in the same logical states, the output of G_3 will be a logical one. It follows then that the phase lag of f_2 with respect to f_1 is indicated by the duration of a logical one at the output of the EXCLUSIVE-OR gate. If the output is a logical one for the entire period of f_1 the phase lag is 360°. A shorter output pulse represents a proportionally smaller phase difference. This is illustrated in the timing diagram (Figure 5.3) which shows that the output of G_3 is a logical "1" for 120°. The output of the EXCLUSIVE-OR gate serves as a clock input to the JK flip-flop FF_3.

The phase difference is modulated using NAND gate G_4 and the timing oscillator f_t. The output of G_4 oscillates between logical "0" and "1" at the rate of f_t only when output of G_3 and the $\overline{C}$ output of binary FF_3 are logical "1"'s. Since FF_3 divides the frequency of f_2 by two, the pulse burst at the output of G_4 occurs once for each two input cycles as shown in Figure 5.3. The number of pulses in each burst is proportional to the phase difference between f_1 and f_2. The timing oscillator is set at a frequency of 10.8 KHz so that each pulse in a burst corresponds to one degree of phase difference between the signals f_1 and f_2.

The number of pulses is counted by the three decode counters D_1, D_2 and D_3. The counter D_1 divides the number of incoming pulses by a factor of ten. The counters D_2 and D_3 provide a binary-coded-decimal count of the phase difference. The registers LA_1 and LA_2 are used to store this information at the end of counting cycle. The output of the registers is altered only if the phase difference between f_1 and f_2 changes.

The setting and resetting of the decode counters is accomplished by a two stage counter made of an EXCLUSIVE-OR gate and flip-flops FF_4 and FF_5.

These two flip-flops have their J and K inputs tied to the output C of FF_3 – the output of the NOR gate G_7 serves as the clock input. The decode counters D_1, D_2 and D_3 are reset if both flip-flops FF_4 and FF_5 are in logical one state. The registers are controlled by the output Q_2 of FF_5 and the output $\overline{C}$ of FF_3.

The system was fabricated from TTL integrated circuits. The circuits used were: Texas Instruments Nos. SN7410N, SN7451N, SN7472N, SN7473N, SN7490N and Fairchild No. 9308. The SN7410N is a triple input NAND gate; The SN7451N is a dual, 2 wide, 2 input AND-OR-INVERT circuit; the SN7472N is a J-K master-slave flip-flop; the SN7490N is a decade counter and the 9308 is a dual 4 bit latch. The system was tested by inserting simulated VOR signals and observing the state of the registers as a function of the phase difference of the input signals. The system operated satisfactority.

5.3 Driver

The driver used originally to drive the perpendicular configuration display comprised a variac, a relay and a step-up transformer. The relay was used to provide the pulsed operation and the primary source of power was the 60 Hz mains. The driving voltage required for good contrast ranged from 100 to 200 volts.

An integrated circuit equivalent of this driver was built around the Dionics D1207N decoder and driver. This unit is rated at 225 volt maximum reverse bias. The circuit diagram for the integrated circuit driver is shown in Figure 5.4. Two square wave generators are used: generator I operates at 1.5 Hz and generator II at 60 Hz. During half the 1.5 Hz cycle the transistors in the Dionics units are turned off and points A and B remain at voltage, V. During the other half cycle the transistors are alternately turned on and off at 60 Hz producing the voltage waveforms at A and B shown in Figure 5.5. In operation, the liquid crystal cell is connected between A and B as shown in Figure 5.5. A typical cell has a measured capacitance of 8.2 pf at 60 Hz and a resistance of about 30 M.

The driver circuit was fabricated and tested. When a dummy resistance load was used to simulate the cell the driver operated satisfactorily. When an operational cell was connected, the cell functioned for a short period of time and then failed. The failure mode was determined to be a drop in cell resistance from many megohms to a few ohms. Similar cells operated on the relay-variac type driver did not fail.

Initially the failures were attributed to dirt in the liquid crystal which caused bridging under the influence of the high fields. Such bridges would also be formed when the relay driver was used, but they would be burnt-out by large surges of current from the driver. Such surges could not be obtained from the integrated driver. This theory was supported by the following experiments. When newly fabricated cells were connected to the relay driver and the voltage was slowly increased some cells burned out; others showed a large variation in resistance and then stabilized at 15 to 30 megohms. Stabilized cells could be driven by the integrated circuit driver for periods of two weeks without failure.

As a consequence of the above data, elaborate precautions were taken to keep the liquid crystal clean, for example the use of a final Teflon filter on the filling syringe as reported in Section 4.2.2. When the carefully prepared cells became available and were tested there was no improvement of performance.

Measurement of cell resistance and capacitance were made to determine if long RC time constants could be influencing the operating conditions. Several models were proposed, but the longest RC time constant obtained in any model was less than a millisecond which is short compared to all the driving frequencies.

The most recent theory is that the failures are due to dielectric breakdown. When operated at 150 volts the driver produces a field of 30,000 volts/cm. Liquid crystals in parallel cells were subjected to fields in excess of 80,000 volts/cm and there was no indication of breakdown. However, in the perpendicular configuration cell the etched lines can contain numerous sharp projections which would serve to intensify the local field perhaps to the extent that local breakdowns occur. If this is the case, low conductance bridges would be formed by the breakdown currents which would be externally limited by the integrated circuit driver.

It was found in the course of these studies, that a cell could be driven from a 60 V DC source if one terminal of the cell is grounded. The cell could be pulsed at a 1.5 Hz rate and the visibility was comparable to that obtained on the relay driver at higher voltages. A cell was driven in this manner for two weeks without change in contrast or resistance. It was then connected to the integrated circuit driver and it failed in ten hours of operation.

Operation on DC was not considered earlier because of anticipated lifetime problems; however, the recent lifetime data suggest that DC operation may be practical. The first program phase data show that a given contrast ratio can be achieved at much lower voltage operation on DC than that required for operation at 60 Hz.

5.4 Decoder

The decoder design was delayed in anticipation of a solution to the driver problem. When operation on a 60 V DC source was demonstrated, a decoder was designed based on the use of that type of drive. The decoding and drive arrangement for three lines is shown in Figure 5.6. To turn a particular display line on, the corresponding switch must be turned on to provide a current path between the voltage source and the ground. In the off state these switches must withstand the 60 V DC supply voltage, have a leakage current of less than 1,000 picoamps and a resistance (R_{off}) of the order of 10^{12} ohms. Commercially available MOS switches, for instance Solid State Scientific, Inc. SCL4016A, satisfy the imposed requirements on the leakage currents and the magnitude of R_{off} but are incapable of switching 60 volts. Thus the proposed selection system is not realizable with today's off-the-shelves devices. Since Dionics can make a driver that has a reverse voltage limit of 225 volts, suitable drivers should be technically feasible.

The arrangement of the complete selection system for 36 lines is shown in Figure 5.7. Except for the switches all components are commercially available. The 36 lines are arranged in four sets, three of ten lines and one of six lines. The data in register LA_2 is decoded and used to connect the voltage source to one of the four sets. The data in register LA_1 is decoded and used to short one of the sets of ten lines (0 to 9) in the vertical columns. Only one line will be connected both to the supply and to ground and so only one line will be selected. Pulsed operation can be achieved by use of the 3 to 5 Hz driving circuits shown to the right of the Dionics Transistor Array.

A total of nine pins is required on the display panel connector: six for address signals, one for the driving voltage, one for the pulsing signal and one for ground.

SECTION 6

SYSTEM EVALUATION AND CONCLUSIONS

6.1 System Evaluation

6.1.1 Display

The display comprised a ten-by-ten inch, flexible array of radial lines. Two designs for the radial lines were considered: parallel and perpendicular configurations.

The parallel configuration line geometry was simpler but severe fabrication and material problems were encountered. Kapton free channels could not be fabricated in the large displays although smaller samples could be fabricated by exercising careful process control. Flexible, transparent, conductive materials for use as electrodes were obtained, but the conductive coating was not stable in the presence of the liquid crystal and practical operating cells could not be made.

Voltage and visibility considerations led to the design of a multiple, fine-line pattern for the perpendicular configuration lines. Suitable display patterns were fabricated from copper-Kapton laminates, but attempts to fabricate displays from the preferred aluminum-Mylar laminates were frustrated by materials problems. The materials problems included quality and availability. These problems could probably be solved if large volume production was anticipated, but the extended fine line pattern required would probably result in low yields and consequent high cost.

Simulated operation of liquid crystal cells indicated that the long term stability of the liquid crystal cell would be adequate if the liquid crystal were maintained in a protective ambient. Operation on DC may even practical. Unfortunately, sealed display cell units did not become available until the end of the program, and lifetime tests on these cells could not be completed. Lifetimes in excess of one year are anticipated.

6.1.2 Electronics

The electronic system comprised a phase detector, an encoder, a driver and a decoder. The driver and decoder were to be contained on the display and as a consequence only nine connections had to be made to the 36-line display.

A practical phase detector and encoder was developed but serious problems were encountered with the integrated circuit driver. These problems resulted in substantial delays and precluded completion of a fully operational display model. These problems were not fully resolved even at the end of the program. Indications at the end of the program that a DC drive could be used led to the design of a very simple drive and decode system. The decoder cannot be implemented until a 60 V FET switch becomes available, but all other components are commercially available integrated circuits. When a suitable switch becomes available and if DC operation is feasible, then the proposed designs represent a simple and practical electronic interface system.

6.2 Conclusions

A navigational aid of the type proposed is technically feasible although some problems must still be solved. However, the projected low cost for the system does appear attainable in the near future. Unless a need for a high priced system of thi type develops, additional work in this area does not appear appropriate.

SECTION 7

BIBLIOGRAPHY

1. "Dynamic Scattering: A New Electro-optic Effect in Certain Classes of Nematic Liquid Crystals," Heilmeier, Zanoni and Barton, Proceedings IEEE, Vol. 56, No. 7, p. 1162 (July 1968).

2. "Note on Transient Current Measurements in Liquid Crystals and Related Systems," Heilmeier and Heyman, Physical Review Letters, Vol. 18, No. 15, p. 583 (10 April 1967).

3. "Transient Behavior of Domains in Liquid Crystals," Heilmeier, Journal of Chemical Physics, Vol. 44, No. 2, p. 644 (1966).

4. "Orientational Oscillations in Nematic Liquid Crystals," Heilmeier and Helfrich, Applied Physics Letters, Vol. 16, No. 4, p. 155 (February 1970).

5. "Possible Ferroelectric Effects in Liquid Crystals and Related Liquids," Williams and Heilmeier, Journal of Chem. Physics, Vol. 44, No. 2, p. 638 (January 1966).

6. "Liquid Crystal Display Devices," Heilmeier, Scientific American, Vol. 222, p. 100 (1970).

7. "Further Studies of the Dynamic Scattering Mode in Nematic Liquid Crystals," Heilmeier, Zanoni and Burton, IEEE Transactions on Electron Devices, Vol. ED17, No. 1, p. 22 (January 1970).

8. "A Simplified Electrohydrodynamic Treatment of Threshold Effects in Nematic Liquid Crystals," Heilmeier, Proceedings IEEE, Vol. 59, No. 3, p. 422 (March 1971).

9. "Anisotropic Ultrasonic Properties of a Nematic Liquid Crystal," Lord and Labes, Physical Review Letters, Vol. 25, No. 9, p. 570 (August 1970).

10. "Liquid Crystals," Fergason, Scientific American, p. 77 (1964).

11. "Cholestric Liquid Crystals for Optical Applications," Kahn, Applied Physical Letters, Vol. 18, No. 6, p. 231 (15 March 1971).

12. "Behavior of Anisotropic Liquids in an Electric Field," Soviet Physics, Vol. 9, p. 235 (1964).

13. "Reflective Liquid Crystal Television Display," John A. Realte, Proceedings IEEE, Vol. 5, No. 12, p. 2147 (1968).

14. "Light Deflection Phenomena in an AC Excited Nematic Liquid Crystal Sample," Sun Lu and Derrick Jones, Journal of Applied Physics, Vol. 42, p. 2138 (1971).

15. "Electrically Scanned Analog Liquid Crystal Displays," Soref, Applied Optics, Vol. 9, No. 6, p. 1323 (1970).

16. "Reversible Ultrasonic Imaging with Liquid Crystals," Mangreen, Nimoy and Young, Applied Physics Letters, Vol. 17, No. 2, p. 51 (1970).

17. "Dynamic Scattering in Room-Temp. Nematic Liquid Crystal," Derrick Jones, Linda Creigh and Sun Lu, Applied Physics Letters, Vol. 16, No. 2, p. 61 (1969).

18. "Electrical Field Distribution Associated with Dynamic Scattering in Nematic Liquid Crystals," Sun Lu and Derrick Jones, Applied Physics Letters, Vol. 16, No.12, p. 484 (1969).

19. "Electrophotographic Imaging with Cholesteric Liquid Crystals," Haas and Adams, Applied Optics, Vol. 7, No. 6, p. 1203 (1968).

20. "Electric Field Hysterisis Effects in Cholesteric Liquid Crystals," Melamed and Rubin, Applied Physics Letters, Vol. 16, No. 4, p. 149 (1969).

21. "Voltage Induced Vorticity and Optical Focusing in Liquid Crystals," Penz, Physical Review Letters, Vol. 24, No. 25, p. 1405 (1970).

22. "New Electro Optic Effect in a Room Temperature Nematic Liquid Crystals," Haas, Adams and Elannery, Physical Review Letters, Vol. 25, No. 19, p. 1325 (1970).

23. "Temperature Dependence of Birefringence in Liquid Crystals, Balzaini, Physical Review Letters, p. 914 (October 1970).

24. "Hydrodynamic Instabilities in Nematic Liquids Under AC Electric Fields," Orsay Liquid Crystal Group, Physical Review Letters, Vol. 25, p. 1642 (December 1970).

25. "Experiment with Cholesteric Liquid Crystals," Fergason, American Journal of Physics, Vol. 38, No. 4, p. 425 (1970).

26. "Scattering of Coherent Light from Nematic Liquid Crystals in Dynamic Mode," Journal of Applied Physics, Vol. 40, No. 10, p. 4049 (1970).

27. "Optical Contrast Enhancement in Liquid Crystal Devices by Spatial Filtering," Applied Physics Letters, Vol. 18, No. 1, p. 5 (1971).

28. "Current and Magnetic Field Induced Order and Disorder in Ordered Nematic Liquid Crystals," Teany and Migim, Journal of Applied Physics, Vol. 41, No. 3, p. 998 (1969).

29. "The Physics and Chemistry of Liquid Crystals," Soref, SID Digest, p. 122 (May 1971).

30. "Light Scattering in Electric Field Devices Nematic Liquid Crystals," Goodman, SID, p. 124 (May 1971).

31. "Transient Scattering of Light by Pulsed Liquid Crystal Cells," L.S. Cosentino, SID, p. 126 (May 1971).

32. "MOS Driven Liquid Crystal Display," Bosell and Robert, SID, p. 128 (May 1971).

33. "Cholestric Nematic Phase Transition Displays," Wysocki, et al, SID, p. 130 (May 1971).

34. "Nematic Liquid Crystals - Cinemicerography of Electrohydiodynamic Instabilities," Kashnow, SID, p. 134 (May 1971).

35. "Guest Host Interactions in Nematic Liquid Crystals - A New Electro Optic Effect," Heilmeier and L. A. Zanoni, Applied Physics Letters, Vol. 13, No. 3, p. 91 (1968).

36. "Solid Facts about Liquid Crystals," R. A. Soref, Laser Focus, p. 45 (September 1970).

37. "Now That the Heat Is Off, Liquid Crystals Can Show Their Colors Everywhere," Joseph Castellano, Electronics, (July 6, 1970).

38. "Electrohydrodynamic Instabilities in Nematic Liquid Crystals," W. H. DeJeu, C. J. Gerritsma and Van Boster, Physics Letters, Vol. 34A, No. 4, p. 203 (8 March 1971).

39. "Performance Characteristics of Nematic Liquid Crystal Display Devices," L.T. Creagh, A.R. Kinetz, and R.A. Reynolds, IEEE Trans. on Electron Devices, Vol ED-18, No. 9, pp. 672-675, (September 1971).

40. "Deformation of Nematic Liquid Crystals with Vertical Orientation in Electric Fields," M.F. Schiekel and K. Fahrenschon, Appl. Phys. Letters, Vol. 19, pp. 391-393, (1971).

41. "Effects of Additions of Cholesterics on Nematic Liquid Crystal Properties," B. Kerllenevich and A. Coche, J. Appl. Phys., Vol. 42, pp.5313-5315, (1971).

42. "Electrically Controlable Domains in Nematic Liquid Crystals," W. Greubel and V. Wolff, Appl. Phys. Letters, Vol. 19, pp. 213-215 (1971).

43. "Effects of Dopants on Display Characteristics of the Nematic 4-Methoxybenzylidence-4-Buttaniline," Linda T. Creagh and Allan R. Kinetz, Meeting Abstracts-ACS Meeting, Wash., D.C. (September 1971).

44. "Dielectric and Resistivity Measurements on Room Temperature Nematic MBBA, F. Rondelez, D. Diquet, and G. Durand, Mol. Cryst. and Liq. Cryst., Vol. 15, pp. 183-188 (1971).

45. "Voltage-Dependent Optical Activity of a Twisted Nematic Liquid Crystal," M. Schadt and W. Helfrich, Applied Physics Letters, Vol. 18, pp.127-128, (1971).

46. "Electrically Controlled Birefringence of Thin Nematic Films," S.A. Soref and M.J. Rafuse, Journal of Applied Physics, Vol. 43, pp.2029-2037(1972).

47. "Theory of Birefringence of Nematic Liquid Crystals," S. Chandrasekhar, D. Krishnamurti, and N.V. Madhusudana, Molecular Crystals and Liquid Crystals, Vol. 8, pp.45-69(1969).

48. "Orientational Order in p-Azoxyanisole, p-Azoxyphenetole and Their Mixtures in the Nematic Phase," S. Chandrasekhar and N.V. Madhusudana, Journal de Physicque, Vol. 30, pp.C4-24(1969).

49. "On the Measurement of Indicies of Refraction of Nematic Liquids," I. Haller, H.A. Huggins and M.J. Freiser, Molecular Crystals and Liquid Crystals, Vol. 16, pp.53-59(1972).

50. A.E. Lord, Jr., "Ultrasonic Investigation of the Cholesteric-Nematic Transition," to be published in *Moleculer Crystals and Liquid Crystals*.

APPENDIX A

Commercially Available Room Temperature Nematics

Eastman Organic Chemicals Rochester, New York	10 - 41°C 5 - 105°C	MBBA No. 11246 No. 11643
Liquid Crystal Industries 460 Brown Avenue Turtle Creek, Pennsylvania	18 - 80°C	Nematic Liquid Crystal
Vari-Light Corporation 9770 Cronklin Road Cincinnati, Ohio	10 - 47°C 10 - 47°C	VL 1047N MBBA (Purified)
EM Laboratories 500 Executive Avenue Elmsford, New York	16 - 74°C -5 - 75°C	Merck, Licristal IV Merck, Licristal V

APPENDIX B

STABILITY DATA

	Electrode	Run	Life (days)	Average Contrast Ratio	Remarks
Eastman MBBA No. 11246	Ag	3/26/72 - 4/25/72	36	3.8	electrode failed-a
		3/20/72 - 5/26/72	67	2.8	electrode failed
	Al	3/19/71 - 5/4/72	46	1.9	electrode failed
		6/28/71 - 8/4/71	39	1.6	
		8/6/71 - 9/8/71	33	1.5	
		9/27/71 - 6/23/72	270	2.8	
		11/17/71- 9/13/72	301	3.4	
	Au	8/6/71 - 8/31/71	25	2.4	electrode failed
		9/27/71 - 11/5/71	39	4.4	electrode failed
		11/17/71- 2/28/72	103	4.1	electrode failed
		3/20/72 - 10/25/72	189	2.3	
		3/20/72 - 8/16/72	149	2.2	
	Cu	3/25/71 - 6/4/71	71	2.2	
		6/28/71 - 9/13/71	77	2.0	
		9/27/71 -10/15/71	18	2.7	electrode failed
		11/17/71-12/17/71	81	2.7	electrode failed
		3/20/72 - 4/25/72	36	1.8	electrode failed
		3/20/72 - 4/25/72	36	2.8	electrode failed
	Ni	3/20/72 - 6/23/72	95	1.8	electrode failed-a
		3/20/72 - 9/13/72	177	2.3	electrode failed-a
	Nesa	3/19/71 - 5/5/71	47	1.7	
		6/28/71 - 7/20/71	22	1.5	
		8/6/71 - 8/17/71	11	1.6	
		9/27/71 - 3/20/72	175	2.1	
		11/17/71- 5/10/72	175	2.4	
	Nesatron	4/28/71 - 6/4/71	37	2.1	
		6/28/71 - 7/30/71	32	1.7	
		8/6/71 - 8/17/72	11	1.8	
		9/27/71 - 6/23/72	270	1.9	
		11/17/71- 3/16/72	120	2.1	
Liquid Crystal Ind.	Al	6/28/71 - 7/20/71	22	2.1	electrode failed
		8/6/71 - 9/27/71	52	2.0	
		9/27/71 - 11/5/71	39	2.3	
		11/17/71- 3/16/72	120	3.3	leaked
	Au	8/6/71 - 10/4/71	59	2.2	
		9/27/71 - 2/28/72	154	3.3	
		11/17/71- 3/16/72	120	2.5	
	Cu	6/28/71 - 9/27/71	91	2.9	electrode failed
		9/27/71 - 11/5/71	39	2.1	leaked
		11/17/72- 1/25/72	69	2.5	electrode failed
	Nesa	6/28/71 - 7/1/72	3	2.0	
		7/6/71 - 7/20/71	14	1.7	
		8/6/71 - 8/17/71	11	2.6	
		9/27/71 - 11/5/71	39	1.9	
		11/17/71- 1/25/72	69	2.3	
	Nesatron	6/28/71 - 8/17/71	50	2.1	
		9/27/71 - 11/5/71	39	2.0	
		11/17/71- 1/25/72	69	2.3	

	Electrode	Run	Life	Average Contrast Ratio	Remarks
Varilight 1047	Ag	3/20/72 - 4/25/72	36	2.4	electrode failed
		3/20/72 - 5/10/72	51	3.0	electrode failed
	Al	8/4/71 - 4/25/72	265	2.3	leaked
		9/27/71 - 6/23/72	270	2.3	
	Au	8/4/71 - 8/17/71	13	2.8	electrode failed
		9/27/71 - 2/28/72	154	4.1	
		3/20/72 - 4/25/72	36	3.1	electrode failed
		3/20/72 - 5/10/72	51	2.0	electrode failed
	Cu	8/6/72 - 9/8/72	33	2.3	electrode failed
		3/20/72 - 4/25/72	36	4.2	electrode failed
		3/20/72 - 4/25/72	36	3.4	electrode failed
	Ni	3/20/72 - 6/23/72	95	2.5	electrode failed-a
		3/20/72 - 7/26/72	129	2.0	electrode failed-a
	Nesa	8/4/71 - 6/23/72	324	2.0	
		9/27/71 - 6/23/72	270	2.4	
	Nesatron	8/4/71 - 6/23/72	324	2.1	
		9/27/71 - 5/26/72	240	1.8	
Merck Licristal IV	Ag	3/20/72 - 4/25/72	36	2.2	electrode failed-a
		3/20/72 - 5/26/72	67	2.5	electrode failed-a
	Al	8/4/71 -	(589)	2.7	
		9/27/71 - 3/14/73	535	2.4	
	Au	8/4/71 - 10/8/71	93	2.8	
		9/27/71 - 11/5/71	39	3.3	electrode failed
		3/20/72 - 3/14/73	360	2.0	electrode failed
		3/20/72 - 4/25/72	36	2.8	electrode failed
	Cu	8/6/71 - 11/5/71	91	2.0	electrode failed
		9/27/71 - 10/8/71	11	2.9	electrode failed
		3/20/72 - 5/26/72	67	1.9	electrode failed-a
		3/20/72 - 6/23/72	95	2.5	electrode failed-a
	Ni	3/20/72 - 9/13/72	177	3.6	electrode failed-a
		3/20/72 - 6/23/72	95	2.4	electrode failed-a
	Nesa	8/4/71 -	(589)	2.0	
		9/27/71 - 4/25/72	211	2.2	
	Nesatron	8/4/71 -	(589)	2.2	
		9/27/71 -	(589)	2.0	
Merck Licristal V	Ag	4/25/72 - 5/26/72	31	2.4	electrode failed-a
		4/25/72 - 5/26/72	31	1.8	electrode failed-a
	Al	4/25/72 -	(324)	2.3	
		4/25/72 -	(324)	2.0	
	Au	4/25/72 - 3/14/73	324	2.6	electrode failed-a
		4/25/72 - 6/23/72	59	1.9	electrode failed
	Cu	4/25/72 - 6/23/72	59	1.8	electrode failed-a
		4/25/72 - 6/23/72	59	1.6	electrode failed-a
	Ni	4/25/72 - 6/23/72	59	1.7	electrode failed-a
		4/25/72 - 6/23/72	59	2.1	electrode failed-a

	Electrode	Run	Life	Average Contrast Ratio	Remarks
Eastman	Ag	4/25/72 - 6/23/72	59	2.9	electrode failed
Nematic		4/25/72 - 7/26/72	93	3.8	electrode failed-a
Mixture	Al	4/25/72 - 3/14/73	324	3.3	isotropic & discolored
No.11643		4/25/72 - 11/15/72	204	2.6	isotropic & discolored
	Au	4/25/72 - 6/23/72	59	3.6	electrode failed
		4/25/72 -	(324)	4.9	
	Cu	4/25/72 - 6/23/72	59	3.5	isotropic and discolored
		4/25/72 - 5/26/72	31	2.3	isotropic and discolored
	Ni	4/25/72 - 8/16/72	113	2.7	
		4/25/72 - 9/13/72	151	2.8	

a - indicates electrode failed only where in contact with air.

() - indicates cell is still running.

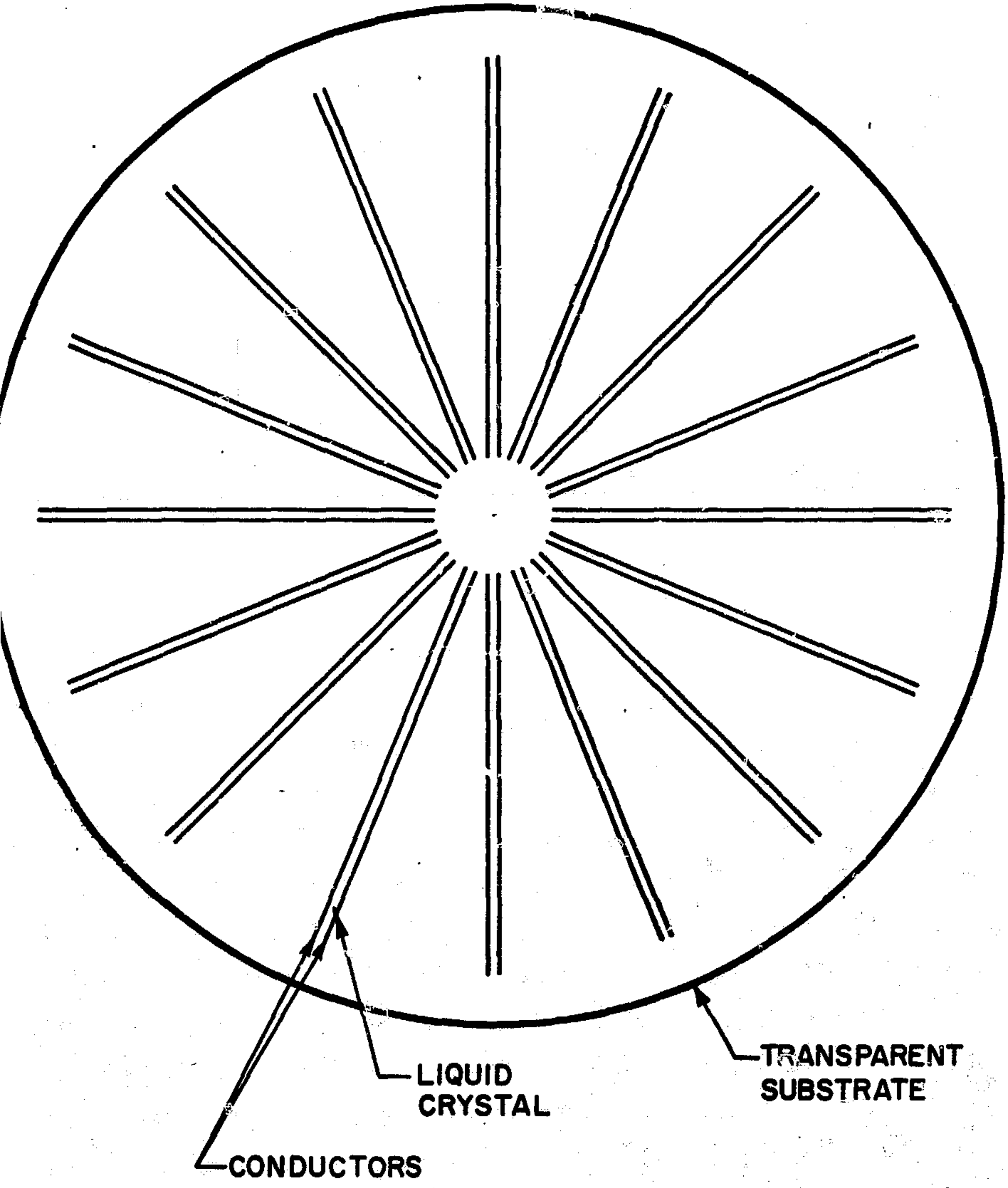
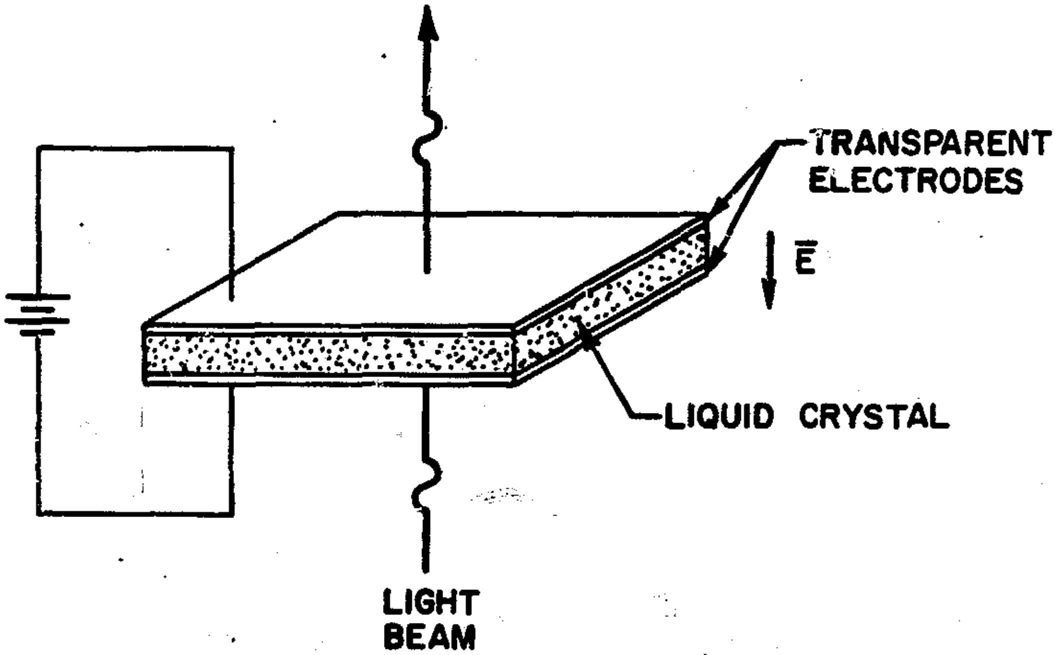
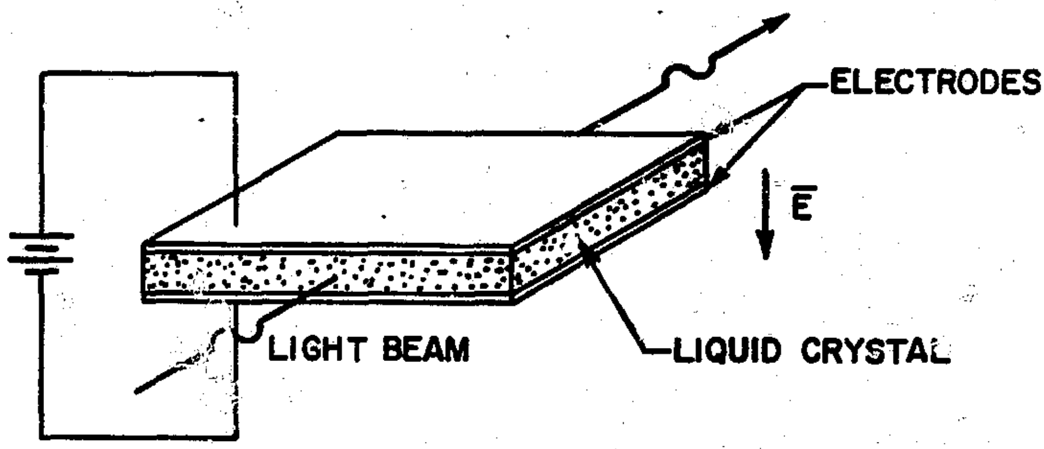


Figure 1.1 Display Panel



(a)



(b)

Figure 2.1 Basic Cell Configurations

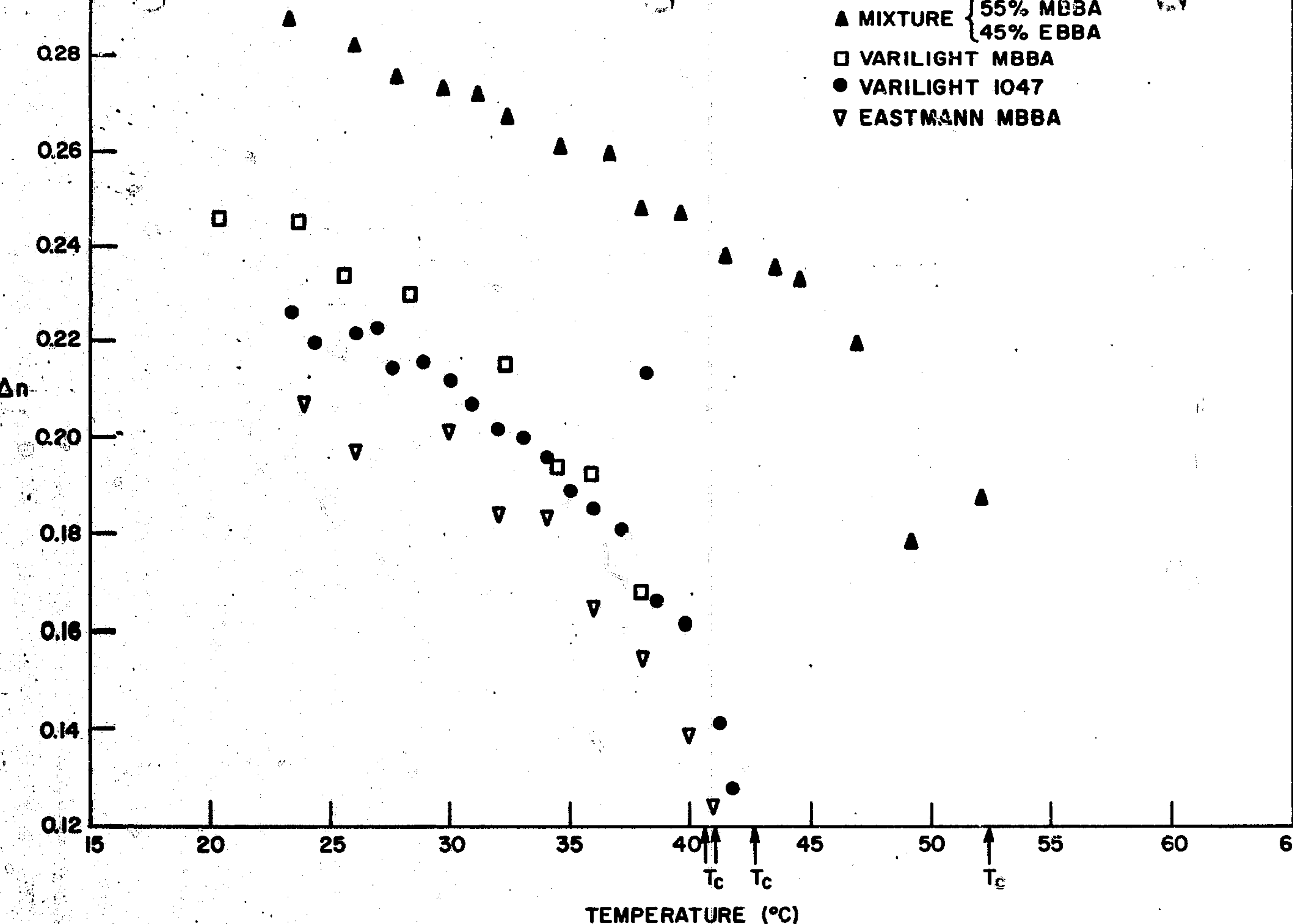


Figure 3.1a . Birefringence as a Function of Temperature

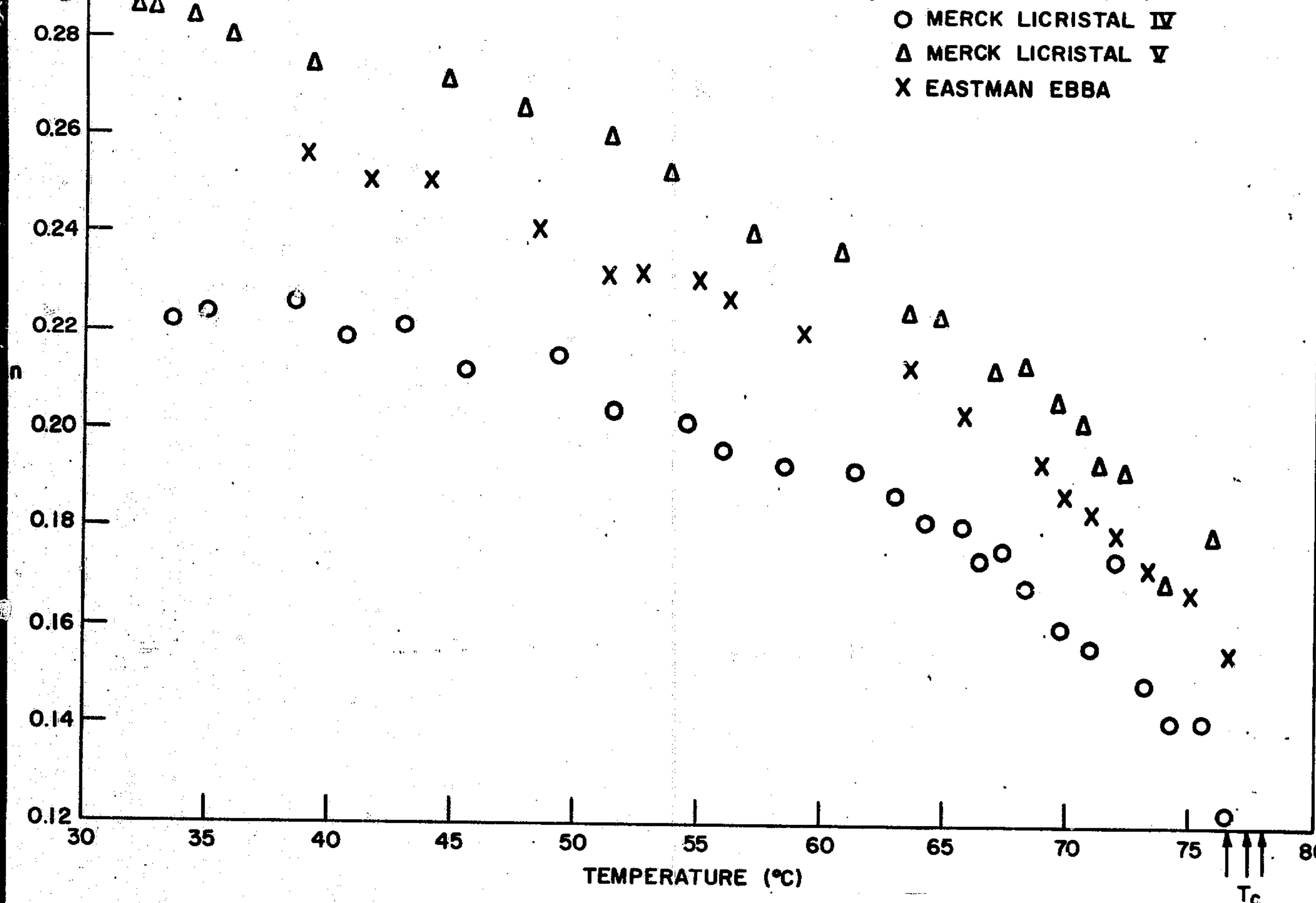
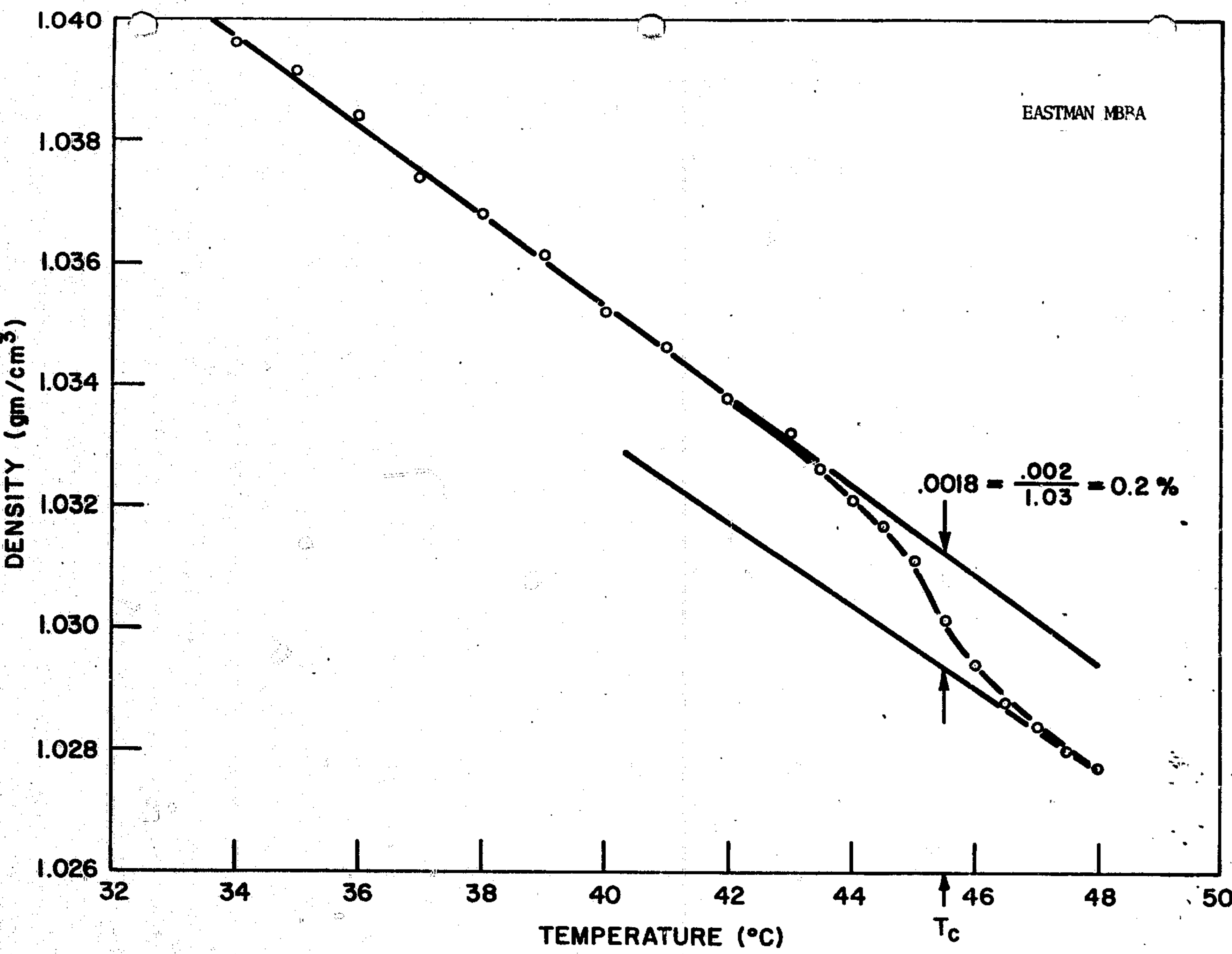


Figure 3.1b Birefringence as a Function of Temperature



3.2a Index of Refraction as a function of Temperature

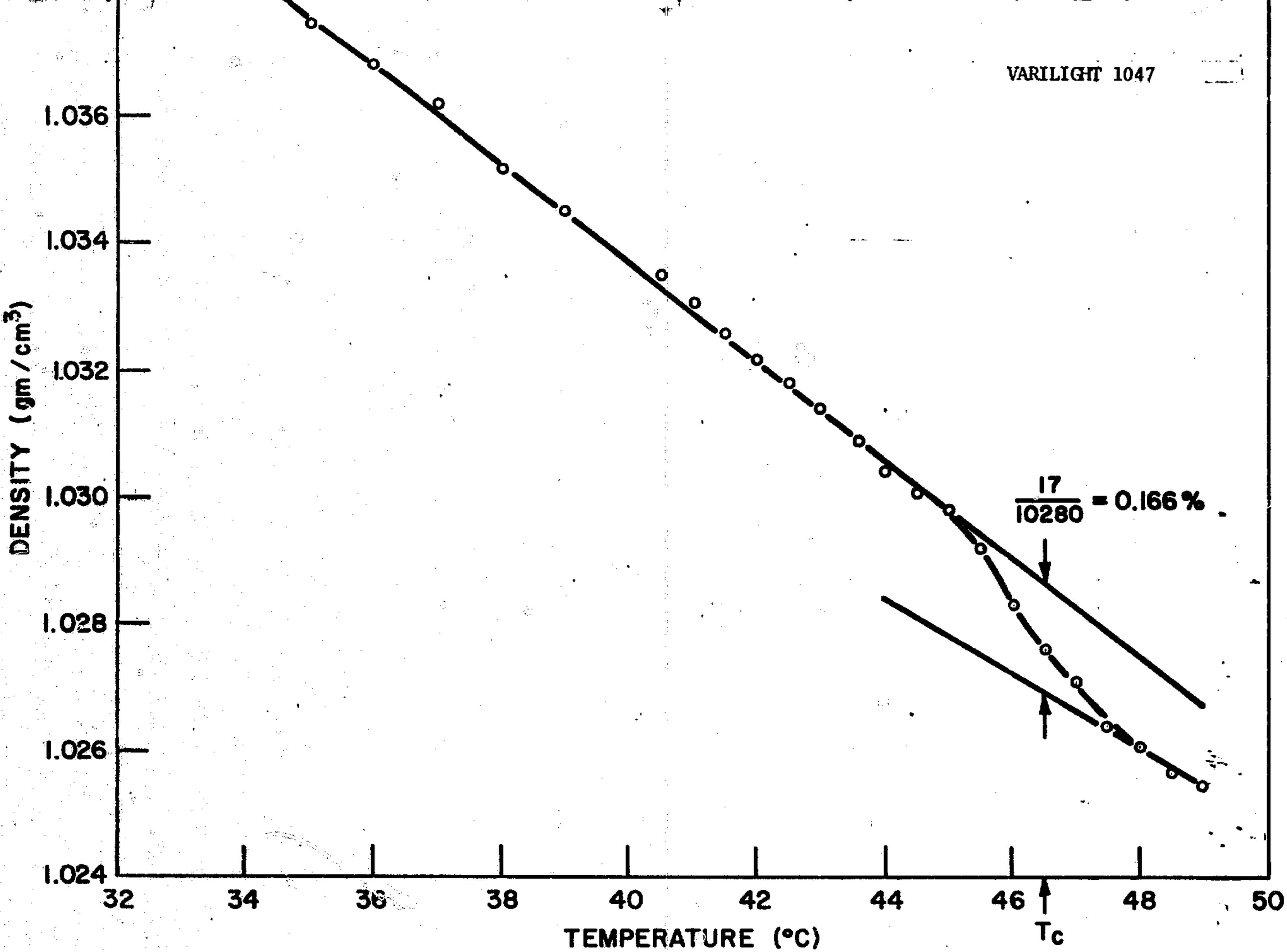


Figure 3.2b Index of Refraction as a Function of Temperature

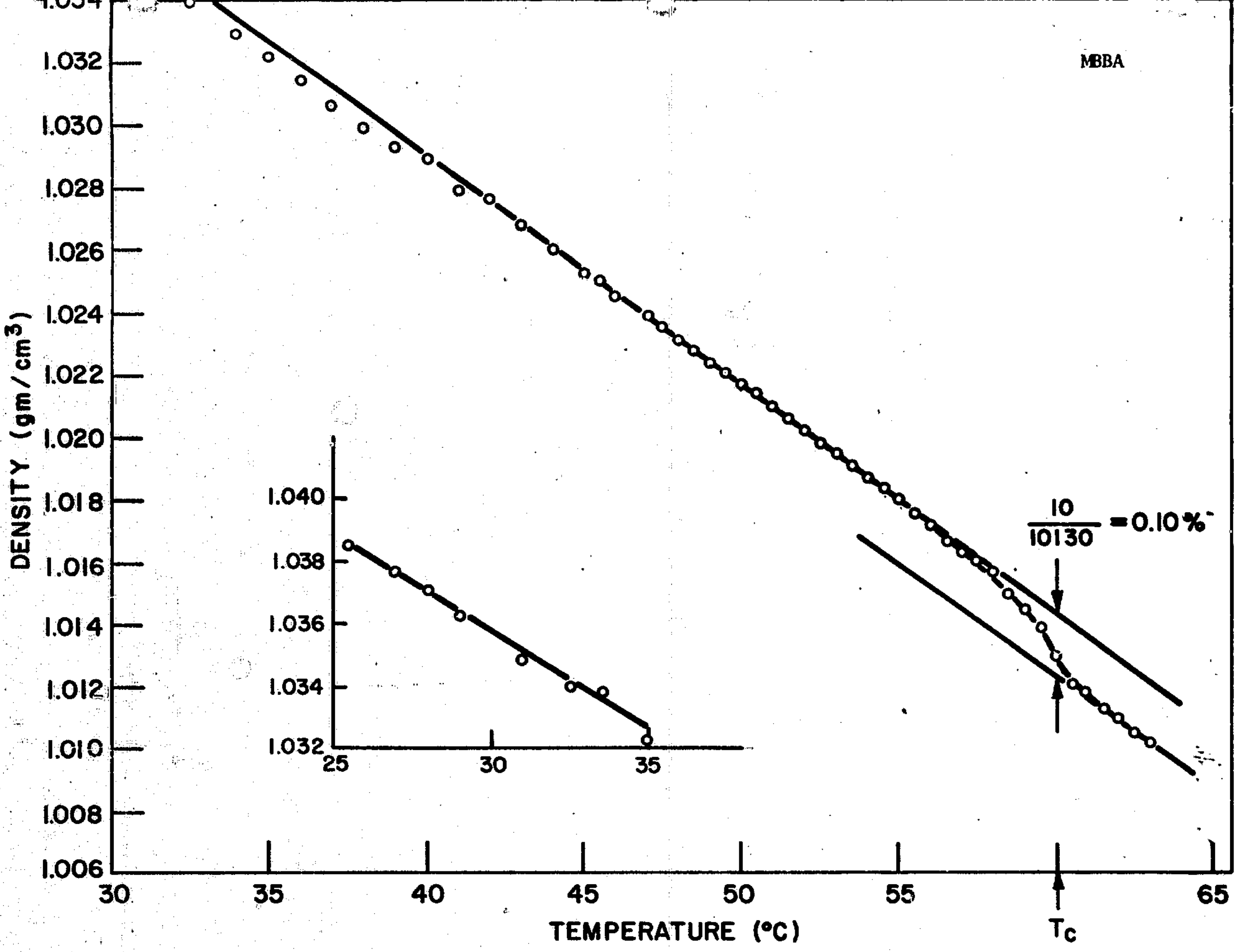


Figure 3.2c Index of Refraction as a Function of Temperature

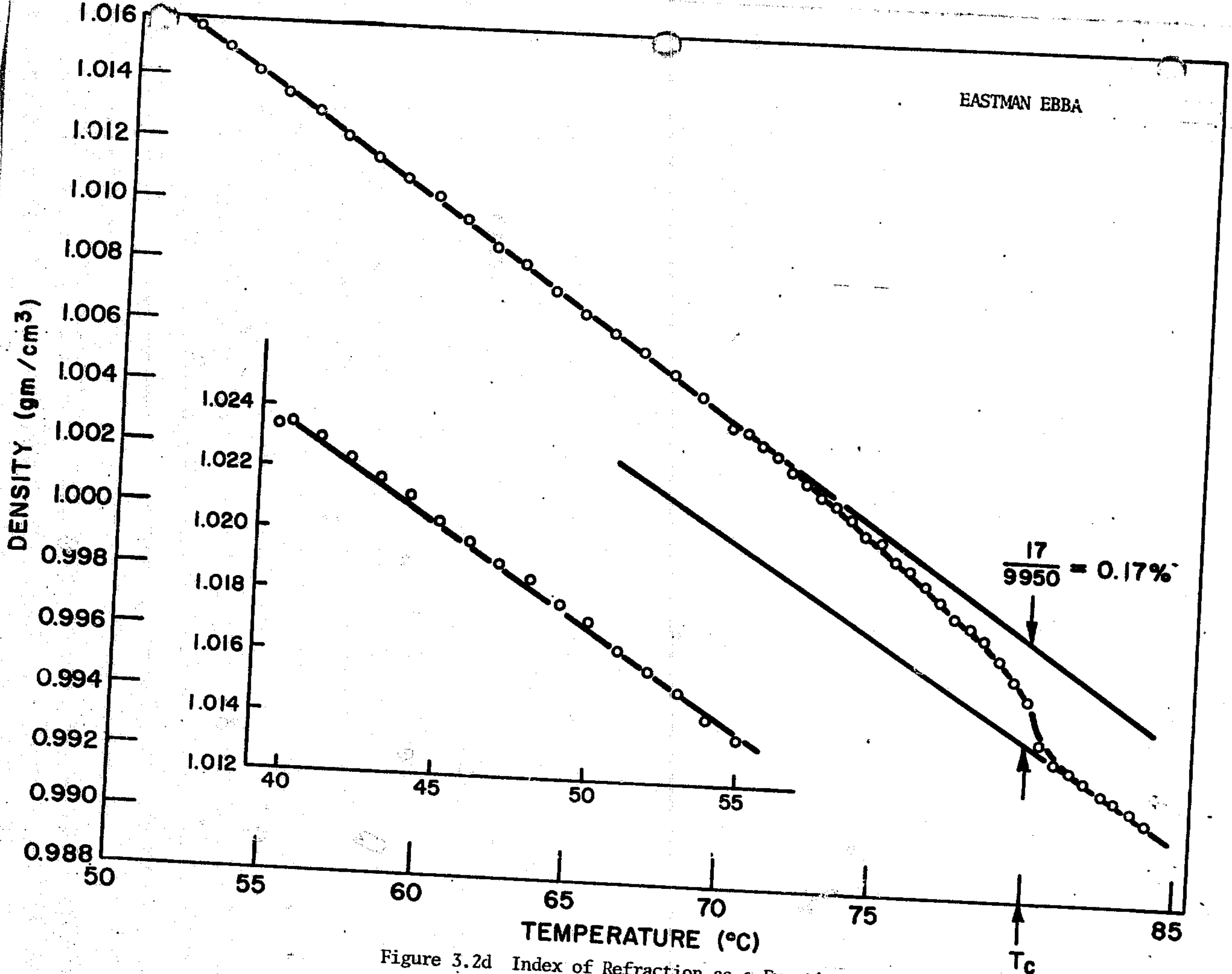


Figure 3.2d Index of Refraction as a Function of Temperature

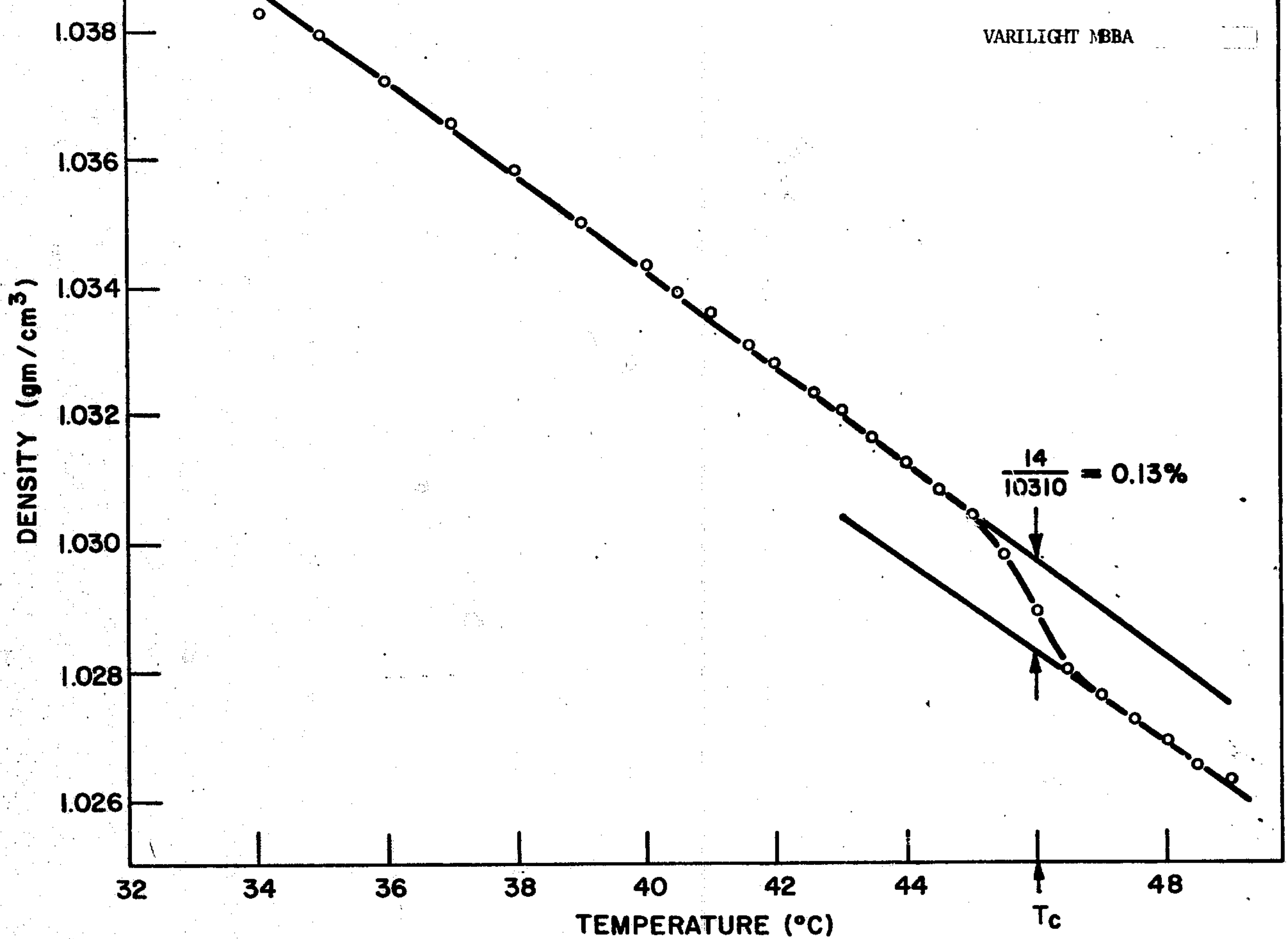


Figure 3.2e Index of Refraction as a Function of Temperature

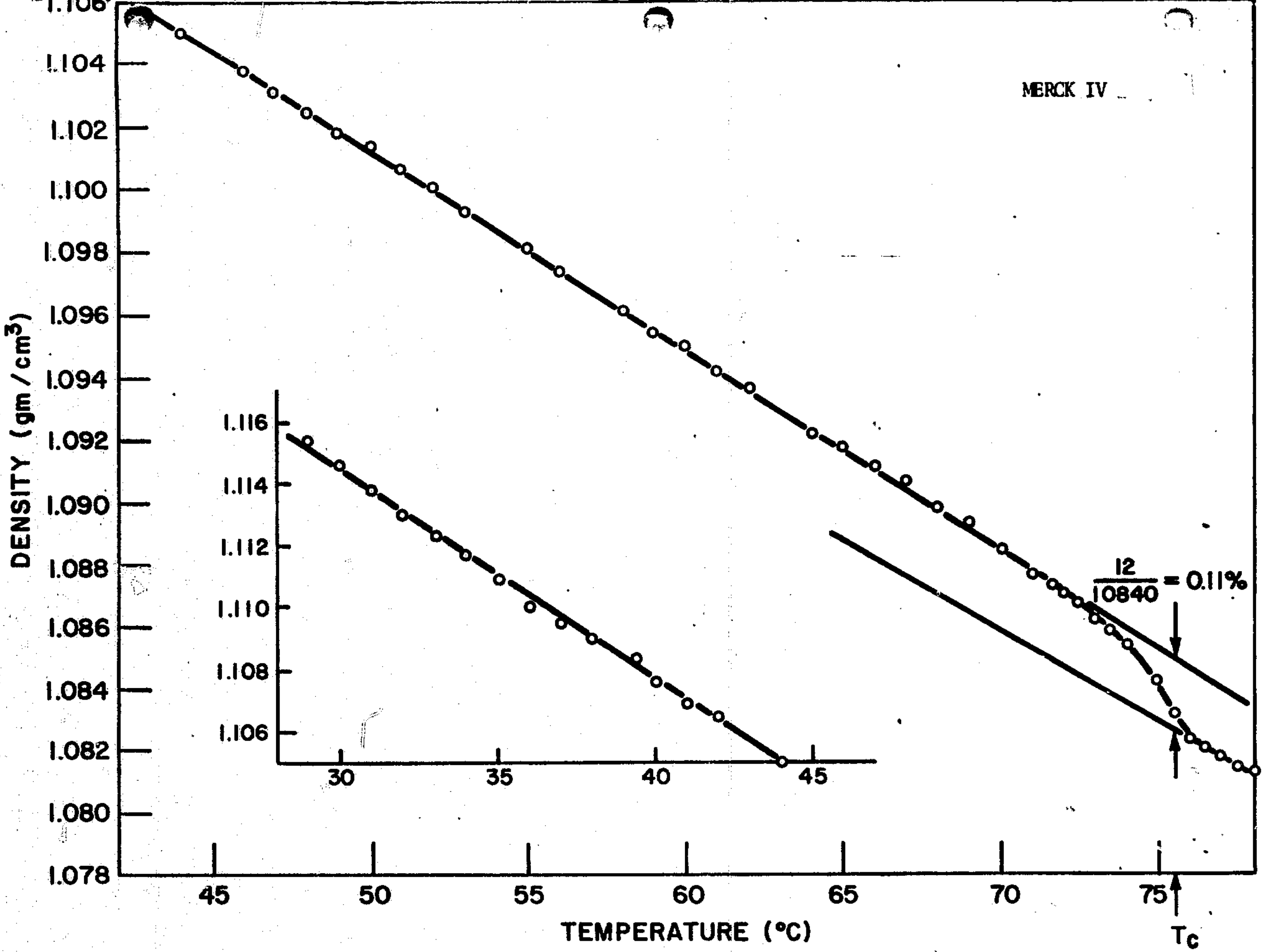


Figure 3.2f Index of Refraction as a Function of Temperature

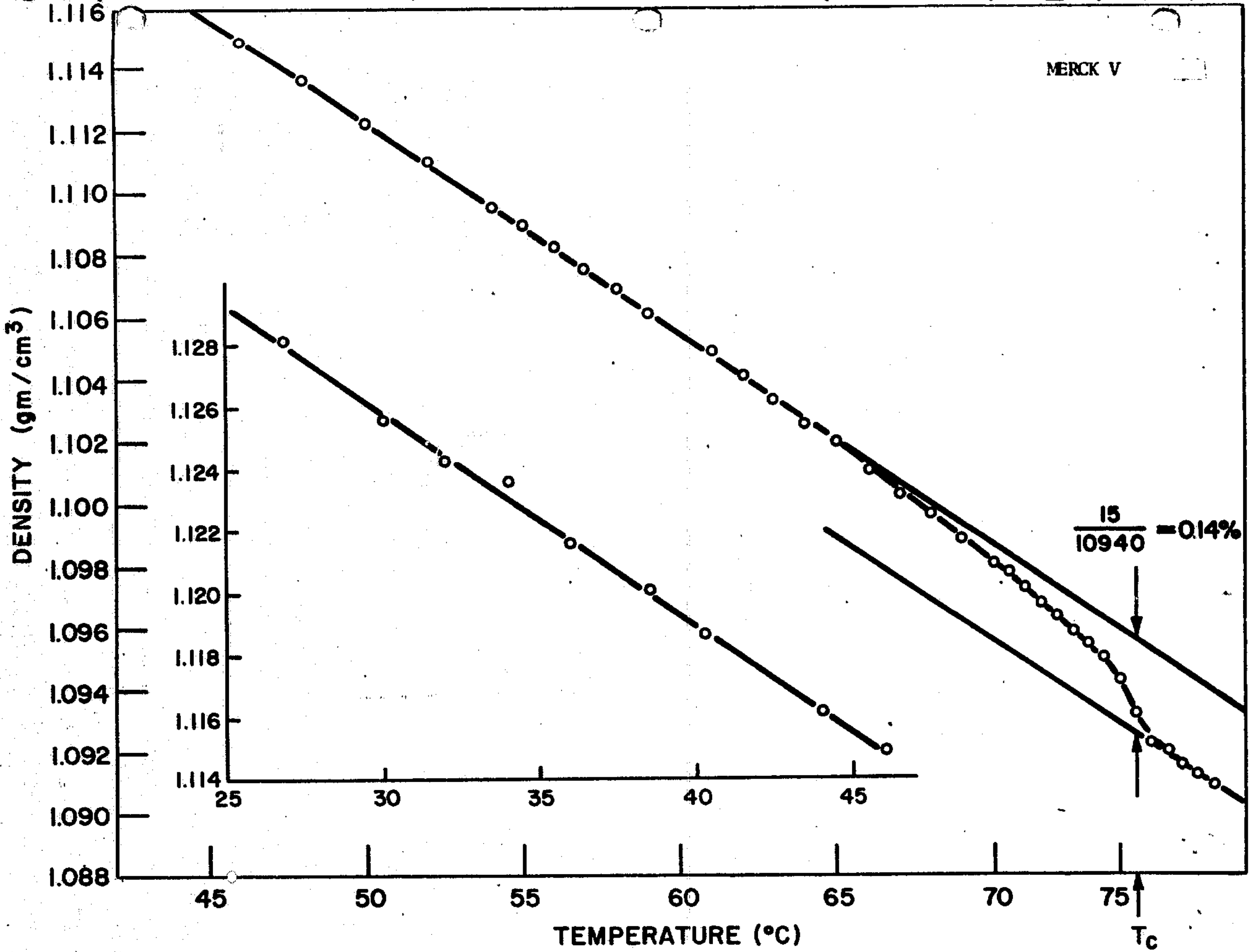


Figure 3.2g Index of Refraction as a Function of Temperature

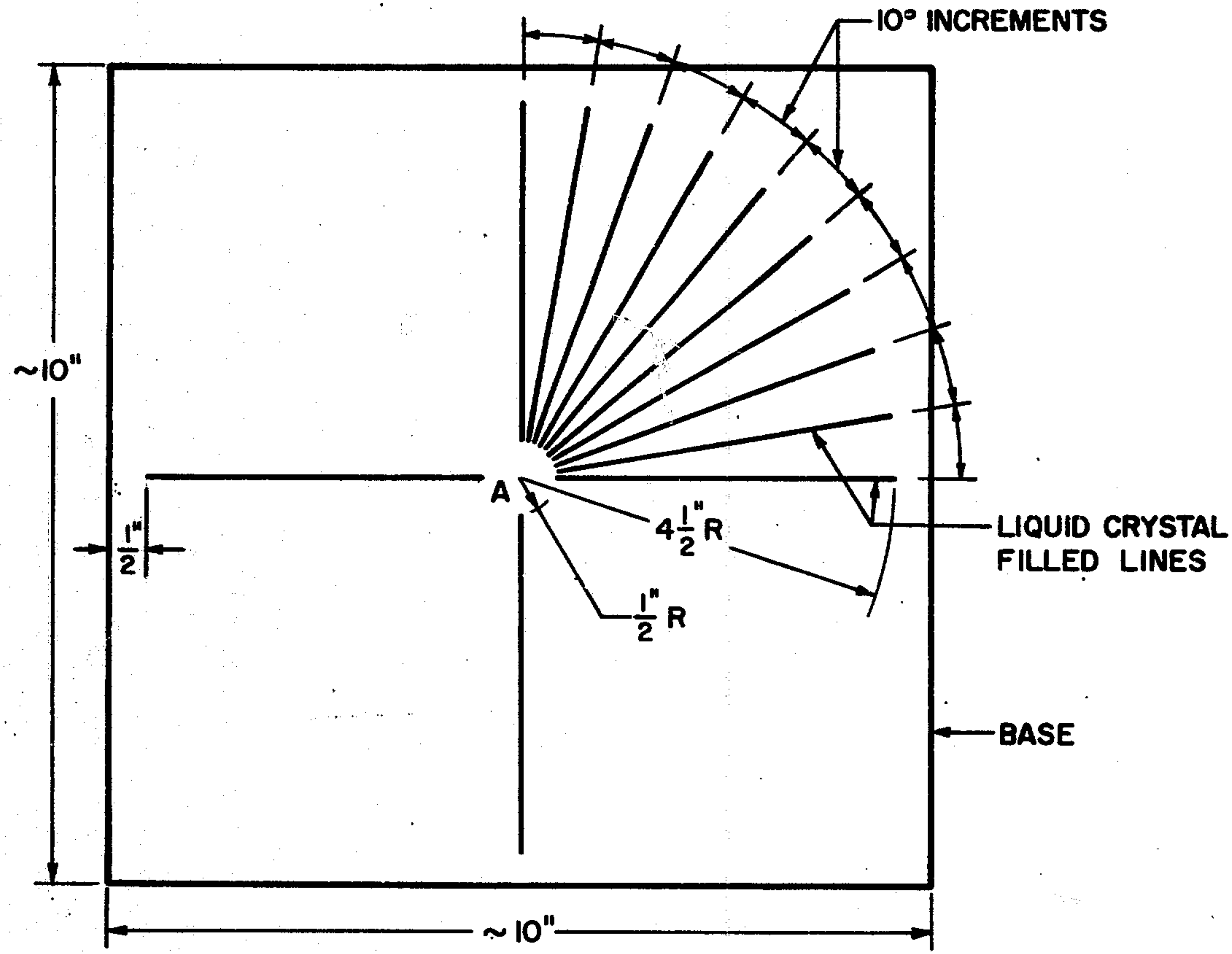


Figure 4.1 General Configuration of Display Model

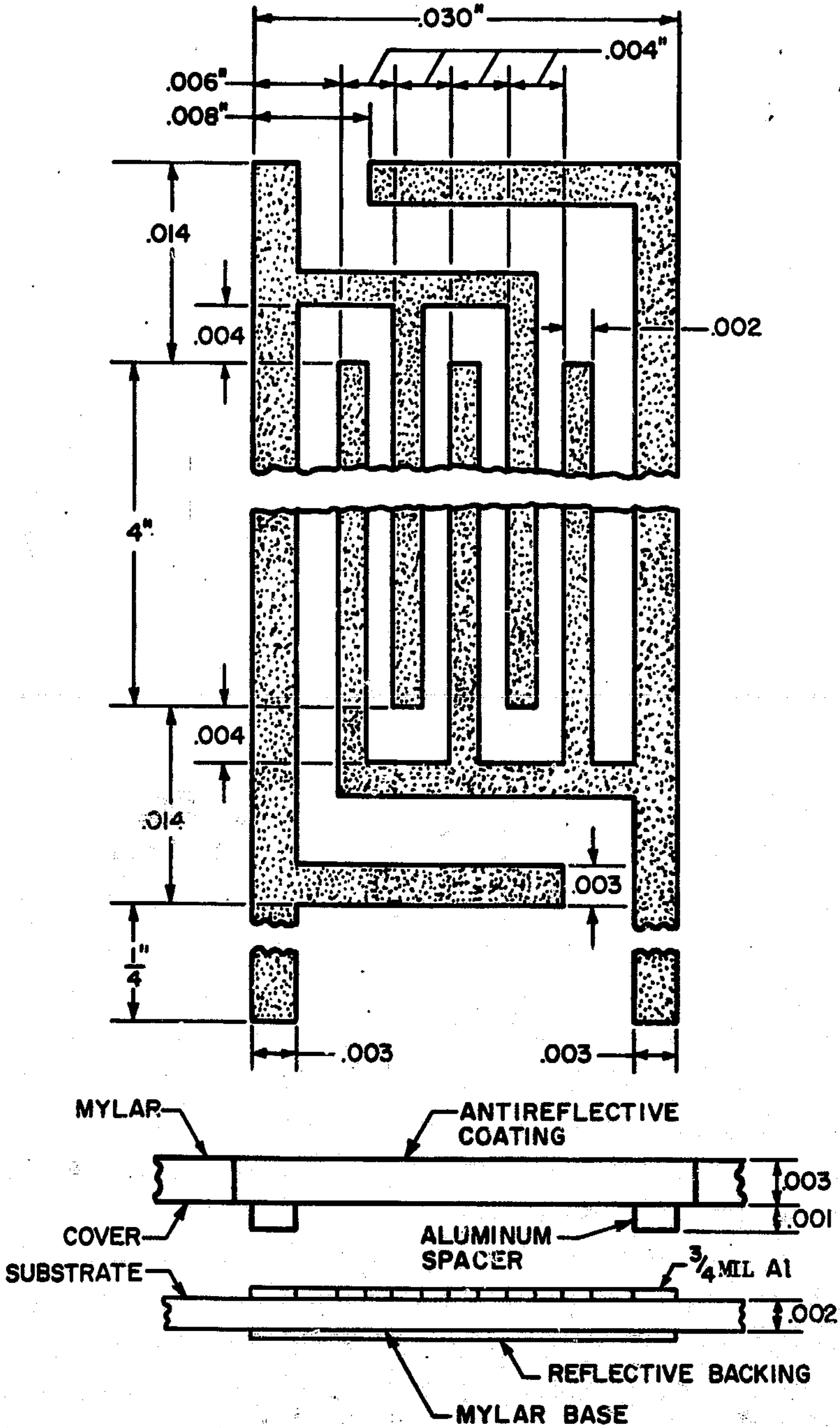


Figure 4.2 Perpendicular Line Detail

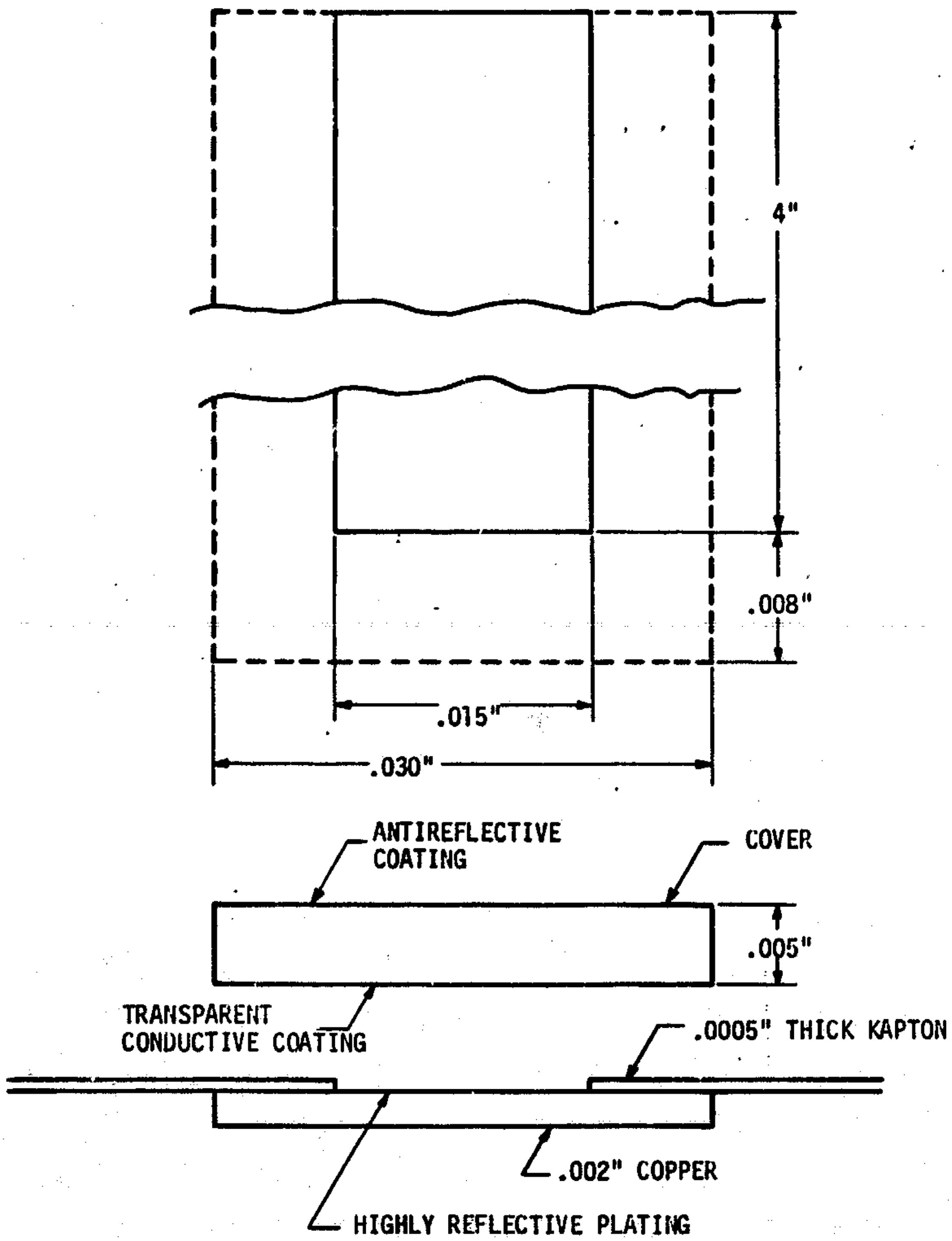


Figure 4.3 Parallel Line Detail

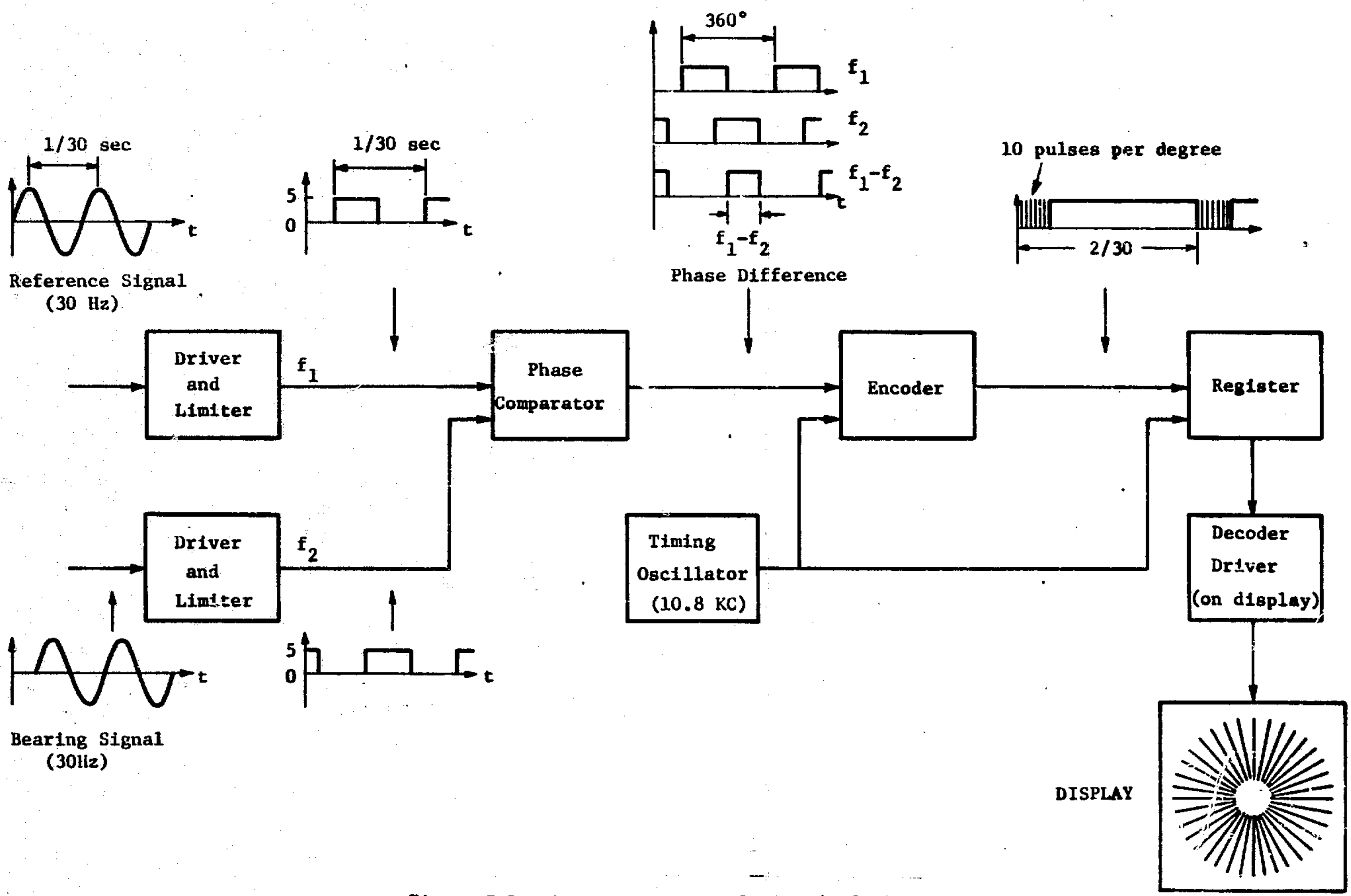


Figure 5.1 Block Diagram of Electronic System

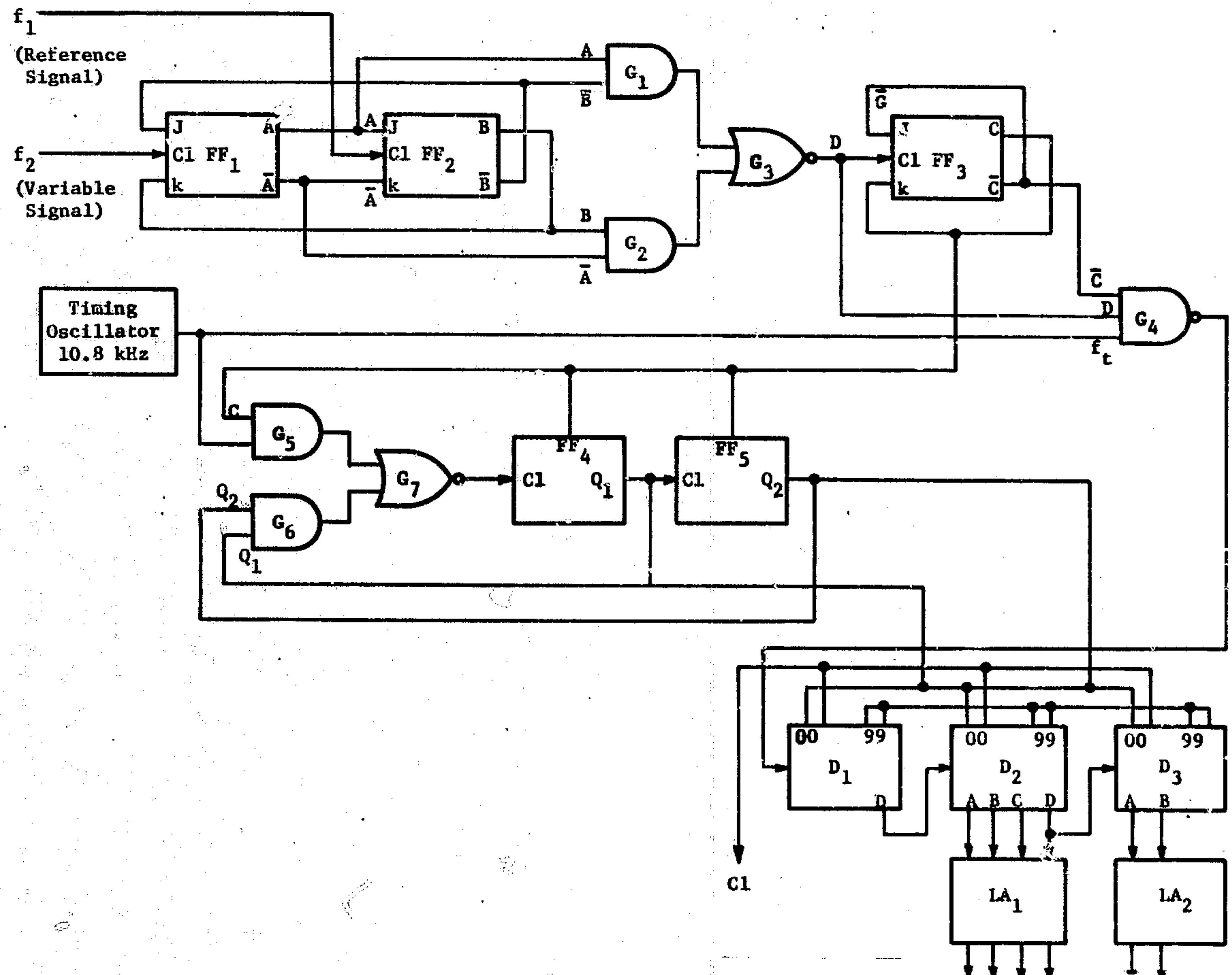


Figure 5.2 Phase Detector and Register

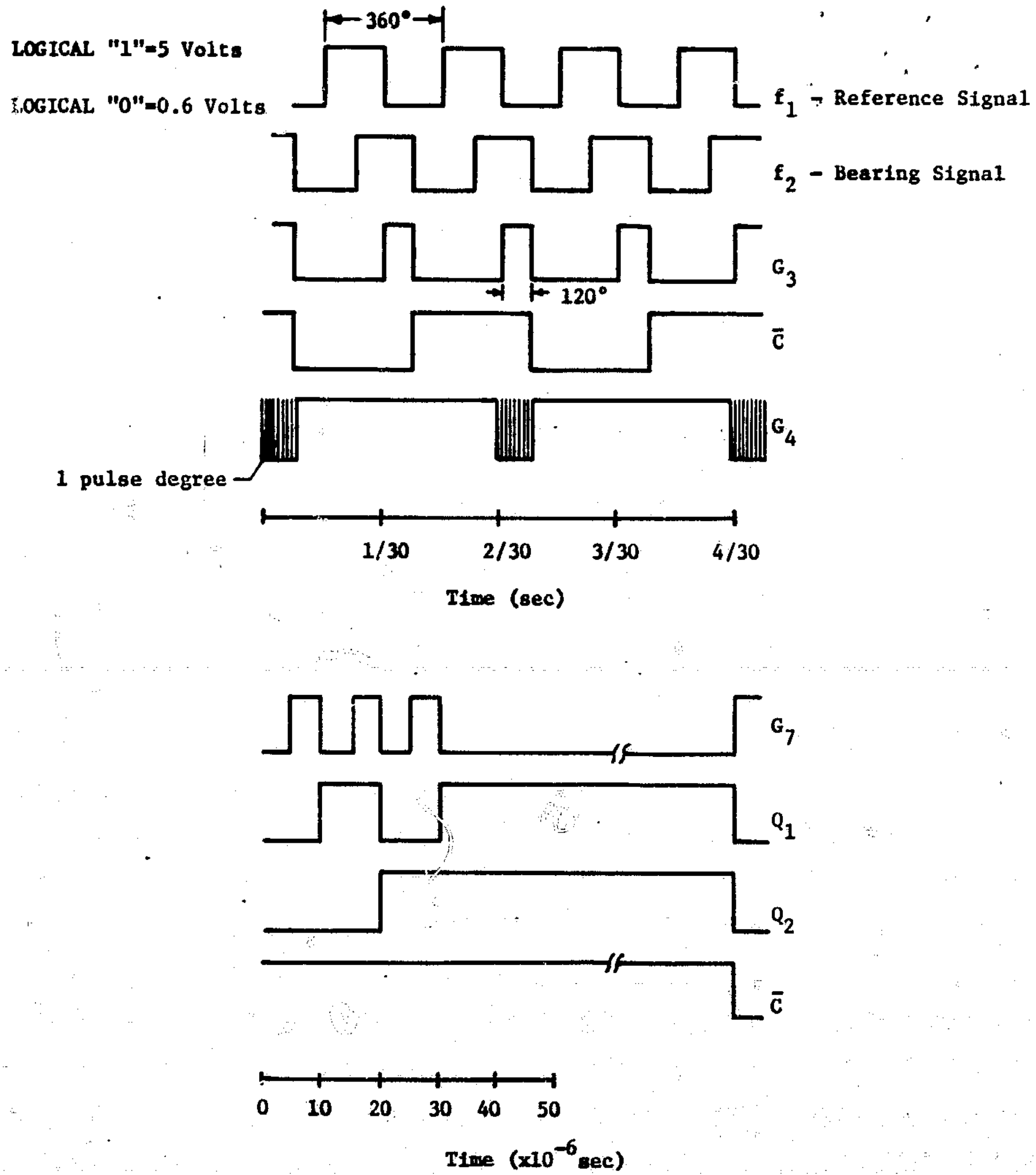


Figure 5.3 Phase Detector Timing Diagram

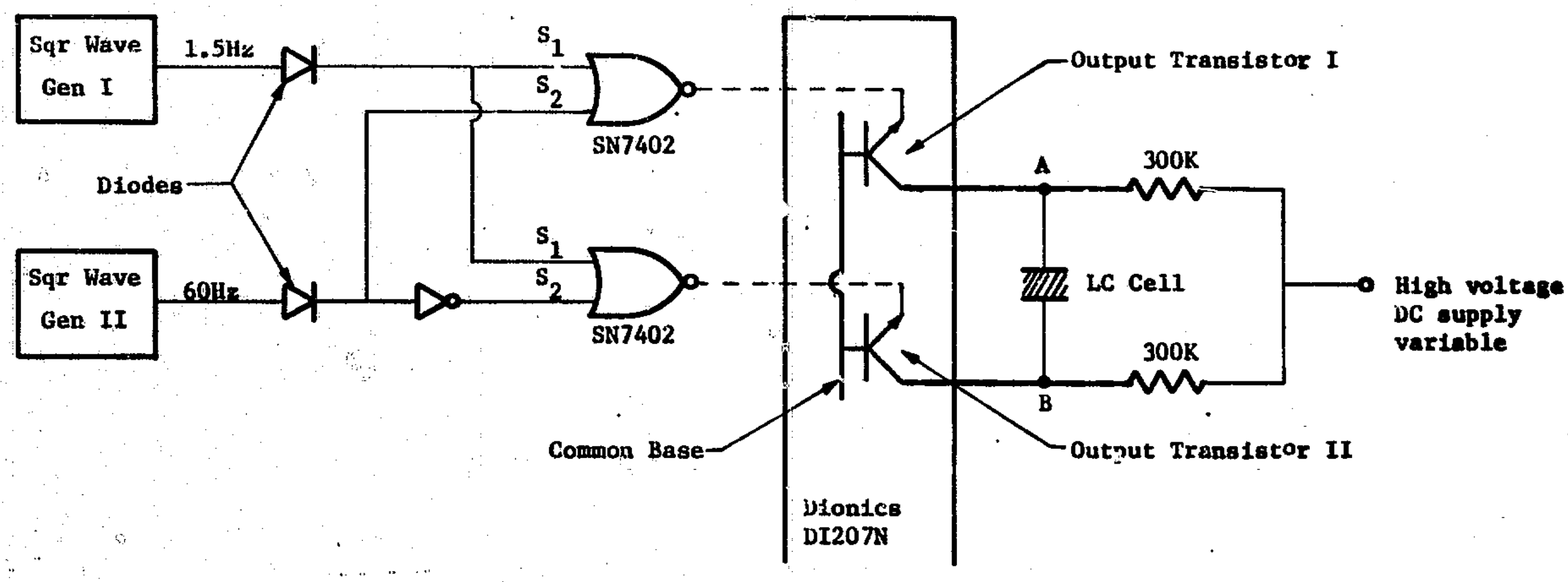


Figure 5.4 Integrated Circuit Driver

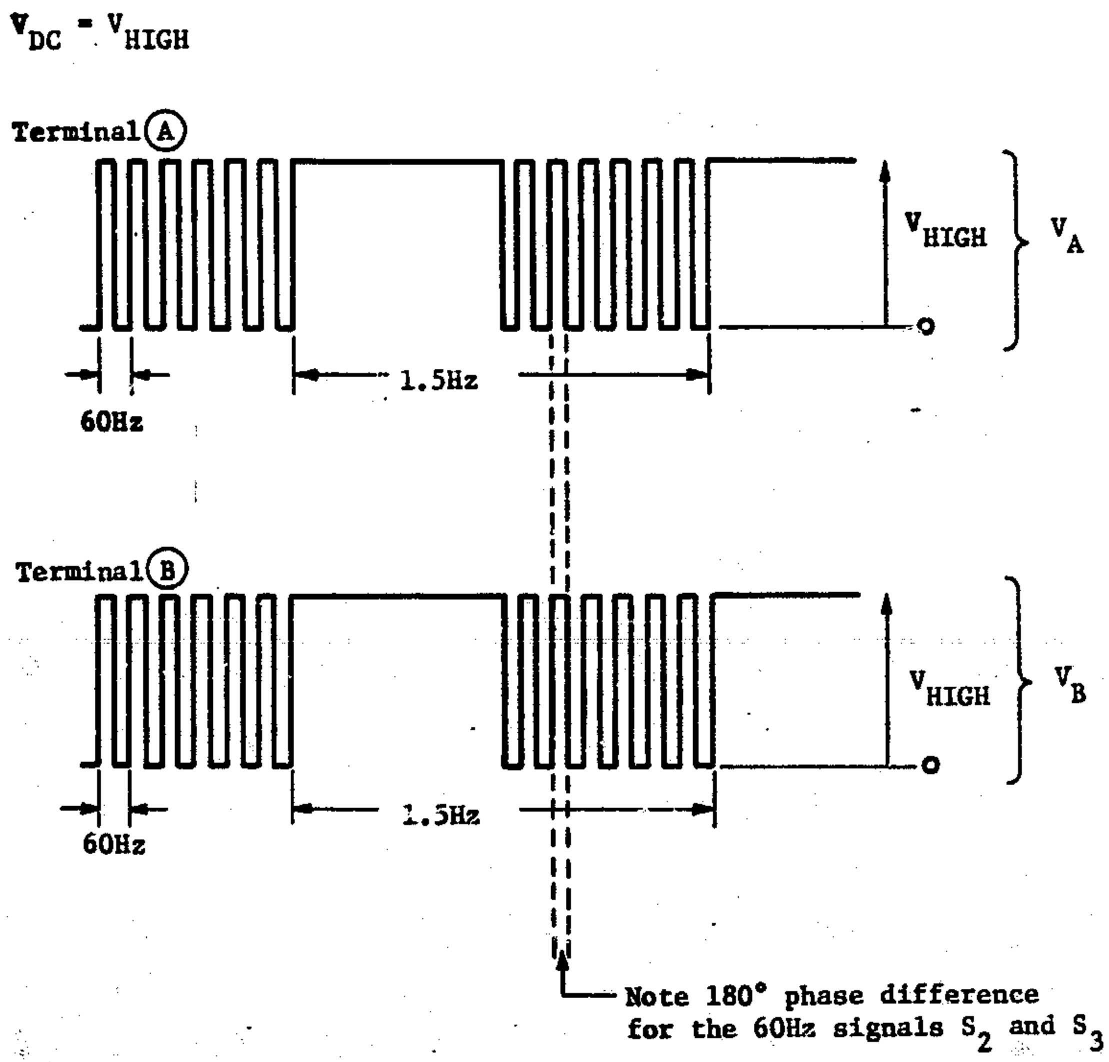


Figure 5.5 Driver Output Voltage

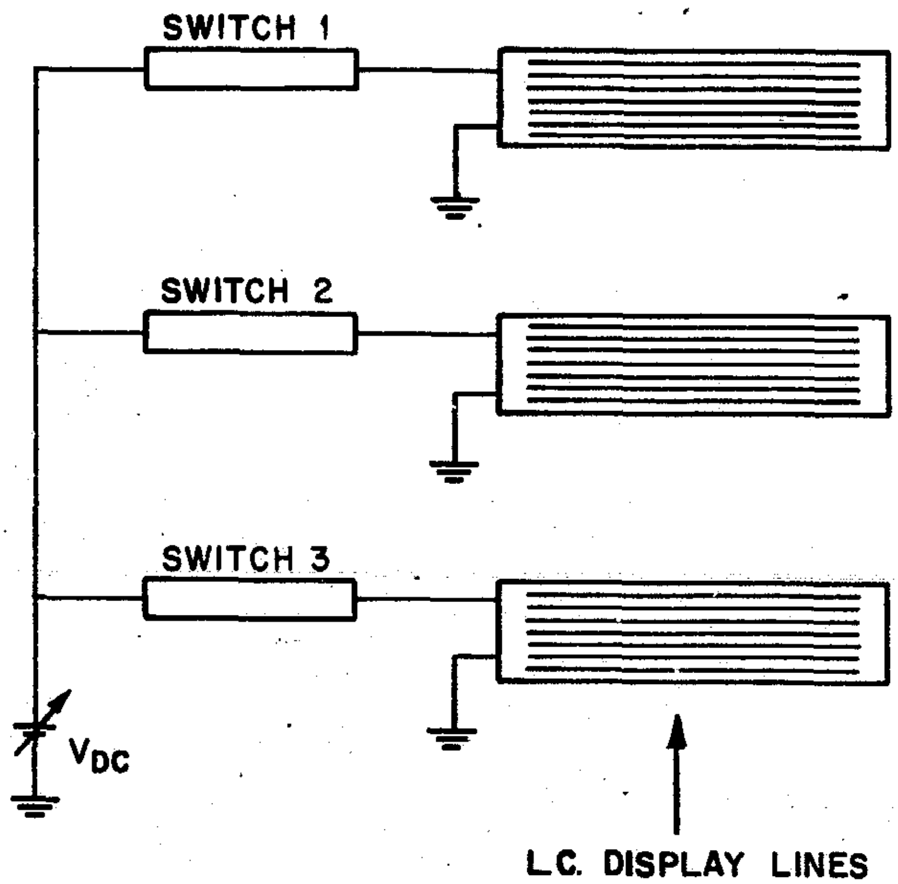


Figure 5.6 Decoder Concept

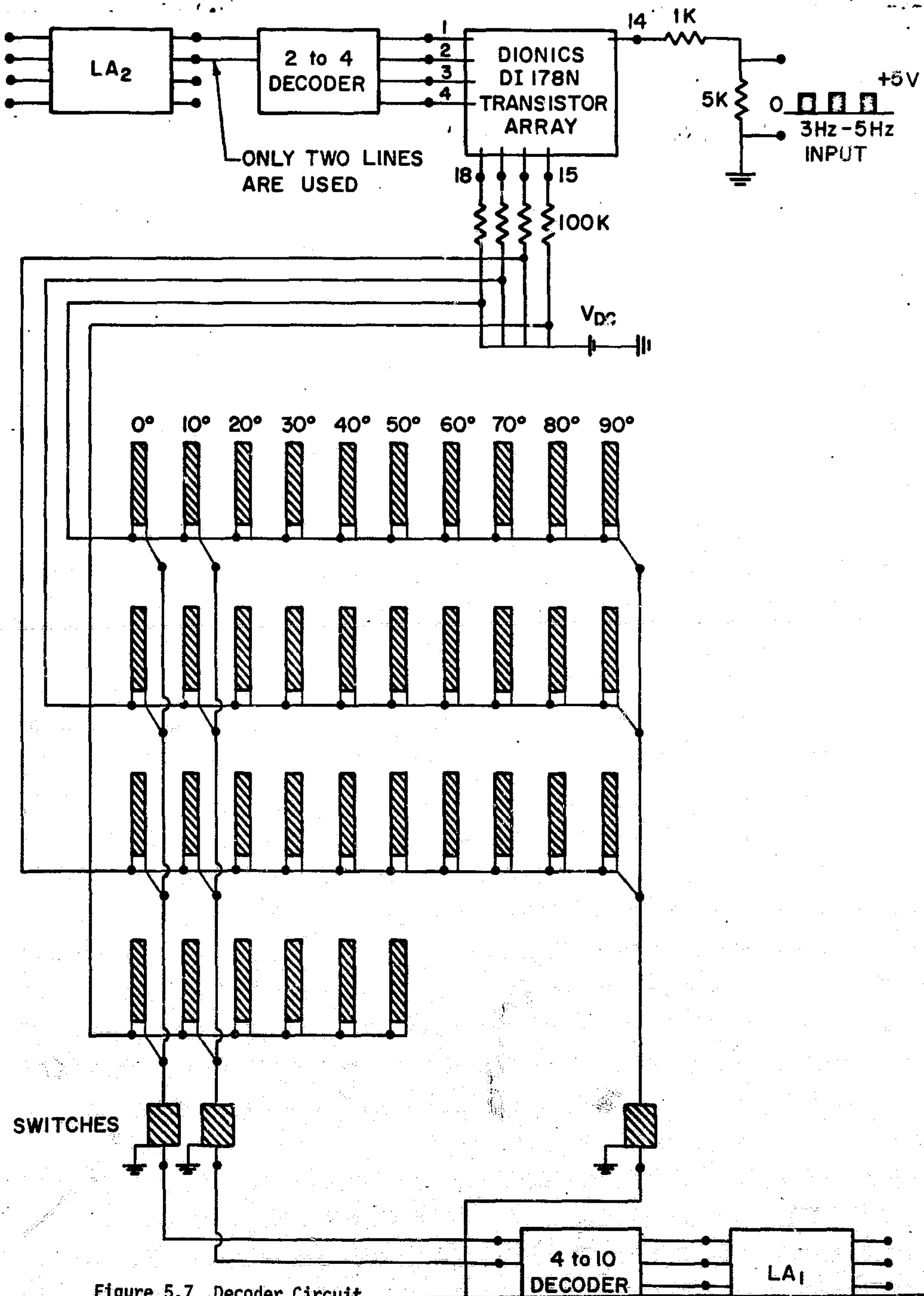


Figure 5.7 Decoder Circuit