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DEVELOPMENT OF LIQUID CRYSTAL MICROWAVE POWER DENSITY METER

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
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DIVISION OF ELECTRONIC PRODUCTS

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DEVELOPMENT OF LIQUID CRYSTAL MICROWAVE POWER DENSITY METER

Prepared by

The Bendix Corporation Research Laboratories
Southfield, Michigan

under

Public Health Service Contract CPE-R-69-28

for

Radiation Measurements and Calibration Branch
Division of Electronic Products

May 1970

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service
Bureau of Radiological Health
Rockville, Maryland 20852

FOREWORD

The Bureau of Radiological Health, formerly the National Center for Radiological Health, continues to carry out a national program designed to reduce the exposure of man to hazardous ionizing and nonionizing radiation.

Within the Bureau, the Division of Electronic Products (1) develops and administers performance standards for radiation emissions from electronic products, (2) studies and evaluates emissions of and conditions of exposure to electronic product radiation and intense magnetic fields, (3) conducts or supports research, training, development, and inspections to control and minimize such hazards, and (4) tests and evaluates the effectiveness of procedures and techniques for minimizing such exposures.

The Bureau publishes its findings in Radiological Health Data and Reports (a monthly publication), the Environmental Health Series, Public Health Service numbered reports, appropriate scientific journals, and Division technical reports.

The technical reports of the Division of Electronic Products (DEP) allow comprehensive and rapid publishing of the results of intramural and contractor projects. The reports are distributed to State and local radiological health program personnel, Bureau technical staff, Bureau advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press, and other interested individuals. These reports are also included in the collections of the Library of Congress and the Clearinghouse for Federal Scientific and Technical Information.

I encourage the readers of these reports to inform the Bureau of any omissions or errors. Your additional comments or requests for further information are also solicited.

John C. Villforth
Director
Bureau of Radiological Health

PREFACE

The development of instrumentation for measuring radiation exposure from electronic products is a major responsibility of the Division of Electronic Products (DEP), Bureau of Radiological Health. The need for improved instrumentation for measuring microwave radiation became evident from DEP studies of the radiation leakage from microwave ovens. In particular, the advantages of an area detector in obtaining more information per unit time than is possible with a conventional probe were recognized, as well as the necessity of obtaining an instrument which would not significantly distort the field being measured.

This report is a product of research carried out by the Bendix Corporation under contract to DEP to develop such an instrument. Mr. C. F. Augustine of Bendix Research Laboratories was responsible for the developmental work described in the report and for the initial concept that liquid crystals could be used in a practical, microwave power density meter. Design, construction, and testing of the liquid crystal membrane and housing were accomplished by Mr. J. A. Walworth of Bendix Research Laboratories.

Robert L. Elder, Sc.D.
Acting Director
Division of Electronic Products

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ABSTRACT

Bendix Research Laboratories, under contract to the Division of Electronic Products, developed a liquid crystal microwave power density meter. The meter has a Mylar membrane with resistive and liquid crystal coatings which serves as a large-area sensing element and uses direct current electrical power for bias and calibration of the membrane. The general operating principles of such an instrument and the design and operating characteristics of the particular meter constructed are described in the report.

DEVELOPMENT OF LIQUID CRYSTAL MICROWAVE POWER DENSITY METER

1. INTRODUCTION

This report describes a program undertaken at the Bendix Research Laboratories to develop a microwave power density meter for the Department of Health, Education, and Welfare, Bureau of Radiological Health in Rockville, Maryland. The program began on July 1, 1969, and was completed on November 30, 1969.

The power density meter that has been developed is a new type of instrument which uses liquid crystals as a basic part of the detection mechanism. At the outset of the program, sufficient experimentation had been completed to establish the concept and to reveal possible advantages compared with other more conventional means of measuring microwave power density. Quantitative measurements had not, however, been made. The basic program objectives were, therefore, to construct a prototype instrument that could be used to make quantitative measurements and to establish the advantages and limitations of the concept. The advantages were largely the overall simplicity and fundamental method of calibration, and the fact that detection takes place simultaneously over a reasonably large, well defined area. Possible limitations of the concept were unknown.

During the program, the advantages were all confirmed. In addition, it was found that overall sensitivity and dynamic range were better than originally anticipated. The most prevalent limitation was a lack of uniform detection over the total area. This was caused by insufficient control in regard to a metal deposition process used in fabricating the power meter. Further development and refinement of the deposition technique is necessary to remove this limitation.

2. BASIC PRINCIPLES OF OPERATION

The construction and operating principles of the liquid crystal field detector have been described in previous publications.[1,2] They will be briefly reviewed here.

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[1]AUGUSTINE, C.F. Field detector works in real time. Electronics 41:118-121 (June 24, 1968).

[2]AUGUSTINE, C.F. and W. G. JAECKLE. Real-time area detection of electromagnetic fields using cholesteric Liquid crystals. Presented at the 18th Annual Symposium, USAF Antenna Research and Development Program, Monticello, Illinois (October, 1968).

The general construction of the detector membrane is depicted in figure 1. A thin, 0.0005-inch-thick sheet of Mylar tightly stretched in a plastic hoop serves as the basic support structure. One side of the

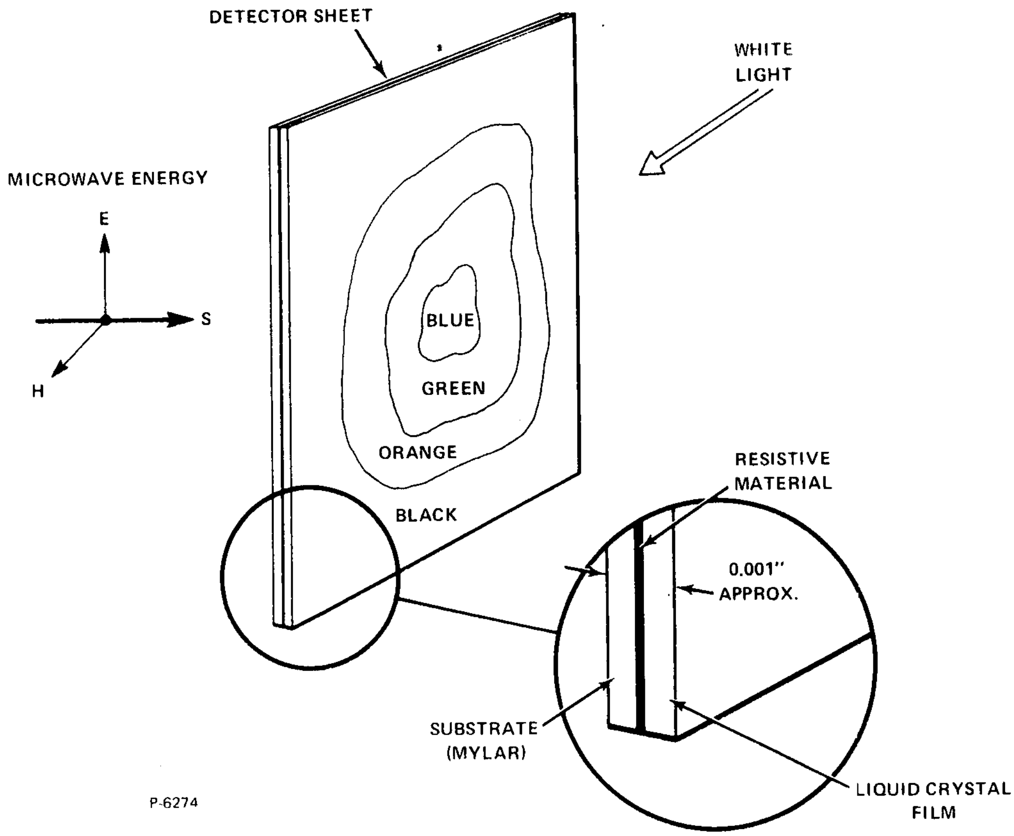

Figure 1. Basic construction of membrane

Mylar is metalized with a thin layer of nichrome to a resistivity of approximately 377 ohms per square. A thin layer of liquid crystals is also applied to the Mylar. When a microwave field is incident on the structure, microwave energy is converted into heat by the metalized layer. The colors scattered by the liquid crystals are a function of the temperature distribution over the membrane. The highest temperatures result in blue colors, and, as the temperature decreases, the color turns from blue to green, to yellow, and to red. The temperature and color distribution over the membrane are, therefore, directly related to microwave field strength. Liquid crystals may be used that change color with very small temperature changes. Thus, the membrane provides a sensitive, real-time graphical depiction of field strength.

The nichrome layer is very thin compared with skin depth at microwave frequencies. The resistivity is, therefore, the same for both direct currents and currents oscillating at microwave frequencies. This equivalence serves as the simple and fundamental method of calibration. Direct currents are passed through the membrane, and the resultant temperature increase serves both as a biasing means to obtain the liquid crystal color threshold and a means of calibration by substitution.

The parameters affecting microwave power absorption by the membrane can be emphasized by using the analogy between plane-wave free-space propagation and transmission lines. This analogy is illustrated in figure 2 where the membrane has a resistivity equivalent to free space, i.e., 377 ohms per square, and the resistive film is thin compared with skin depth. The membrane is backed by a parallel metal conductive plane having a very low resistivity. When the spacing between the metal conductive plane and membrane is one-quarter wavelength, all incident microwave energy propagating in a direction perpendicular to the membrane plane is absorbed by the membrane. Similarly, all energy propagating down a transmission line having a characteristic impedance of 377 ohms terminated by a shunt 377-ohm resistor and a quarter wavelength short circuit will be absorbed by the resistor. The general case where the incident microwave energy is not precisely normal to the membrane is

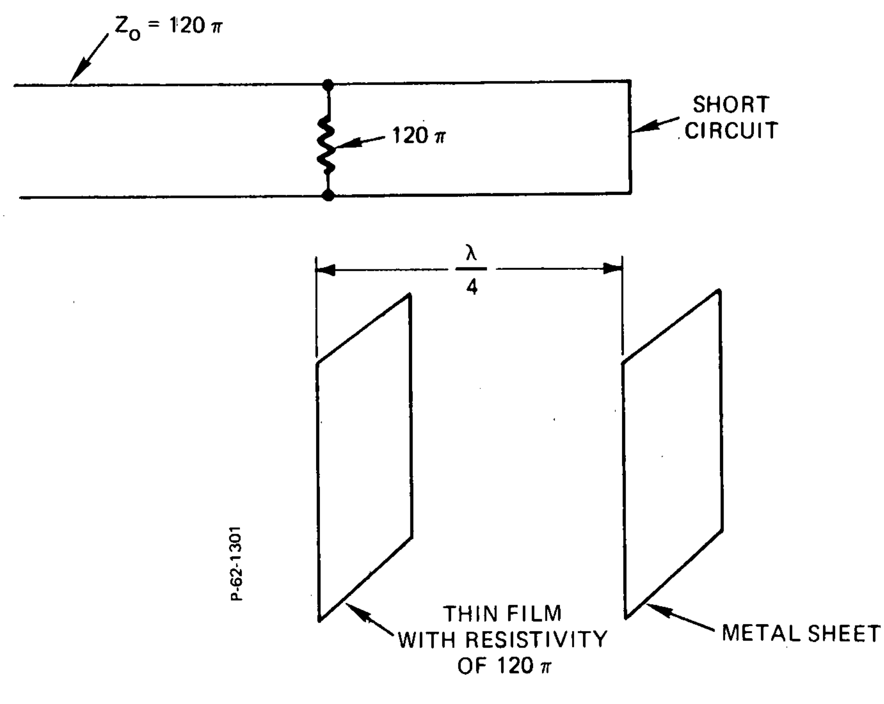

Figure 2. Analogy between plane-wave free-space propagation and transmission lines

treated in Reference 2. For present purposes, however, it is sufficient to note that the absorptivity does not vary rapidly with incident angle; angles up to 20 degrees from normal decrease the absorptivity by only about 1 percent.

3. INITIAL TESTS

At the outset of the program, a series of tests was conducted to determine various unknown parameters that would influence the final design.

3.1 LIQUID CRYSTAL TEMPERATURE CHARACTERISTICS

Tests were performed to determine the preferred active temperature range and the end points of the liquid crystal. The sensitivity of the membrane is a function of temperature range while the dynamic range is largely a function of the end points.

In general, the sensitivity is greatest with narrow temperature ranges. In rather loose terms, sensitivity is defined as the change in power required to produce a discernible color change. Since the color-temperature relationship of liquid crystals is not linear, this depends to a certain extent on the initial color. The greatest sensitivity is obtained when the absorbed power and resultant temperature are adjusted so that the initial color is yellow. This initial, most sensitive setting was used in the measurements.

The dynamic range is increased as the temperature of the end points is increased. The dynamic range is defined as the amount of power required to maintain a particular temperature or color. Since microwave power can always be substituted for or combined with power supplied by d.c. currents to maintain a particular color, it is not necessary to specify the nature of the power.

Tests were performed using liquid crystals having four different temperature ranges. A metalized Mylar membrane was coated with the liquid crystals and heated by passing direct currents through the metal coating. The amount of power in terms of milliwatts per square centimeter required to maintain particular colors was recorded. The results are shown in table 1.

Table 1. Power required to maintain various colors using liquid crystals having various temperature ranges with an ambient temperature of 24° C

Liquid Crystal Temperature Range		Milliwatts Per Square Centimeter
33-35° C	Red	5.4
	Green	6.5
	Blue	7.8
35-37° C	Red	7.8
	Green	8.7
	Blue	9.6
37-39° C	Red	12.9
	Green	14.1
	Blue	15.2
39-41° C	Red	15.2
	Green	16.6
	Blue	17.4

The liquid crystal solutions used in these tests were commercial preparations having the temperature end points indicated in the table. There is, however, an obvious lack of overlap between the 35-37°C solution and the 37-39°C solution.

Largely as a result of the test results shown in table 1, a National Cash Register commercial liquid crystal preparation designated as S38 was selected for use in the final instrument. This preparation has a one-degree range, i.e., it has a faint red color at 38°C and is blue at 39°C. Approximately 14 milliwatts per square centimeter are required to sustain a blue color at 24°C ambient. The red and green colors differ by 0.9 milliwatt per square centimeter and the green and blue differ by about 1.1 milliwatts per square centimeter. The sensitivity, i.e., the smallest power change that will cause a discernible color change when the initial color is near yellow is less than 0.3 milliwatt per square centimeter. A graph relating the color with temperature for S38 is shown in figure 3.

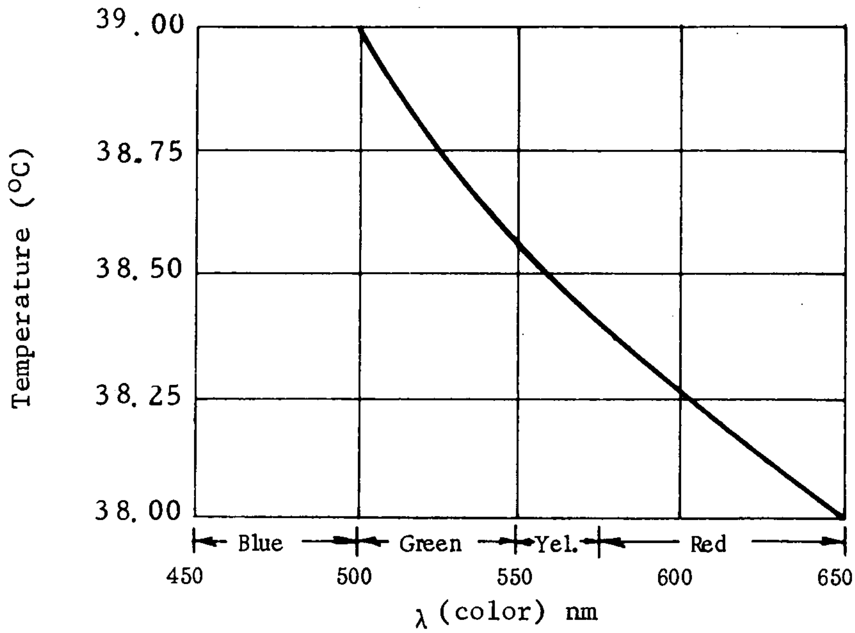

Figure 3. Temperature-color relation for NCR-S38 liquid crystal

3.2 POSITIONING AND CONSTRUCTION OF THE SHORTING PLANE

The initial technical proposal submitted to the Bureau of Radiological Health was Bendix Research Laboratories Proposal No. 4745 entitled "Proposal for the Development of a Microwave Power Density Meter." Figure 2 of this proposal illustrated the use of two independent membranes, one backed by a shorting plane spaced $\lambda/4$ from the membrane, and the second backed by a shorting plane spaced $\lambda/2$ from the membrane. Because of the $\lambda/2$ spacing, the second membrane would receive no microwave energy. It would function as a reference membrane sharing the same ambient temperature and infrared radiation field with the measurement membrane. The two membranes would be biased independently. The microwave power absorbed by the measurement membrane would be determined by observing the difference in biasing power required to achieve the same color on both membranes.

When the initial proposal was prepared, it was believed that an operator would be able to achieve much better accuracy by comparing colors rather than exercising judgment in regard to the absolute color of a single membrane. However, the first tests conducted using the S38 liquid crystal preparation demonstrated that this was not the case. The tests showed that an operator could reset the power required to achieve a particular color, particularly red or green, to within about 1 percent. This surprisingly good resetability significantly reduced the need for the reference membrane; therefore, the decision was made to use one membrane only and set the spacing to the shorting plane at $\lambda/4$ at 2.45 GHz.

The initial intent was to use a fine mesh wire screen as the shorting plane. Apart from providing the shorting plane, the screen would have sufficient optical transmissivity to allow viewing the detector membrane through the screen. Initial tests on screens having various weaves and colors revealed that any screen that had the desired shorting effect drastically reduced the operator's ability to judge membrane colors. After this rather unexpected discovery, experiments were performed using glass having a nearly transparent coating of metal oxide applied to one surface. A glass bearing the trade name Nesatron manufactured by P.P.G. Industries in Pittsburgh, Pennsylvania, was found to have both the desired optical and electrical properties. The metal oxide coating has a resistivity of about 5 ohms per square to provide the shorting plane. The optical characteristics are such that there is essentially no impediment of an operator's ability to judge colors when viewing the membrane through the glass.

The fact that the resistivity is not extremely low, a fraction of an ohm per square for example, results in a small predictable error in measuring power. Simple transmission line calculations show that the 5-ohm-per-square resistivity results in a total power absorption by the membrane of about 2 percent less power than would be the case if the resistivity were a very small fraction of an ohm per square. This loss is due to the combined effects of a slight impedance mismatch, power absorbed by the 5-ohm-per-square film, and power transmitted through the film. However, only 0.03 percent of the total power incident on the detector membrane is actually transmitted through the shorting plane. More than adequate shielding for the operator's eyes from excessive microwave radiation is therefore provided.

3.3 CONVECTION CURRENTS

Some microwave ovens are designed to exhaust hot air through the protective screen in the oven door. Leakage measurements must be made within a few inches of this screen. It is not possible to make a meaningful measurement when the hot air is allowed to come in direct contact with the detection membrane. The membrane must therefore be housed in an essentially air-tight enclosure. There was no concern, however, that convection currents and variation in air temperature within the enclosure could cause smearing and errors.

At the beginning of the program, a membrane was placed within an airtight enclosure having transparent windows. Small areas of the membrane were subjected to various intensities of microwave radiation, and it was observed that there was no appreciable smearing of the resultant image due to convection currents within the enclosure. To substantiate this observation, a focused microwave beam having a diameter of about one inch was aimed at the center of the membrane, and by using d.c. substitution, the width of the beam at the 3-dB points was determined for a series of energy levels of the beam. In this experiment, the measured width of the beam remained constant for all energy levels. From this measurement, it was concluded that there was no appreciable error introduced due to energy coupling between various membrane segments by convection currents.

3.4 CALIBRATION CONSIDERATIONS

The basic method of calibration is to determine how much heating power derived from passing direct currents through the membrane must be added or subtracted to maintain a given color when the microwave field is either removed or added. The upper temperature limit of the liquid crystals and the active area of the detector membrane determine the upper limit of the power that may be substituted. The upper dissipation limit for the S38 liquid crystal with a room ambient temperature of about 22^{o}C is approximately 15 milliwatts per square centimeter. The membrane area is 361 square centimeters; therefore, 5.6 watts must be supplied by the calibration source. The membrane area is essentially a square having a resistivity of 377 ohms per square; hence, the calibration supply must deliver 121 ma at 45 volts. Early experiments with a 361-square-centimeter, 377-ohm membrane demonstrated that an operator could clearly discern color changes resulting from bias current changes of 1 ma at the 120-ma level. This is equivalent to a power change of about 2.5 percent. To take advantage of the good sensitivity, the bias current power supply should provide short-term current stability better than $\pm$1 ma, and the device used to read the current should be accurate to within $\pm$1 ma.

The regulation requirements were met by selecting a Hewlett-Packard 6217A regulated power supply as the source of bias current. This supply will provide a maximum of 60 volts at 250 ma, and has regulation capability exceeding the requirement.

A Weston Model 1260, 0 to 200 ma digital panel meter was selected to provide the current readout. The digital meter was selected over conventional pointer types of meters because it is more accurate, has greater resolution, and is much easier to read. The accuracy of the Weston model 1260 is $\pm$0.5 percent of full scale or $\pm$1 digit.

4. DESIGN AND CONSTRUCTION

The complete power density meter is shown in figure 4. It can best be described as three separate components: the detector membrane, the detector membrane housing, and the bias and calibration circuitry. A brief description of factors affecting the design and construction of each component follows.

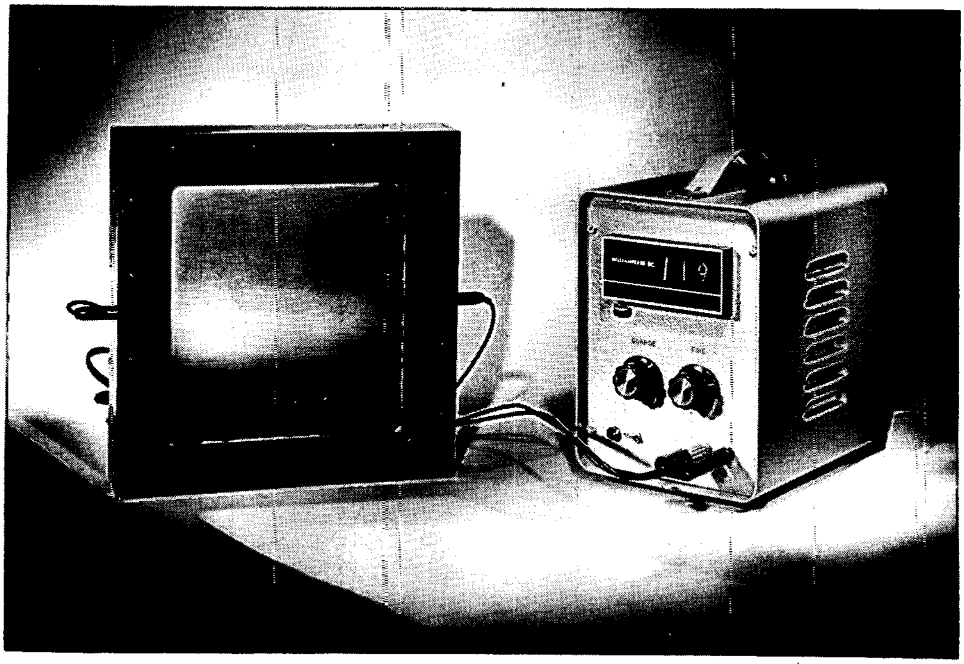

Figure 4. Complete power density meter

4.1 THE DETECTOR MEMBRANE

The basic supporting material for the detector membrane is 0.0005-inch-thick C-grade Mylar that has been dyed black. It is available from the Martin Processing Co. in Martinsville, Virginia. It is tightly stretched and glued between two 1/8-inch-thick square plexiglass frames. A drawing of the frames is shown in figure 5.

The first step in preparing the membrane is to stretch a piece of Mylar very tightly in a large circular loop. One side of each of the two frames is then painted with Cadco BA420 cement available from Cadillac Plastic Co., Detroit. The painted surfaces are then placed on either side of the Mylar stretched in the hoop such that an area is sandwiched between the two frames. In several hours when the cement has cured the frames are cut from the circular loop.

Before processing the basic membrane structure further, it must be thoroughly cleaned. The most effective cleaning procedure found was immersion of the membrane in an agitated solution of ordinary detergent and water. After an hour or so in the detergent solution, the membrane was then immersed in an agitated solution of distilled water, and then

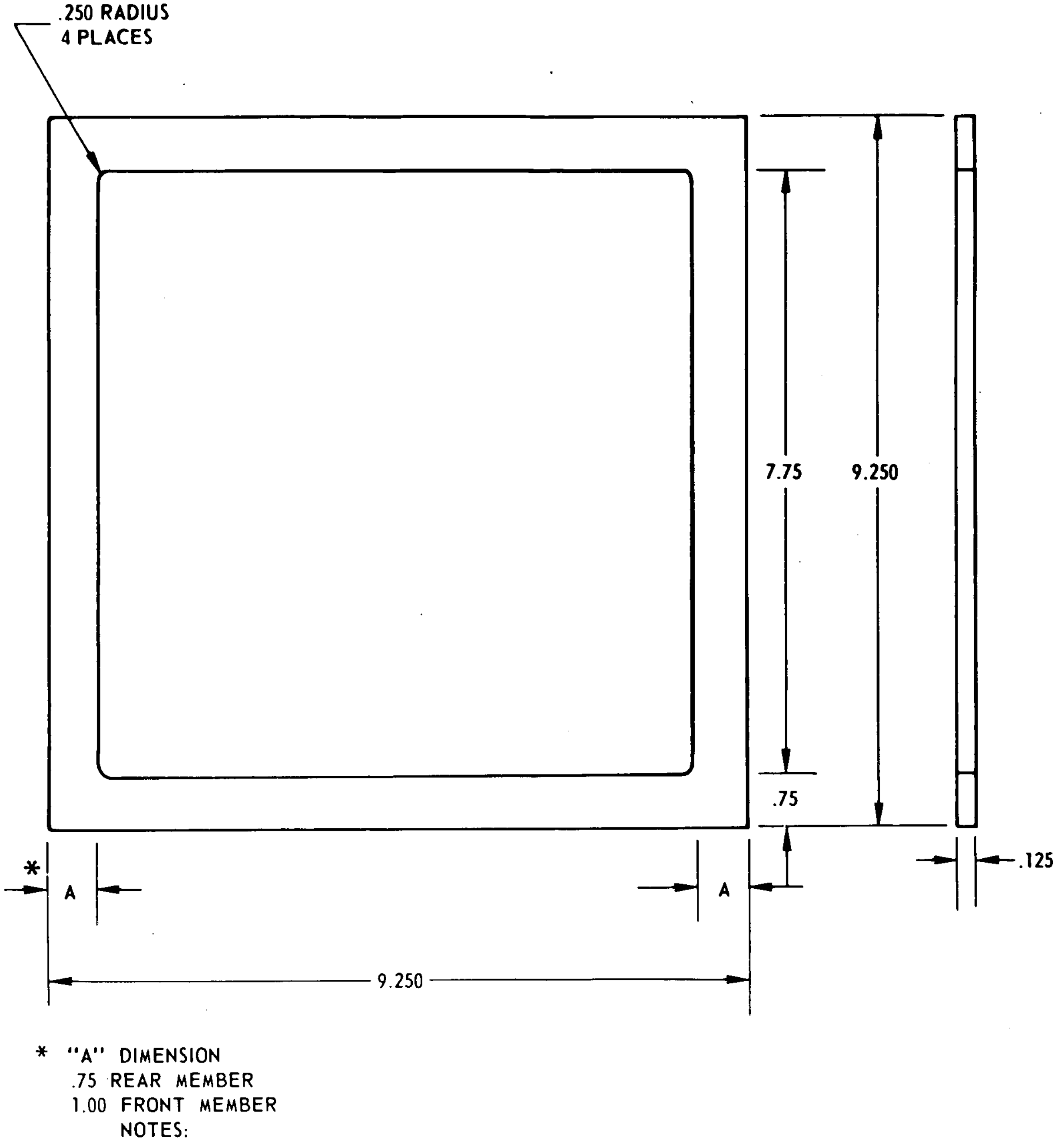

Figure 5. Membrane frames

repeatedly rinsed with distilled water and finally vacuum dried. Clean room procedures were used throughout the cleaning process.

The cleaned membrane was then metallized with nichrome using vacuum deposition techniques to a resistivity of approximately 377 ohms/square.[1] Electrodes for d.c. biasing and calibration were then attached by painting a 1/4-inch-wide strip of silver painted along two opposite sides of the frame. A length of thin copper foil was attached to the painted strip for use in making the actual electrical connection.

4.2 MEMBRANE HOUSING

A drawing of the membrane housing is shown in figure 6. It consists of a flat square box having outside dimensions 9-3/4 inch x 9-3/4 inch x 2-1/8 inch and open at two opposite sides. The viewing side is closed with a panel of Nesatron glass that allows light transmission but acts as a shorting plane for microwave transmission. The opposite side is closed by the detector membrane and two plain Mylar membranes. The plain membranes are on the outside and act as buffers to seal the box and protect the detector membrane from drafts and convection currents. Provision is made for electrical connections to the membrane from the calibration and bias supply.

4.3 CALIBRATION AND BIAS SUPPLY

The calibration and bias supply consists of a Hewlett-Packard model 6217A regulated d.c. power supply and a Weston Model 1260, 0 to 200 ma Digital Panel Meter. The meter and power supply are packaged in a Bud Co. Model 91F615 portable cabinet. The front panel controls consist of a line switch and coarse and fine current controls. The coarse control allows continuous variations of voltage from 0 to 60 with a maximum current of 200 ma. The fine control allows current variations of about 3 ma with a 377 ohm-load.

5. TEST RESULTS

A series of tests initially described in the technical proposal were performed on the completed power density meter.

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[1]No unusual procedures were used in the deposition process and anyone skilled in vacuum deposition should be able to perform this task. However, some refinement of the technique is desirable to obtain a more uniform nichrome deposition over the membrane area.

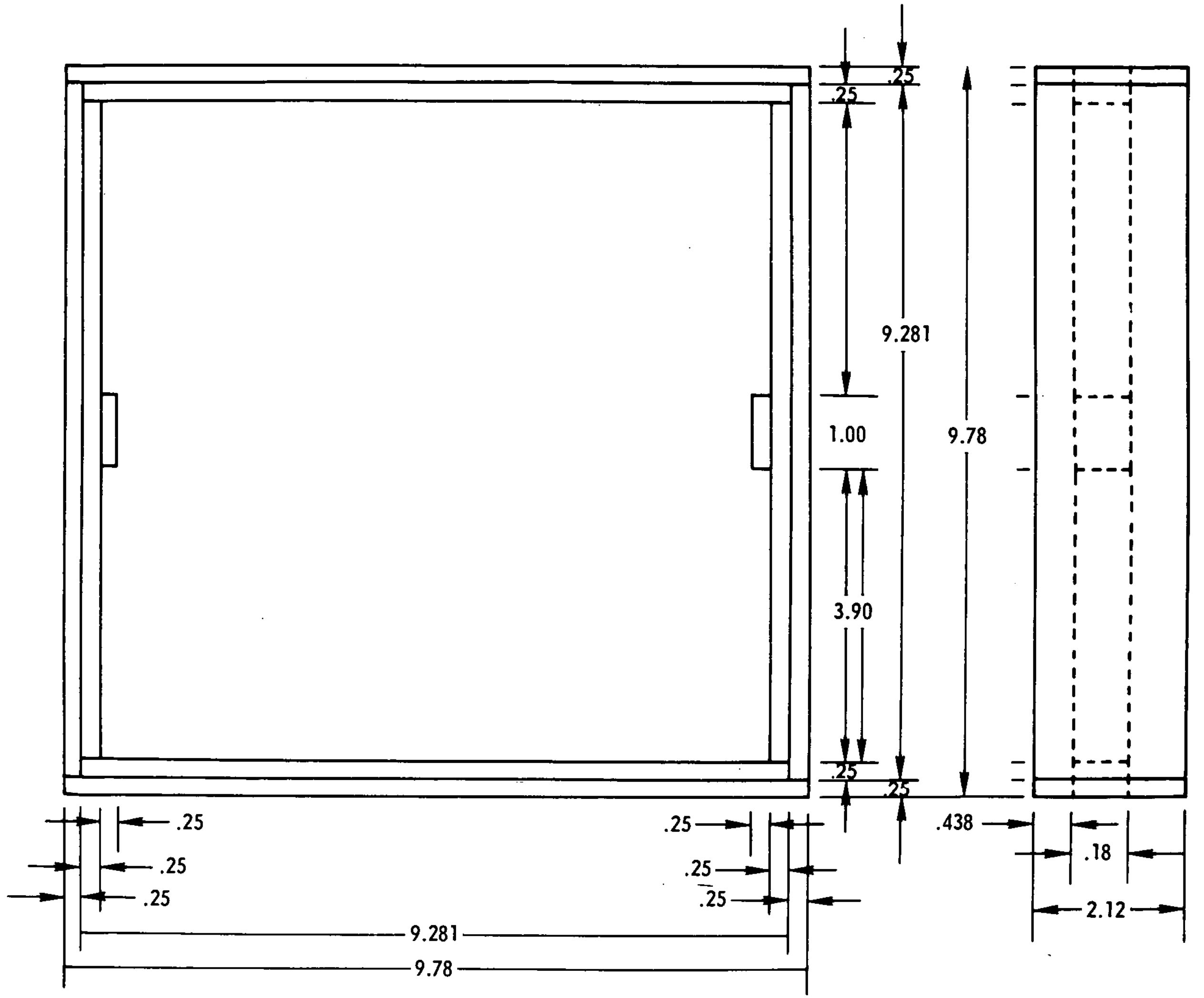

Figure 6. Membrane housing

5.1 ACCURACY TESTS

A field of known intensity was generated using standard gain antenna horns. A standard horn used as a receiver was placed several feet from a transmitting horn. The effective area of the receiving horn was computed from the gain. A power meter was used with the standard gain horn to determine the total power received; the field strength could then be determined in terms of milliwatts per square centimeter. Using this procedure, a field was generated having an intensity of 3.1 milliwatts per square centimeter. This field was repeatedly measured using the liquid crystal power density meter as 3.0 milliwatts per square centimeter. This close agreement was better than could be justified by the uncertainties in initially calibrating the field. These uncertainties are primarily in regard to the calibration accuracy of the standard gain horn and in uncertainty regarding the location of the phase center of the standard gain horn.

The general impression received while making these measurements was that the liquid crystal power density meter had fewer variables and was basically more accurate than the calibration technique using the standard gain horn. However, a more extensive testing program would have to be completed to determine absolute accuracy under all commonly encountered testing circumstances.

5.2 LONG-TERM STABILITY

The membrane delivered with the power density meter was used daily for about three weeks. It was cycled through its color spectrum many times during this period. There were no discernible changes in the membrane characteristics during this time.

5.3 HYSTERESIS EFFECTS

There are no apparent hysteresis effects. There is no notable difference in bias current when setting to a particular color from temperatures either above or below that represented by the color.

5.4 UPPER POWER LIMITS

The upper power limits that will damage either the nichrome film or liquid crystal have not been established. However, no damage was caused when the membranes were exposed to power levels up to 50 milliwatts per square centimeter.

6. PROBLEM AREAS

The principal remaining problem is in regard to membrane nonuniformities. The nonuniformity can be observed by adjusting the bias and calibration current to obtain a red color in the center of the membrane. When the center is red, the color near the membrane edge next to the electrodes is nearly blue. At normal ambient, the difference in power represented by the red and blue colors is about 2 milliwatts per square centimeter. The membrane does not therefore function as a true area detector until well defined radiation patterns having power densities two or three times greater than the 2 milliwatts per square centimeter are measured. It would be desirable to reduce this nonuniformity by about a factor of three so that the nonuniformity is less than the 1 milliwatt per square centimeter hazard threshold level.

Essentially, all the nonuniformity can be attributed to the nonuniform nichrome deposition. The deposition method that was used deposited more metal in the center than on the edges of the membrane. The uniformity can undoubtedly be increased after further experimentation.

Part of the nonuniformity can also be attributed to convection currents within the membrane enclosure. These could be essentially eliminated in subsequent designs by placing a series of transparent baffles inside the enclosure.

7. CONCLUSIONS AND RECOMMENDATIONS

This program has achieved the basic objectives of determining the advantages and limitations of the liquid crystal microwave power density meter. The advantages apparent at the beginning of the program--overall simplicity, fundamental method of calibration, and simultaneous detection over a reasonably large, well-defined area--were all confirmed. In addition, it was found that greater sensitivities and accuracies were possible than had been anticipated. The sensitivity was less than 0.3 milliwatt per square centimeter, and the overall accuracy was better than could be evaluated using ordinary standard gain horns.

The principal remaining problem is the nonuniformity of the membrane. This problem could undoubtedly be eliminated by a further refinement of the nichrome deposition method and through the use of buffers to reduce convection currents. A continuation of the development program should have the elimination of nonuniformities as the principal objective.

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KEY WORDS:
Liquid Crystal, Microwave, Power Density

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