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**EVALUATION OF ANTISTATIC AGENTS
ON NYLON PARACHUTE CLOTH**

JAMES W. SWEENEY

LOWELL TECHNOLOGICAL INSTITUTE
RESEARCH FOUNDATION

SEPTEMBER 1955

WRIGHT AIR DEVELOPMENT CENTER

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JAMES W. SWEENEY

*LOWELL TECHNOLOGICAL INSTITUTE
RESEARCH FOUNDATION*

SEPTEMBER 1955

PROJECT No. 7320

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
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FOREWORD

This report was prepared by the Lowell Technological Institute Research Foundation under USAF Contract No. AF 33(616)-458. The contract was initiated under Project No. 7320, "Air Force Textile Materials"; Task No. 73201, "Textile Materials for Parachutes", formerly RDO No. 612-12, "Textiles for High Speed Parachutes", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. J. H. Ross acting as project engineer.

This report covers work conducted from March 1953 to March 1955.

We are grateful to the companies who contributed the various antistatic finishes evaluated in this program. The interest and technical assistance offered by many of the concerns have been of considerable value in our work.

Because of the nature of this program, several people were called upon to contribute to various specialized phases of work. Prof. J. H. Skinkle, Mr. G. O. Langlais, Mr. R. K. Devejian, and Mr. H. Brown were instrumental in the program formulation during the initial stages of this work. We would also like to acknowledge the assistance of Dr. O. K. Mavardi and Mr. A. A. Janszen in the evaluation of existing theories of static electricity and the various instruments used to indicate the relative effectiveness of antistatic agents.

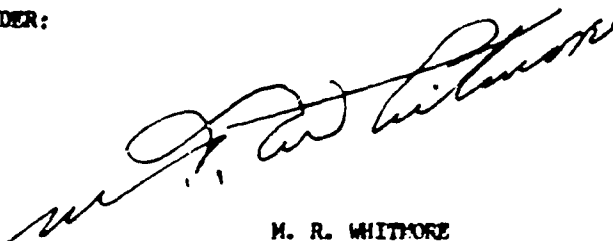
ABSTRACT

A literature search covering instrumentation, antistatic agents, and theories of static electrification was conducted to provide a foundation for the evaluation of antistatic treated nylon parachute cloth. An appraisal of the techniques employed by other investigators, in the evaluation of the static behavior of materials, justified the utilization of fabric surface resistance as the measurable parameter. Special instrumentation was developed to provide the desired test conditions of -30°F and 10% RH and permit the required range of resistance measurements. While no permanent antistatic agent studied was found to be effective at the low temperature test conditions, specific non-permanent agents gave the treated material a surface resistance at the test conditions which was comparable to the resistance of untreated nylon fabric at standard test conditions of 70°F and 65% RH.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:



M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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I INTRODUCTION

The Problem of Static Electricity on Parachutes

Nylon parachutes under normal conditions usually function without any noticeable difficulty produced by static electricity. However, a significant number of delayed parachute openings have been reported where cold, dry atmospheric conditions prevailed. These delayed openings may have been caused, in whole or in part, by the accumulation and retention of strong electrostatic charges on the nylon fabric. Because of the magnitude of the charge existing on the nylon under extreme climatic conditions, there is a greater tendency for the panels of the parachute to cling together during opening. The object of this investigation was to carry out a program of research, development, and evaluation to determine the antistatic agent most suitable for the treatment of personnel type nylon parachute fabrics to eliminate the possibility of malfunctioning caused by electrostatic charges.

Although the literature contains an ever increasing quantity of information on such subjects as the phenomenon of static, the effects of antistatic agents, and the techniques for measuring the static properties of materials, no reported work has been conducted at conditions of extremely low temperature and low relative humidity. In addition, there is no satisfactory experimental criterion with which the acceptability or non-acceptability of a fabric's electrostatic behavior can be predicted.

In the case of the electrostatic difficulties encountered with untreated nylon in the manufacturing processes and in many consumer uses, the reduction of the static tendencies of treated nylon to a magnitude comparable with the static properties exhibited by cotton at normal ambient conditions is considered to be a satisfactory goal. However, this goal would be too ambitious for the case of parachutes operating at sub zero temperatures. As nylon parachutes function properly under conditions of normal operation, the electrostatic properties of the material at those normal conditions is undoubtedly satisfactory even though they are much greater than for cotton fabrics under similar conditions. Should these properties be retained by the material, after antistatic treatment, when the conditions of use are those which are considered to be extreme, then the electrostatic behavior of the treated nylon should, likewise, be satisfactory. With this interpretation of the requirements, the desired target properties of a treated nylon fabric were considered to be as follows:

1. The treated fabric, when tested at conditions of -30°F and 10% RH, should have electrostatic properties comparable with the electrostatic properties of untreated nylon tested at 70°F and 65% RH.
2. The antistatic agent should be essentially nonvolatile at temperatures below 130°F .
3. The treatment should be fast to laundering and dry cleaning at temperatures up to 120°F .

4. The treated fabric should retain the tensile strength, tear strength, weight, color, and air permeability of the untreated fabric, both before and after accelerated ageing.

The program to achieve these target properties was divided into three phases: first, an extensive review of the technical literature available on static electricity, techniques for determining the electrostatic properties of textile materials, and textile antistatic agents; second, an investigation to determine the most satisfactory method for evaluating agents at conditions of low temperature and low relative humidity; and, third, the application and evaluation of nylon antistatic agents supplied by the various manufacturers.

Phenomenon of Static

The phenomenon of static electrification was man's first insight into the field of electricity. As far back as 600 B. C., it was recognized that amber, which is a fossilized vegetable resin, after being handled acquired the ability to attract light particles of matter. Thus, from the Greek "elektron" meaning "amber", the word "electricity" was derived.

A search of the scientific literature on static electricity (a bibliography is presented in Appendix I) disclosed that, although an impressive amount of work has been done, little effort has been directed toward an understanding of the basic phenomenon. This situation exists in spite of the fact that the manifestations of static electricity are a common occurrence, and are observable both in the productive utilization of static as well as the hazards created by its presence. In the field of medicine, static electricity is utilized in Electrotherapy, the treatment of disease by electricity; yet, the fear of ether explosions due to static electricity is constantly present in the operating room. Electrostatic flocking produces a highly desirable commercial textile product; yet, processing difficulties brought about by static charges on textile fibers, yarns, and fabrics continue to produce costly and hazardous situations.

Recently, as a result of the difficulties encountered in the fabrication and performance of textile materials, the need for a study of the basic aspects of static has become acute. It is common knowledge that since the advent of the newer synthetic fibers, operational hazards and failures have been multiplied because of the greater tendency of these fibers to accumulate and retain static charges than is the case for the natural fibers. Thus, recent investigations have been concerned primarily with the manifestations of static electricity rather than with its causes. This can be attributed to the urgent need of corrective measures for the abatement of operational difficulties.

On the other hand, it is hardly surprising that the fundamental aspects of static electricity have received such meager attention from the scientists. It has been only recently, with the inception of the new theories of solid state physics, that the tools needed for such an investigation have begun to appear. Through the study of solid state physics, the great complexity of factors that enter into the determination of the characteristics of a surface have become more apparent; yet, the characteristics of the surface of a material are only one set of factors of the total number that affect the electrostatic properties of a material.

A significant commentary on the status of solid state physics was reflected by the recent trip of a prominent research scientist to another scientist at the Massachusetts Institute of Technology. The meeting was to discuss the probability that a single clue had been found which might lead to the isolation of a single factor which would regulate the surface characteristics of a germanium crystal. When it is considered that germanium can be purified to a degree that has not been possible for any other element, and has been the subject of more research than any other material up to the present time, the problems that must be faced in the study of fabric surfaces can be more fully realized. It seems probable that much effort will be expended before quantitative answers are available to the questions concerning static electricity on textiles.

The term "static electrification" was defined by Lobe (39) as all processes for producing segregation of positive and negative electrical charges by mechanical actions which operate by contact or impact between solid surfaces, between solid and liquid surfaces, or in the rupture of solid or liquid surfaces by gases.

The generation of static charges on so called non-conductors, of which most synthetic fibers are typical, has been ascribed to a number of causes. Among these are frictional or triboelectric effects, Volta mechanism or double-layer separation effects, and electrolytic effects. A logical, partial explanation of static charges was given for the first time by Frenkel (16) in 1917. The theory, however, was far from complete, and has been subjected to many revisions based upon new developments, (1), (21). Gonsalves (21) did not isolate the triboelectric effect from the double-layer effect, but rather considered that both terms referred to the transfer of electrons across an interface. Although his study was confined to the case of little or no friction, Gonsalves recognized the opinion of other physicists, that in the case of strong friction between the surfaces of materials, other mechanisms of charge transition would occur.

Of the several theories advanced to explain the mechanism of frictional static generation, the modern theory, based upon quantum mechanical considerations (4), (21), (57), (64), (70), is the most satisfactory. An explanation of this theory, given in Appendix II, has been prepared by Dr. O. K. Mawardi.

Parameters for the Measurement of Static Propensity

The parameters that are known to be important in the determination of one or more aspects of the electrostatic behavior of textile materials are:

1. The Specific Resistance, or Resistivity.

This quantity can be a composite, being determined by the physical properties of both the surface and the volume of a material.

2. The Dielectric Constant.

This is a quantity that enters into the capacitance of a given configuration with respect to its surroundings.

3. The Magnitude of the Electrostatic Voltage Generated Across an Interface.

These parameters determine the magnitude of the instantaneous voltage generated across an interface for a given set of external conditions. It is to be understood that the term "interface" is used to refer to surface dimensions as small as those of a large molecule, for it has been observed (34), (69), that on sheets of plastic and paper the distribution of charges over a surface can be extremely complex, generally being a mosaic in which the pattern is produced by differences in charge density and polarity. Although the magnitude of the voltage generated across an interface may be small, the field strength may be extremely high (21), being limited to the value at which ionization of the gas at the interface occurs. Separation of the two surfaces comprising such an interface may result in a large rise in potential, since the charge may remain nearly constant while the capacitance of the system is reduced. Whether this voltage remains at a high value, i. e., whether the charges on the interface remain immobile, depends on the presence or lack of discharge paths. Such paths can exist to ground through the material, along its surface, or between oppositely charged areas on the material. Ion paths, likewise, can cause dissipation of charge by means of corona discharge between adjacent areas or by the attraction of ions from an external ion source. However, when the total "parallel" resistance of the shunt discharge paths is extremely high, charges can be developed and retained.

Although there has been general agreement on the detrimental effects of static electrical charge accumulation and the need for alleviating measures, agreement has not been so general concerning the methods to be used. Nevertheless, all corrective measures are based on either the prevention of the formation of the charge or the rapid dissipation of any charge developed.

At least for certain operations in mills, one successful artifice for the dissipation of the static charge has been the installation of "static control bars" consisting of generators of both positive and negative ions. The area surrounding the point of static formation is rendered conducting, thus allowing a rapid dissipation of the charge.

A second method of control has been the application of finishes to the yarns or fabrics which reduce the instantaneous value of the charge. It is generally assumed that such agents owe their effectiveness to their ability to reduce the surface and/or volume resistivity of the material, thereby providing paths of low resistance through which charges may be dissipated to ground or through which they can neutralize each other (1), (2), (5), (11), (14), (18), (19), (20), (26), (27), (28), (29), (33), (40), (41), (45), (48), (54), (55), (59), (60), (61), (66).

Graham (22), however, is of the opinion that "the main function of an anti-static agent is to form an electrostatic shield between fiber and metal in order to reduce or eliminate the contact potential between them. Surface active agents are effective as antistatic agents because they are oriented on the surface of the fiber thus forming a more effective electrostatic shield." He refers only to the performance of fibers during fabrication, during which process, he states, most of the electrification is the result of fiber-to-metal contacts.

In order to assign figures of merit to various agents that might be used for static control, it is necessary to make observations on their effects. These observations have been made at operational levels as well as in the laboratory, and have been reported in the literature. At least one prominent authority on anti-static agents is of the opinion that of all the measurements that are practical at

the present time, none can provide an accurate indication of the operational electrostatic behavior of a textile (13). It is undoubtedly true, however, that order-of-magnitude indications of relative performance under specific sets of conditions can be obtained by making measurements of one or more of the parameters affecting electrical performance.

The experimental techniques, reported in the literature, used in evaluating electrical characteristics are measurements of:

1. The electrical charge
2. The electrical potential
3. The specific resistance or resistivity
4. The rate of rise of the charge
5. The rate of decay of the charge
6. The relation between the resistivity and the potential gradient

The measurements of charge are difficult to make when applied to plastic and paper sheets (14), (69), and even more difficult when applied to fabrics because of the following considerations:

1. Except when extremely small samples are used (43), (44), it has not been possible to achieve a uniform charge density of a single polarity over a large enough area to permit measurements to be made with accuracy.
2. Since the charge density is small (21), measurements must be made over an area so large that the total charge is much greater than the charge required to give an accurate indication on the measuring instrument.
3. The time constant of the capacitance under measurement and the internal resistance of the sensing instrument must be large in comparison to the time required for an observation.
4. The internal resistance of the measuring instrument must be large compared to the resistance of the discharge paths that exist on the material under test.
5. The method of generating the charge may affect the electrical properties of the test specimen.

The measurements of charge and potential that have been made (with the exception of those made by Medley (43), (44)) appear to give readings of the sum of the multiple charges of opposite sign that existed on the surfaces under measurement. Graham (22) rubbed surfaces, on which various agents had been deposited, and measured the potential generated as a function of the concentration of various types of agents both surface-active and surface-inactive. It would seem unavoidable that such rubbing would change the surface properties and thereby possibly affect the antistatic performance of the agents. This criticism could be applied, likewise, to the works of Chandler (9), Fishback and Horewith (15), Hayek (28), and Pariaud and Goullioud (50), all of whom used friction, with the attendant possibility of

abrasion, as the means of generating the quantity under measurement.

Although it would be useful to obtain data on the effect of various artifices, including antistatic agents, through measurements of the rate of charge generation, the maximum value of the charge, the potential gradient, and the rate of dissipation of charge, the experience of the last two years has indicated that too many uncontrollable factors exist to make such measurements useful except possibly to point out new directions of research. On the other hand, a considerable amount of success has attended those efforts directed toward the measurement of the resistivity of materials. Because of the relative ease of measurement, and because of the realization that if the resistivity can be brought down to a low enough value then the magnitude of the other parameters becomes unimportant. In line with this reasoning, most of the recent investigations have been directed toward the measurement of the effect of various factors on the resistivity of the material.

Whether resistivity is a reliable indication of electrostatic behavior depends, at least in part, on whether such resistivity is ohmic or dependent on the potential gradient. Most experimenters reported that the resistivities observed were ohmic over the range of potential gradients used in their experiments (18), (15), (20), (33), (66). However, Murphy (45) reported non-ohmic behavior in resistivity measurements.

Evershed (14), on the other hand, in his work with cotton and other materials, found that only those materials that were either entirely free from water content or were saturated with water exhibited an ohmic nature. Between these limits, the behavior was found to be non-ohmic, with the resistance decreasing as the potential gradient was increased. It should be pointed out, however, that the gradients he used were high, and that the curves obtained were not clearly defined for the gradients commonly used in measuring the resistance of fabrics.

Mr. Harold McLean (65) of the General Electric Engineering Laboratory stated that the resistivity was a function of the potential gradient, reaching a peak value and then decreasing as the gradient is further increased.

Thus, the calculation of resistivity obtained from readings of E/I may or may not describe the instantaneous behavior of the material, depending on whether or not the resistivity is a function of the field strength.

Other than the ohmic or non-ohmic nature of the resistivity measurements, several variables in the test procedure must be given due consideration. The heterogeneous nature of the samples, and the non-uniformity of antistatic application both produce variations in the resistivity values obtained. Likewise, the pressure between the sample under measurement and the contact electrodes must be considered; however, this source of variation can be substantially reduced by appropriate design of the equipment, as reported in the AATCC Inter-Laboratory Resistivity Tests (18), and by Teixeira and Edelstein (66) in using their guard ring electrode.

The foregoing review of the literature pointed out the numerous difficulties to be expected in an evaluation of antistatic agents on parachute fabric. While the measurable parameters are rather well defined, the correlation between laboratory evaluation to actual service results remains undetermined.

Instruments

As mentioned previously, the methods employed for determining the electrostatic properties of textiles may be separated into two general classifications; first, instrumentation which generates a charge on the test specimen through friction and measures the resulting electrostatic potential, electrostatic charge, and/or the half-life period of the charge; and, second, instrumentation which measures the surface or volume resistance of the specimen under investigation.

In an effort to determine which of the two categories could be expected to give the more desirable technique for the project, three series of evaluations were performed.

1. Measurement of Electrostatic Charge

An Electrostatic Susceptibility Meter was used in conjunction with a friction device for generating a charge on the fabric sample. This arrangement allowed the measurement of the charge generated as well as the half-life period of the charge.

Tests were designed and conducted to determine the reproducibility of results obtained on a single test sample, and to determine the range of variations to be expected in the measurement of several test samples representing the same anti-static treatment.

The inability of this instrumentation to provide reproducible results on a single test specimen indicated its shortcomings and undesirability for further investigation.

2. Measurement of Electrostatic Potential

The Fabric Contact Potential Meter developed by the General Electric Company was loaned to the Research Foundation, and was utilized in a series of tests for measuring the electrostatic potential developed on fabric surfaces.

This instrument, discussed in Appendix III, was found to give results with a non-reproducibility sufficient to regard the apparatus as unsatisfactory for a quantitative indication of electrostatic behavior.

3. Measurement of Surface Resistance

An instrument, modeled after the Hayek and Chromey Resistivity Meter, was loaned to the Foundation by the Ames Worsted Company, Lowell, Massachusetts. This instrument was utilized in the evaluation of fabric surface resistance as a measure of the electrostatic properties of the nylon parachute fabric.

Fourteen different antistatic agents, applied to both white and orange nylon fabric, were evaluated at standard conditions to determine their effect on the fabric surface resistance. A tabulation of the results obtained, and a statistical analysis of the data is presented in Appendix IV. In general, the investigation gave reproducible readings for a single fabric specimen, and demonstrated the reliability of the resistance values obtained.

As a result of the foregoing investigations, little doubt existed concerning the parameter to be utilized in the evaluation of antistatic agents on nylon fabric. Measurements of resistivity on the test specimens was selected as the only available

method by which reliable data could be obtained. Such a selection was in keeping with the feelings of other investigators in the field, and was further authenticated when the American Association of Textile Chemists and Colorists Committee on Static Electricity accepted such resistivity measurements as the Tentative Test Method for the evaluation of antistatic agents.

The problem with which this project was concerned, however, required further considerations. Since the base reference value to be used as the criterion of effectiveness of an antistatic treatment was selected as the antistatic properties of untreated nylon at standard conditions (70°F and 65% RH), what then was the resistance value of nylon at these conditions? Teixeira and Edelstein (66) reported a value of 2×10^{13} ohms for nylon at these conditions. However, it was reasonable to assume, in view of the work of other investigators, that the resistance range of untreated nylon might reach the order of magnitude of 10^{15} ohms.

Another factor to be considered was the establishing of the maximum resistance that a treated parachute can have before difficulties due to electrostatic attraction occurs. The only information available in regard to this question was that the standard nylon parachute under ordinary ambient temperature and relative humidity conditions will usually function properly. Thus, without actual experimental data available, a maximum allowable value of resistance was unknown, and a treated fabric with a resistance of as high as 10^{16} ohms at -30°F and 10% RH might function just as well as a parachute having a resistance of only 10^{12} ohms.

These considerations determined the primary characteristics of the test equipment required for the project. The instrumentation had to be designed to allow the measurement of fabric surface resistivities in the order of 10^{16} ohms. Likewise, the test apparatus had to be capable of obtaining ambient conditions in the order of -30°F and 10% RH.

In an effort to ascertain which of the many possible direct-reading instruments would be most suitable for the measurements of such high resistances, an extensive search of the literature was made, and the market was surveyed for commercially available units. Of the instruments encountered in the survey, the "Cenco Electronic Electrometer" and the "Keithley Electrometer" could be expected to provide accurate readings into the region of 10^{15} ohms. Likewise, the "Sensitive Inverter", a chopper amplifier sold by Ballantine Laboratories, Inc., Boonton, N. J., might also give readings up to 10^{14} or 10^{15} ohms. The Cenco Electronic Electrometer was finally selected because it met all the necessary requirements and was rather inexpensive.

Although the circuit stability of the electrometer used for direct readings of resistances in the 10^{15} ohm region may be of a high order, these readings would be difficult to obtain because of the susceptibility of the instrument to external disturbances. For example, when a short length of wire was attached to the "hot" input terminal of the Cenco Electronic Electrometer, it could detect the breathing of an operator at a distance of ten feet if it were set in its most sensitive position. Likewise, leakage currents, capacitance changes between charged objects in the vicinity of the test set-up, and electrical transients increased their nuisance effects as the resistance values under measurement were increased.

In order to eliminate many of these inherent difficulties, an instrument for resistance measurements was considered which would be essentially an integration type of meter. Such an instrument is described in Appendix V. Although it offered

considerable promise, further development of circuit components would have been a costly and time consuming process. In view of the modicum of success in test results achieved with the early Hayek Chromey resistance meter, work was directed to the development of a similar resistance meter having a higher resistance range as well as an improved electrode assembly.

II INSTRUMENTATION

Electrodes and Accessories

Design and Construction

The Electrodes designed for instrumentation (Figures 1 and 2) were a modification of the concentric-ring design of Texeira and Edelstein (66). This design permitted two major advantages over the conventional parallel electrode design. First, the circular area of the fabric test specimen automatically eliminated the need for separate measurements in the warp and filling directions. Second, the design allows simple conversion of the electrodes for their utilization to measure either surface or volume resistance of the material.

The upper electrode consisted of two concentric stainless steel rings set up on a highly polished Polystyrene stand-off insulator. While the use of a bonding agent was sufficient to attach the two materials under normal conditions, a unique design was required for low temperature work since the difference in the coefficients of expansion of the materials was sufficient to cause separation at -300°F . By fabricating the electrodes and Polystyrene insulators in such a manner that they were held together by a tongue and groove joint, and inserting cement into the joint by means of a hypodermic needle, a permanent bond was obtained. In addition, considerable care was taken in order to maintain close tolerances and highly polished surfaces on the electrodes and the insulators.

The lower electrode, utilizing a movable steel-Polystyrene disk, provided for a uniform contact between the fabric specimen and the upper electrode.

The manipulation of the electrodes was accomplished by means of the electrode assembly shown in Figures 3 and 4, where the air dashpot establishes a fixed rate of loading for all specimens.

The measuring circuit (Figure 5) is comprised of a Source Voltage (E_s), a Cenco Electrostatic Electrometer, and a meter shunt. The source voltage was constructed to permit the selection of 300, 100, 30, or 3 volts. The meter shunt was made up of nine calibrated resistors ranging from 10^6 to 10^{14} ohms with a suitable selector switch (Figures 6 and 7).

Calibration

For the circuit (Figure 5) it can be shown that:

$$R_g = \frac{E_g}{E_v} \times R_{shv} - R_{shv},$$

where R_g = Fabric surface resistance in ohms,

E_g = Supply voltage (300, 100, 30, or 3 volts),

E_v = Cenco reading (0 to 5 volts),

R_{shv} = Meter shunt resistance in ohms.

Since fabric resistivity has been defined as the resistance per square of fabric, then:

$$\text{Fabric resistivity} = \frac{R_g \times \text{Width of specimen}}{\text{Distance between electrodes}} \quad \text{ohms,}$$

and where Width of specimen = $1-5/8" \pi = 5.106$ inches

Distance between electrodes = 0.125 inches,

thus:

$$\text{Fabric resistivity (ohms)} = R_g \times 40.8.$$

The circuit arrangement was calibrated against resistances of the values 9.5×10^8 ohms and 9.3×10^{11} ohms, using each of the four supply voltages and the appropriate R_{shv} resistances. From the data obtained, the correction factor required to convert the calculated resistance to the true resistance was determined. The results are presented in Table 1 and are shown graphically in Figure 8.

While the application of a correction factor was desirable to convert all measurements to a true resistance value, the variations between true and calculated values could not be considered as detrimental to the test procedure. Nevertheless, this correction factor indicated the limitation to be expected in any attempt to correlate results obtained using the various source voltages and shunt resistances available with the test apparatus.

In addition to the calibration of the test apparatus against known resistances, the apparatus was also checked by measuring the surface resistance of seven samples supplied by the AATCC.

The samples consisted of one untreated and six antistatic treated nylon fabrics, the resistances of which had been measured at six different laboratories in a "round-robin" test program. The results obtained on our apparatus were converted to the logarithm of the resistivities, and have been tabulated (Table 2) in comparison with the range of results reported to the AATCC by other laboratories.

In general, the results obtained showed good agreement; although all resistance values for the treated fabrics were slightly higher than the maximum values reported

to the AATCC from other laboratories.

Temperature and Humidity Chamber

Required Control

In the preliminary consideration of the design of the Test Chamber, it was deemed necessary to control both the temperature and relative humidity within very close tolerances. This opinion was based on the results obtained by other experimenters on resistance measurements as a function of humidity, where a slight change in humidity resulted in a large variation in resistance (resistance varying as an inverse function of humidity). Those studies, however, were conducted at conditions with relative humidities of 30% to 70% and with temperatures greater than 32°F, while the data desired for this project was for conditions of -30°F and 10% RH.

From Figure 9 we see that a slight change in relative humidity at 60°F to 80°F results in a considerable change of absolute humidity, while at -30°F a corresponding change in the RH produces only a slight change in the absolute humidity.

As can be seen from Figure 9, the water vapor present during resistance measurements by other workers was quite high, and hence a slight change in humidity would produce a large change in resistance. At the extremely low values of absolute humidity required for this project, the resulting effect of small changes in humidity on the resistance should be small.

Thus, it was deemed unnecessary to construct equipment for rigidly controlled conditions of temperature and relative humidity, and therefore in the final design a manual control system was used by which the temperature and humidity could be held within the limits of $\pm 5^\circ\text{F}$ and $\pm 5\%$ RH.

Construction

The conditioning test chamber was constructed as shown in Figures 10, 11, and 12. Although the basic design was relatively simple, i. e., a double-walled chamber with a 1/2 inch air space between walls, the fabrication difficulties encountered in the assembly were extremely time consuming and tedious. Nevertheless, every precaution had to be taken to incorporate the features of air-tightness and good insulating properties.

The cooling chamber (Figure 13) was incorporated within the conditioning chamber, with a mixture of dry ice and acetone serving as the refrigerant. The dehumidifying and heating systems were constructed as shown in Figure 14. The manually controlled dehumidifying system was such that while one drying cell was in use, the alternate drying cell could be reactivated. The small volume of air retained within the test chamber and the relatively large quantity of available desiccant permitted a rapid reduction in humidity. The heating system allowed a positive control of the temperature by providing, when necessary, a counteracting effect to the cooling chamber.

A Minneapolis Honeywell Temperature Recorder with a range of -70°F to 160°F, and a standard mercury thermometer were utilized for temperature measurements; while an Amisco Recording Electric Hygrometer, and a Serdex Hygrometer (Type HGS-HY-1) were used as indicators of the relative humidity within the test chamber.

The completed LTIRF Resistivity Tester was placed within a Faraday Cage to eliminate external disturbance effects. The Resistivity Meter Assembly and the Faraday Cage are shown in Figure 15.

III ANTISTATIC AGENTS

The AATCC Yearbook and Hall's Modern Textile Auxiliaries were used as the principal source of information in obtaining the names of companies who manufactured antistatic agents. Thirty-five companies were contacted for samples of antistatic agents capable of withstanding washing and dry cleaning procedures without losing their efficiency. While a large number of such agents were received, no agent was suggested as being fast to both washing and dry cleaning.

The antistatic agents received and subsequently tested were those identified in Table 3.

The thirty-nine agents were applied to both Neutral White and International Orange nylon Type I, 1.1 ounce, rip-stop weave, parachute cloth. The material was obtained from Cheney Brothers, Manchester, Connecticut, and corresponded to United States Government Specification MIL-C-7020.

Application of the agents to the fabrics was carried out using a laboratory Butterworth padder. The per cent difference between the conditioned weights (75°F and 65% RH) of each sample before and after the antistatic treatment was considered as the per cent solids deposited on the material. In Table 4, the per cent solids add-on and the manufacturer's claim for the fastness properties have been tabulated.

If the manufacturer made recommendations as to the amount of antistatic agent required for maximum effectiveness, then the add-on applied was in keeping with those recommendations. Where no specifications were available, an attempt was made to apply a 2% active add-on. If no specifications were furnished and if the agent had a limited solubility or dispersibility in the application medium which prevented an add-on of 2%, then the maximum possible concentration (for maximum add-on) was used.

From an evaluation standpoint, it would have been more desirable to apply each antistatic agent at different levels of concentrations and determine experimentally the most effective add-on. This method, however, was not practical due to the large amount of work that would be involved. On the other hand, it was felt (in keeping with the views of many manufacturers) that if a sufficient amount of agent were applied, then the maximum efficiency should be obtained. This theory is shown in Figure 16, where the addition of antistatic agent concentrations greater than "M" produce a negligible change in the efficiency of the treatment.

The highest value of "M" reported by manufacturers who specified the most efficient concentration of their agent was given as approximately the 2 per cent level. This constituted the basis for selecting 2 per cent or higher concentrations where recommendations were not supplied.

IV TEST RESULTS

A. Orange vs White Nylon

Early in the program the Air Force indicated that a greater number of operational failures were reported for the orange-white parachutes than for the solid colored (white or orange) parachutes. This posed the question as to whether or not the electrostatic properties of orange dyed nylon were substantially different from those of undyed nylon.

In conjunction with the analysis of antistatic treated fabrics using the Hayek-Chromey Meter (Appendix IV), resistance measurements were made on both orange fabric and white fabric to determine if any differences existed between the two fabrics.

Based upon the supposition that the electrostatic properties of the white and orange nylon fabrics are the same, the application of several antistatic agents to the two materials should give antistatic properties with a high degree of correlation between the orange and white fabrics. The relative mean effectiveness of fourteen antistatic agents have been listed in Table 5, and presented in graphic form in Figure 17.

The data indicated that a certain order exists in regard to the relative effectiveness of each agent for the two fabrics. Two methods of correlation, based on ranks, were applied to the data. (The possible value limits are -1 to +1, with -1 indicating high negative correlation, 0 indicating no correlation, and +1 indicating high positive correlation.) The correlation coefficient, using the Spearman technique, was found to be +0.81, while the coefficient using the Kendall method was +0.69. From these results it is possible to conclude that, from among the several antistatic agents, the one showing the most effectiveness on white fabrics will also be most effective on an orange fabric. However, the actual numeric resistivities of the agent on each fabric will not be equal.

B. Resistivity as a Function of Temperature

Using the LTJRF Resistivity Meter, measurements of resistivity as a function of temperature with approximately constant relative humidity were made on white nylon fabrics treated with antistatic agents No. 13 and No. 15. Each value obtained was the average of five resistance measurements on a single fabric sample. Each specimen selected for the evaluation had a resistivity value close to the mean resistivity value of the treated fabric when measured at 64°F and 63% RH. All measurements were made on the same surface of each specimen.

The results of the investigation have been tabulated in Table 6 and shown graphically in Figure 18.

C. Resistivity as a Function of Relative Humidity

Measurements of resistivity versus relative humidity at constant temperature were carried out on three fabric samples. The results obtained are shown in Table 7 and Figure 19. The tests were made on the specimens used for the resistivity vs temperature study, and the same precautions were followed in the evaluation.

D. Resistivity Measurements

Using the LTIRF Resistivity Meter, the thirty-nine antistatic treated fabrics were evaluated at various conditions of temperature and relative humidity. The results obtained are tabulated in Tables 8 and 9.

The tests conducted at $-30^{\circ}\text{F} \pm 5^{\circ}$ and $10\% \text{ RH} \pm 2\%$ indicate that treatments No. 6, 7, 9, 13, and 15 were the only samples worthy of further evaluation. These five treatments (on both white and orange fabric) were subjected to a laundering procedure in accordance with the AATCC Tentative Test Method 40-52, and re-evaluated for their antistatic properties. All treatments, after laundering, had resistivity values beyond the range of the test apparatus (greater than 6.12×10^{16} ohms).

The mean resistivity and the range of values were calculated for each treatment. In those cases where one or more values were within the range of the apparatus while the remaining measurements were greater than the test limits, the average resistivity was reported as a value greater than the maximum range, and the minimum value measured was incorporated in the tables as the lower limit.

V DISCUSSION

A. Electrostatic Differences Between Orange and White Parachute Cloth

The results of the rank correlation data for orange treated fabric to white treated fabric gave a Spearman coefficient of +0.51 and a Kendall coefficient of +0.69. Based upon the hypothesis that no difference existed in the electrostatic properties of the dyed and undyed materials, and since the amount of antistatic agent applied to the two fabric samples was substantially the same, then it was logical to assume that a high positive coefficient of correlation (near +1) would be found. While the correlation coefficients are fairly high, little doubt existed that a variation does exist between the resistivities (and hence between the electrostatic properties) of the dyed and undyed nylon parachute fabrics.

An examination of the mean values for each antistatic treatment on the orange vs white fabric, shows that, in general, the resistivity of the orange material has a higher value than that of the white fabric.

In the light of these data, it may be interpreted that the orange dyed fabric is of a higher resistance than the original undyed material. Thus, a greater electrostatic potential (increased attraction) could exist between the different colored panels in the orange-white parachutes than in a single color parachute. Hence, at threshold conditions, the increased attraction between the orange and white portions of a combination parachute might be sufficient to cause increased operational failures reported for this type of parachute.

B. The Effect of Temperature on Resistivity

Even though good reproducibility was obtained in the resistivity-temperature data for treatments No. 13 and No. 15 (Figure 18), the results achieved were not sufficient to determine the exact relationship between temperature and fabric resistivity. The slight variations during the tests of relative humidity and, probably more important, the variations in absolute humidity have been reflected, undoubtedly, in the curves produced.

The variations in both relative and absolute humidity during the investigation are shown in Table 10. The table shows that the moisture content of the air at 32°F and 16% RH was thirty times greater than the content at -30°F and 10% RH.

Since Marsh and Montgomery (33), Meggin, Morris, and Yuill (36), and Slater (61) reported that resistivity is primarily a function of moisture content rather than chemical structure, and since the moisture content of the material depends on the absolute humidity rather than on the relative humidity, an evaluation of resistivity vs temperature measurements would require a rigidly controlled absolute humidity. Nevertheless, the data acquired describe satisfactorily the phenomenon involved, wherein the surface resistivity increases as the temperature decreases.

C. The Effect of Moisture on Resistivity

As in the case of the resistivity vs temperature measurements, the data obtained for the resistivity vs relative humidity were insufficient for the determination of a quantitative evaluation of the results. However, the data clearly illustrated the fact that fabric surface resistance increases as the relative humidity decreases.

D. Resistivity Measurements

The mean surface resistivity of untreated nylon parachute fabric at conditions of 70°F and 65% RH was determined to be:

6.12×10^{14} ohms for white material, and

10.8×10^{14} ohms for orange material.

These values compared favorably with the value of 2×10^{13} ohms reported by Teixeira and Edelstein (66) for untreated nylon fabric surface resistivity.

In line with the target properties discussed previously, these resistivity values were used as a reference point for establishing the relative effectiveness of a given antistatic treatment at low temperature and low humidity conditions.

While none of the thirty-nine agents tested withstood laundering, five fabric treatments, Nos. 6, 7, 9, 13, and 15, possessed antistatic properties at the conditions of -30°F and 10% RH which were in the range of the reference values of 6.12×10^{14} and 10.8×10^{14} ohms for nylon at standard conditions.

VI CONCLUSIONS

From the evaluation of antistatic treatments on nylon fabrics, the following conclusions may be drawn:

1. The surface resistance calculated from the E/I values obtained with the LTIRF Resistivity Tester required a correction factor to determine the actual resistance value. The magnitude of this factor depends upon the supply voltage and meter shunt resistance used in the circuit. While the correction factors are normally very near 1.0 (indicating little difference between calculated and true resistance), they must be taken into consideration when attempting to correlate data obtained with different instruments.
2. The calculated mean resistivity of untreated nylon parachute fabric, Type I, 1.1 ounce, rip-stop weave at standard conditions of 70°F and 65% RH was:
 6.12×10^{14} ohms for Neutral White, and
 10.2×10^{14} ohms for International Orange.
3. A given antistatic agent differs in its effectiveness when applied to white nylon and to orange nylon fabrics. For the agents tested, all but one were more effective on the white fabric than on the

orange fabric. The rank correlation of orange fabric to white fabric indicated a difference in the electrostatic properties of the two materials. These factors are important in the light of verbal reports that a greater number of operational failures occur with orange-white parachutes than with solid color parachutes.

4. No permanent (to laundering and dry cleaning) antistatic agent was found to be effective for electrostatic protection of nylon at -30°F and 10% RH.
5. Two non-permanent agents (Nos. 13 and 15) gave the nylon the desired antistatic properties at -30°F and 10% RH. In addition, treatments Nos. 6, 7, and 9 were relatively effective and deemed worthy of further consideration and evaluation prior to a selection of any one "best" agent.
6. The fact that several antistatic agents proved to be effective under conditions of extremely low absolute humidity is of significance in the theory of antistatic action. Under such conditions the resistance cannot be primarily a function of the absorption of water by the agent. Although conduction due to moisture content may be the predominating characteristic under normal atmospheric conditions, the electrical behavior encountered under adverse conditions must reflect the physical and/or chemical properties of the agent.

This evaluation of antistatic agents cannot be considered as a completed program in the establishment of the best commercial antistatic agent for nylon parachutes. Since no permanent agent was found satisfactory, a non-permanent treatment of sufficient efficiency should constitute the desired goal. While five such possible agents were selected from the thirty-nine materials tested, the final selection would have to be based on a continued investigation to establish statistical significance to the choice made in light of the effectiveness of treatment and the final properties of the nylon fabric.

In establishing the antistatic efficiency (or other characteristics) of agents investigated, consideration must be given to the range of resistance values measured for each treatment. While two given treatments may have the same mean resistivity, the treatment with the smaller variance must be considered as providing the better finish, and consequently providing the better electrostatic protection.

In this investigation there was a considerable difference in the variances of the resistivity measurements for the various agents. These differences may be a consequence of the effectiveness of the agent, or a function of the evenness of application. If the antistatic properties of a given agent tend to change due to chemical or physical modification of the finish, then a large variance may result. On the other hand, when the electrostatic properties change rapidly with the concentration of the applied agent, the method of application must be considered. It is well known that in the application of a finish, differences in pickup will occur over the length of fabric as well as from side to side of the piece. These two possibilities are worthy of consideration in the final selection of an agent for use as an antistatic finish.

Up to this point, it has been assumed that the malfunctioning of parachutes in the dry arctic regions is due to the retention of static charges. Should this be the case, then (based upon the investigation conducted) the application of a suitable non-permanent antistatic agent would alleviate those difficulties. As suggested by Mr. H. T. McLean, (General Electric Co.), not only the parachute but all other dielectric materials in the entire parachute assembly and container should be treated with an antistatic agent, for maximum possible efficiency.

As previously stated, the effectiveness of the antistatic agents has been evaluated through the investigation of only one of the measurable parameters known to be important to electrostatic behavior - fabric surface resistivity. How well such laboratory results correlate with actual service performance remains unanswered. This question, along with numerous others prevailing in this field can be answered only through a continued and expanded investigation of the phenomenon of static electricity.

Several avenues of approach should be followed in an effort to understand further and combat the problems created by static charges. The method of measuring fabric resistance may be greatly improved by an investigation of the utilization of the Integration Circuit (discussed in Appendix V). Other parameters affecting the electrostatic behavior of materials (i. e., the dielectric constant and the magnitude of the electrostatic voltage generated across an interface) should be studied to obtain accurate and reproducible methods of measurement, and to determine the relative importance of all parameters. The various basic materials, such as nylon, must be studied and understood from the point of view of electrostatic susceptibility. Such a study may be more effective through the use of homogeneous nylon sheeting rather than a woven fabric. And, finally, the nature of the finishes, applied as antistatic agents, requires a greater understanding, wherein the significance of the chemical structure, possible chemical action, and physical properties can be interpreted in terms of antistatic properties.

In general, the problems of static cannot be wholly overcome until a thorough understanding of the phenomena is made available by an expanded program into the many related fields.

APPENDIX I

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APPENDIX II

A THEORY OF STATIC ELECTRIFICATION

Of the several theories which have been suggested to explain the mechanism of static electrification by friction, none can explain the phenomenon as well as those based on quantum mechanical consideration (1), (2), (3), (4), (5).

The explanations which have been presented, however, cannot account for all the details of static electrification and are far from being complete. The analytical investigation of the problem of static electrification is so complex that recent investigations have been primarily restricted to metal to insulator friction. It is hoped that an understanding of this simpler case may eventually lead to a solution of the more complicated instance of insulator to insulator friction.

This review does not deal with such microscopic effects as double layer effects, electrolytic effects, etc. It is felt that an atomistic understanding of the phenomena is of primary importance in pointing the way to the solution of the problem of electrification from the point of view of the properties of the material.

There are essential structural differences between metals and the so-called insulators. When an electron coming from infinity (with a given energy) passes through a metal, its potential energy is reduced. The total energy, however, remains unaffected. The states of motion of the electron in the metal are possible only in a number of discrete energy states. Not more than two electrons can occupy any one energy level (Pauli's exclusion principle). In the case of an insulator, some of the energy levels are fully occupied in the sense that the electrons in them are bound and cannot participate in the conduction of electricity.

It is not reasonable to consider an insulator as possessing allowable bands since these could be occupied by free electrons, i.e., the insulator would conduct electricity which is against our conventional concept of a true insulator. It is more realistic, instead, to visualize allowable states which can be occupied by electrons of restricted freedom of movement. This point of view can then explain the adherence of the charging electrons on the surface of an insulator, and it can also account for the possible existence of "holes" whenever these semi-free electrons can be detached from the surface of the insulator.

An explanation of the electrification can now be had on the basis of the previous argument. The schematic shown in Figure 20 is very helpful to the discussion.

Three cases are considered for a block of metal and insulators brought into the proximity of each other. The above figures also show the manner in which the potential barrier is expected to change with the separation between the metal and insulator. Case III, shown in detail in the lower part of the figure, indicates the two possibilities of having the metal charged negatively by friction according to the holes left in the insulator being due to electrons leaving a state of restricted freedom or the reverse case for which the metal becomes positively charged.

The point of view which has been adopted above can explain the influence of the effect of applying mechanical pressure when electrifying bodies by friction. It also is able to yield a plausible explanation for the retention of the charge by an insulator, i.e., the appearance of holes as indicated in the expanded Case III.

The quantum mechanics approach to this problem is new, and very few papers dealing with this immediate question have been written. Nevertheless, the scientific tool required for a satisfactory explanation of the phenomenon of static may well be that of quantum mechanics, and future investigations may lead to explanations of static generated by insulator to insulator friction.

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APPENDIX III

THE FABRIC CONTACT POTENTIAL METER

The General Engineering Laboratory of the General Electric Company has developed a Fabric Contact Potential Meter for the measurement of electrostatic potential to indicate the electrostatic nature of the surface of materials and the effectiveness of applied antistatic agents.

This instrument is shown in Figure 21, and is operated in the following manner: The upper and lower plates are circular disks of polished chromium. The upper plate is separated from the electrostatic shield by a polyethylene block. The test specimen is clamped securely over the lower plate, and the upper plate is grounded. The lower plate is brought into close contact with the upper plate, and held securely by means of a special clamp. The ground is removed from the upper plate, and then the lower plate is quickly released and allowed to fall away from the upper plate at a constant rate. The potential existing on the upper plate is measured by a Keithley Electrostatic Voltmeter and represents the voltage existing on the fabric specimen. The polarity of the charge indicated is opposite to that existing on the fabric.

It was found necessary (by General Electric) to rub the test specimen manually with a sheet of Mylar (a Dacron film) to build up a charge on the fabric prior to the measurement of the electrostatic potential. Through this technique, the General Electric representatives claimed that it was possible to obtain reproducible results.

APPENDIX IV

STATISTICAL ANALYSIS OF RESISTIVITY DATA WITH THE HAYEK-CHROMERY METER

Instrumentation

The instrument used in this phase of the project was modeled after the Hayek-Chromery Resistivity Meter. The design and construction was such that surface resistances from 10^6 to 4.0×10^{13} ohms could be measured with an accuracy of about 5% over the greater part of the range.

Experimental

Fourteen different antistatic agents, applied to both white and to orange nylon parachute fabrics, were evaluated at standard conditions (70°F and 65% RH). Five samples were taken from each fabric, and ten resistance readings were made for each sample, thus obtaining a cumulative total of fifty resistivity readings per treatment. In a statistical sense, fifty tests allowed an accurate evaluation of the effectiveness of the various treatments.

Results

A tabulation of the results of the resistance measurements, and the statistical calculations therefrom has been presented in Table 11. The antistatic treatments applied were identified in Table 3. Table 11 shows the test mean, test variance, standard error of the mean, and the estimated population limits for each of the fabrics involved. The estimated population limits are further illustrated by their graphical representations in Figure 22.

Discussion

The measurement of the surface resistance of untreated nylon was prohibited by the limited range of the instrumentation, thus the data obtained could not be interpreted in terms of the absolute effectiveness of the antistatic agents. Nevertheless, the relative effectiveness of these agents was obtainable.

In order to establish the fact that a given antistatic agent was more effective than another, it must be shown that the mean values of the resistivities of the respective treatments differ from each other by an amount greater than that which can be attributed to chance. In addition, it must also be shown that the distributions of the individual test values for each treatment are statistically alike. If they are not alike, it is necessary that they do not influence any analyses applied to the means. Generally speaking, formal statistical tests for measuring the probability of unlike means of groups of test information are necessary only when the differences, of themselves, do not appear to be significant. In considering the test data, it was also decided to calculate estimates of both the standard error for each group mean and estimates of the population limits for expected future tests

for each treatment. The standard error of the mean is an index of the confidence that can be placed in each mean value. From a visual examination of the population test limits, the degree of overlap of the test results from one treatment to another can be gauged, and a decision reached as to the necessity for a formal statistical test to evaluate the probability that the groups included are alike or unlike.

In considering the mean values, as tabulated in Table 11 and represented graphically in Figure 22, it was obvious that the differences in the means were so great that a formal statistical test designed to measure the probability of the means being alike was unnecessary.

In considering the uniformity of application of each agent on a given fabric (white or orange), the range of test results for all agents would tend to be of the same magnitude provided that all other factors remained equal. Since the testing procedure was standardized to hold the other factors constant, then the application of an "L₁" test would measure the probability that the variances (a measure of the range of test results) were statistically alike. For the agents tested, the probability that the variances were equal was found to be considerably less than one per cent. Thus, the chances were 99 to 1 that the variances were different. Hence, the assumption that the distributions of the test results for the various agents were alike was not upheld, and therefore a variation existed in the uniformity of application between the various agents.

As an example of the range of variances encountered, Treatment No. 5 had a variance that was 1,713,000 times larger than that of Treatment No. 8 when these agents were applied to white nylon fabric.

APPENDIX V

RESISTANCE BY INTEGRATION

In contrast with instrumentation for the direct reading of high resistance values, a method which should improve the accuracy of the measurements is suggested using the principle of integration. In this system (Figure 23), the textile sample constitutes a series charging resistor for an air condenser which has a shunt resistance that is high compared to the value under measurement.

After the charging current (E_s) has been allowed to flow for a predetermined length of time, the condenser (C) is connected across the terminals of an electrometer. From the known quantities, namely, the capacitance of the condenser, the charging time, the external voltage, and the voltage across the air condenser, the value of the unknown resistance can be calculated since it can be shown that

$$R_x = \frac{t}{C} \cdot \frac{1}{-\log_e \frac{(1-E_s)}{E}}, \text{ where}$$

R_x = Resistance in ohms

t = Charging time in seconds

C = Capacitance of the air condenser in farads

E_s = Source voltage

E = Voltage across the air condenser after time t

Thus, with a source voltage of 1000 volts, a charging time of 100 seconds, and realizable values of C , then values of R_x up to about 10^{18} ohms should be measurable if an electrometer is used as an indicator of E . Likewise, if a more sensitive element were used for the indication of E , it would be possible to extend the range to a higher value.

TABLE 1

RESISTANCE MEASUREMENTS WITH CALIBRATED RESISTANCE

A. $R_s = 9.5 \times 10^8 \text{ ohms} \pm 1\%$

E_s (volts)	R_{shv} (ohms)	E_v (volts)	Calculated R_s (10^8 ohms)	Correction factor $= \frac{9.5 \times 10^8}{\text{calculated } R_s}$
295	10^6	0.3	9.8	0.97
295	10^7	2.9	10.0	0.95
98	10^6	1.0	9.7	0.98
98	10^7	0.1	9.8	0.97
30	10^7	0.3	10.0	0.95
30	10^8	2.5	11.0	0.86
3	10^8	0.3	9.0	1.05
3	10^9	1.2	15.0	0.63

B. $R_s = 9.3 \times 10^{11} \text{ ohms} \pm 1\%$

E_s (volts)	R_{shv} (ohms)	E_v (volts)	Calculated R_s (10^{11} ohms)	Correction factor $= \frac{9.3 \times 10^{11}}{\text{calculated } R_s}$
295	10^9	0.5	5.9	1.58
295	10^{10}	5.0	5.9	1.58
98	10^9	0.1	9.8	0.95
98	10^{10}	1.3	7.6	1.22
30	10^{10}	0.3	9.9	0.94
30	10^{11}	2.9	9.4	0.99
3	10^{11}	0.3	9.0	1.03
3	10^{12}	1.1	17.0	0.55

TABLE 2
LTIRF RESULTS VS AATCC RESULTS

<u>Fabric</u>	<u>Log of Resistivity</u>	
	<u>LTIRF</u>	<u>Range of AATCC Results</u>
Untreated Nylon	15.4	12.4 to greater than 15.0
Treatment A	12.2	9.8 to 10.4
Treatment B	13.5	11.7 to 13.4
Treatment C	10.1	8.6 to 9.7
Treatment D	9.8	8.4 to 9.4
Treatment E	10.7	9.1 to 10.5
Treatment F	10.6	9.4 to 10.4

TABLE 3

ANTISTATIC AGENTS RECEIVED AND TESTED

<u>Treatment No.</u>	<u>Agent</u>	<u>Manufacturer</u>
1	Zelec DP	E. I. du Pont de Nemours & Co.
2	S-1347	Glyco Products Co.
3	S-1348	Glyco Products Co.
4	S-1349	Glyco Products Co.
5	Polyethylene Glyco 400 Mono Laurate	Glyco Products Co.
6	Avcosol 20	Atlas Powder Company
7	Tween 20	Atlas Powder Company
8	G-263	Atlas Powder Company
9	GRL 48916	Atlas Powder Company
10	Aerotex Antistatic	American Cyanamid Co.
11	Aerotex Softener H	American Cyanamid Co.
12	G 3350 (GRL 48917)	Atlas Powder Company
13	G 3780 (GRL 48913)	Atlas Powder Company
14	Decersol SE	American Cyanamid Co.
15	G 202 (GRL 48915)	Atlas Powder Company
16	Silver Lube A S	Carolina Aniline
17	Silver Lube NFW	Carolina Aniline
18	Silver Lube F	Carolina Aniline
19	Lektrostat B	Dexter Chemical Corp.
20	Lektrostat GY	Dexter Chemical Corp.
21	Lektrostat C	Dexter Chemical Corp.
22	Nopcostat 5V	Nopco Chemical Co.
23	Nopcostat YW	Nopco Chemical Co.
24	Arkansas SW	Arkansas Company
25	Trepostat 30	Treplow Products
26	Triton K60	Rohm & Haas
27	Ahco III Paste	Arnold, Hoffman & Co.
28	Antistat R-50-N	Tanatex Corp.
29	Antistat M-50-N	Tanatex Corp.
30	Cellolube Antistat	Tanatex Corp.
31	Tanalube Q 200%	Tanatex Corp.
32	Cellolube CS 200%	Tanatex Corp.
33	Cellolube	Tanatex Corp.
34	Silver Lube NF	Carolina Aniline
35	Silver Lube FW	Carolina Aniline
36	Antistat M-50-N	Tanatex Corp.
37	Ceraminc MC Conc.	Sandoz
38	Nopcostat ST	Nopco Chemical Co.
39	Nopcostat AS-40	Nopco Chemical Co.

TABLE 4
AGENTS APPLIED TO NYLON FABRIC

Treatment No.	% Solids Deposited on Fabric		Manufacturer's Claims Regarding Fastness to	
	White	Orange	Laundering	Dry Cleaning
1	0.8	0.6	Yes	No Claim
2	3.7	3.0	Partially	Partially
3	3.4	3.1	Partially	Partially
4	3.7	2.8	Partially	Partially
5	4.3	3.0	Partially	Partially
6	4.2	4.0	No	No
7	4.1	3.6	Unknown	Unknown
8	1.4	1.8	Unknown	Unknown
9	3.9	4.0	Unknown	Unknown
10	3.0	3.4	Limited	Limited
11	1.2	0.7	No	Limited
12	3.8	4.0	Unknown	Unknown
13	3.3	3.3	Unknown	Unknown
14	2.3	2.2	Limited	Limited
15	3.3	3.4	Unknown	Unknown
16	1.4	1.4	Yes	Unknown
17	1.8	1.0	Yes	Unknown
18	1.8	1.8	Yes	Unknown
19	1.0	0.5	Fair	Fair
20	0.4	0.2	Fair	Fair
21	0.4	0.3	Fair	Fair
22	1.2	1.0	No	No
23	3.5	2.6	No	No
24	0.4	0.3	No	Partially
25	0.9	0.6	Partially	Partially
26	0.3	0.3	No	No Claim
27	0.3	0.2	Good	Fair
28	0.9	0.9	No	Unknown
29	0.8	0.9	No	Unknown
30	1.2	1.2	No	Unknown
31	1.4	1.1	No	Unknown
32	0.7	0.5	No	Unknown
33	0.3	0.4	No	Unknown
34	3.7	1.8	Yes	Unknown
35	0.9	0.5	Yes	Unknown
36	0.4	1.0	No	Unknown
37	2.3	2.0	Partially	Unknown
38	1.0	0.8	No	No
39	2.1	1.8	No	No

TABLE 5

RELATIVE MEAN EFFECTIVENESS OF THE ANTISTATIC AGENTS TESTED

(Ranking is in ascending order, with the most effective agent assigned Rank 1, and the least effective assigned Rank 14.)

White Fabric			Orange Fabric			Correlation Ranking			Correct Sequences
Agent	Mean (obs $\times 10^5$)	Agent	Mean (obs $\times 10^5$)	Agent	White Fabric	Orange Fabric	Rank Diff.		
8 - W*	644	8 - O**	547	8 - W, 8 - O	1	1	0	13	
9 - W	1360	9 - O	1810	9 - W, 9 - O	2	2	0	12	
1 - W	1680	13 - O	1840	1 - W, 1 - O	3	4	+1	10	
13 - W	1770	1 - O	5050	13 - W, 13 - O	4	3	-1	10	
10 - W	2710	10 - O	5570	10 - W, 10 - O	5	5	0	9	
16 - W	6740	11 - O	21800	16 - W, 16 - O	6	14	+8	0	
6 - W	9180	12 - O	32000	6 - W, 6 - O	7	8	+1	5	
11 - W	14600	6 - O	44100	11 - W, 11 - O	8	6	-2	5	
12 - W	17200	18 - O	53500	12 - W, 12 - O	9	7	-2	5	
18 - W	43800	3 - O	58800	18 - W, 18 - O	10	9	-1	4	
3 - W	48200	5 - O	105000	3 - W, 3 - O	11	10	-1	3	
2 - W	52800	17 - O	123000	2 - W, 2 - O	12	13	+1	0	
17 - W	60200	2 - O	176000	17 - W, 17 - O	13	12	-1	0	
5 - W	102000	16 - O	298000	5 - W, 5 - O	14	11	-3	0	

* W = White Nylon
 ** O = Orange Nylon

TABLE 6

RESISTIVITY AS A FUNCTION OF TEMPERATURE

<u>Sample Treatment</u>	<u>Temp °F</u>	<u>RH %</u>	<u>Resistivity (ohms)</u>	<u>Log Resistivity</u>
#13 White	32	16	7.90×10^{11}	11.9
#13 White	5	13	3.70×10^{12}	12.6
#13 White	-4	12	1.32×10^{13}	13.1
#13 White	-15	11	3.48×10^{14}	14.5
#13 White	-25	11	8.45×10^{14}	14.9
#13 White	-30	10	1.97×10^{15}	15.3
#15 White	32	16	4.23×10^{11}	11.6
#15 White	5	13	1.32×10^{12}	12.1
#15 White	-4	12	8.45×10^{12}	12.9
#15 White	-15	11	2.15×10^{14}	14.3
#15 White	-25	11	5.92×10^{14}	14.8
#15 White	-30	10	7.40×10^{14}	14.9

TABLE 7

RESISTIVITY VS RELATIVE HUMIDITY (AT CONSTANT TEMPERATURE)

<u>Sample Treatment</u>	<u>Temp OF</u>	<u>RH %</u>	<u>Resistivity (ohms)</u>	<u>Log Resistivity</u>
Untreated White	64	63	10.3×10^{14}	15.0
Untreated White	64	42	app 12×10^{15}	16.1
#13 White	64	63	1.48×10^{10}	10.2
#13 White	64	45	8.45×10^{10}	10.9
#13 White	64	42	9.12×10^{10}	11.0
#13 White	64	32	1.32×10^{11}	11.1
#13 White	64	22	1.82×10^{11}	11.3
#13 White	64	18	2.37×10^{11}	11.4
#15 White	64	63	less than 2.45×10^9	-
#15 White	64	45	app 2.45×10^9	9.4
#15 White	64	23	2.82×10^{10}	10.5
#15 White	64	18	3.06×10^{10}	10.9

TABLE 8
RESISTIVITY MEASUREMENTS FOR TREATED AND UNTREATED NYLON FABRICS

Fabric Treatment	Temp °F	RH %	Average Resistivity (ohms) (Resistance/Square)	No. of Specimens Tested	Tests per Specimen	Total Readings	Limits of Resistivities for Individual Tests
Untreated - W*	70	65	6.12 x 10 ¹⁴	10	5	50	3.71 to 8.16 x 10 ¹⁴
Untreated - O**	70	65	10.2 x 10 ¹⁴	10	5	50	7.20 to 17.5 x 10 ¹⁴
Untreated - W	64	60	10.8 x 10 ¹⁴	5	5	25	5.15 to 13.1 x 10 ¹⁴
Untreated - O	64	60	22.4 x 10 ¹⁴	5	5	25	8.97 to 77.8 x 10 ¹⁴
# 9 - W	64	60	1.48 x 10 ¹⁰	5	5	25	0.91 to 3.48 x 10 ¹⁰
# 9 - O	64	60	1.25 x 10 ¹⁰	3	5	15	0.91 to 1.98 x 10 ¹⁰
# 12 - W	64	60	10.9 x 10 ¹⁰	5	5	25	6.57 to 16.9 x 10 ¹⁰
# 12 - O	64	60	16.9 x 10 ¹⁰	3	5	15	13.1 to 23.6 x 10 ¹⁰
# 13 - W	64	60	3.04 x 10 ¹⁰	5	5	25	1.46 to 5.63 x 10 ¹⁰
# 13 - O	64	60	1.28 x 10 ¹⁰	5	5	25	1.18 to 3.88 x 10 ¹⁰
# 15 - W	64	60	less than 2.45 x 10 ⁹	5	-	-	-
# 15 - O	64	60	less than 2.45 x 10 ⁹	5	-	-	-
# 1 - W	-20	12	greater than 8.16 x 10 ¹⁵	5	-	-	-
# 1 - O	-20	12	greater than 8.16 x 10 ¹⁵	5	-	-	-
# 8 - W	-20	12	greater than 8.16 x 10 ¹⁵	5	-	-	-
# 8 - O	-20	12	greater than 8.16 x 10 ¹⁵	5	-	-	-
# 16 - W	-20	12	greater than 8.16 x 10 ¹⁵	5	-	-	-
# 16 - O	-20	12	greater than 8.16 x 10 ¹⁵	5	-	-	-
# 10 - O	-20	12	greater than 8.16 x 10 ¹⁵	5	-	-	-
# 6 - W	-20	12	13.9 x 10 ¹⁴	4	10	40	9.85 to 29.5 x 10 ¹⁴
# 9 - W	-20	12	25.7 x 10 ¹⁴	5	10	50	19.7 to 59.2 x 10 ¹⁴
# 9 - O	-20	12	19.7 x 10 ¹⁴	4	10	40	13.9 to 29.6 x 10 ¹⁴
# 13 - W	-20	12	7.40 x 10 ¹⁴	5	10	50	4.74 to 10.8 x 10 ¹⁴
# 13 - O	-20	12	7.90 x 10 ¹⁴	5	10	50	5.65 to 13.2 x 10 ¹⁴

* W = White Nylon
** O = Orange Nylon

TABLE 9
FABRIC RESISTIVITY AT -30°F AND 10% RH
(LTIRF RESISTIVITY TESTER)

Temperature -30°F
Relative Humidity 10%
No. of Specimens per Fabric 5
No. of Tests per Specimen 5
Total Readings per Fabric 25
Source Voltage 300 Volts

W* = White Fabric

O** = Orange Fabric

<u>Fabric Treatment</u>	<u>Average Resistivity (ohms)</u>	<u>Limits of Resistivities for Individual Tests</u>
Untreated - W*	Out of Range	
Untreated - O**	Out of Range	
1 - W	>6.12 x 10 ¹⁶	Minimum of 9.4 x 10 ¹⁵
2 - W	Out of Range	
3 - W	Out of Range	
4 - O	>6.12 x 10 ¹⁶	Minimum of 1.2 x 10 ¹⁶
5 - W	1.22 x 10 ¹⁶	0.61 to 1.83 x 10 ¹⁶
6 - W	5.18 x 10 ¹⁵	3.95 to 7.20 x 10 ¹⁵
7 - W	3.65 x 10 ¹⁵	1.75 to 5.84 x 10 ¹⁵
8 - W	Out of Range	
9 - W	2.45 x 10 ¹⁵	2.04 to 4.08 x 10 ¹⁵
9 - O	6.02 x 10 ¹⁵	3.01 to 12.0 x 10 ¹⁵
10 - O	>6.12 x 10 ¹⁶	Minimum of 1.75 x 10 ¹⁶
11 - W	>6.12 x 10 ¹⁶	Minimum of 1.75 x 10 ¹⁶
12 - W	Out of Range	
13 - W	16.9 x 10 ¹⁴	9.10 to 23.6 x 10 ¹⁴
13 - O	17.7 x 10 ¹⁴	11.8 to 33.8 x 10 ¹⁴
14 - W	>6.12 x 10 ¹⁶	Minimum of 1.72 x 10 ¹⁶
15 - W	6.23 x 10 ¹⁴	3.95 to 8.45 x 10 ¹⁴
15 - O	7.40 x 10 ¹⁴	4.94 to 16.9 x 10 ¹⁴
16 - W	Out of Range	
17 - W	2.04 x 10 ¹⁶	1.53 to 6.10 x 10 ¹⁶
19 - W	Out of Range	
20 - W	Out of Range	
21 - W	>6.12 x 10 ¹⁶	Minimum of 2.40 x 10 ¹⁶
22 - W	Out of Range	
23 - W	>6.12 x 10 ¹⁶	Minimum of 3.01 x 10 ¹⁶
25 - W	>6.12 x 10 ¹⁶	Minimum of 1.50 x 10 ¹⁶
26 - W	Out of Range	
27 - W	>6.12 x 10 ¹⁶	Minimum of 2.45 x 10 ¹⁶
28 - W	Out of Range	
29 - W	Out of Range	

TABLE 9 (Continued)

FABRIC RESISTIVITY AT -30°F AND 10% RH
(LTIRF RESISTIVITY TESTER)

Temperature -30°F
Relative Humidity 10%
No. of Specimens per Fabric 5
No. of Tests per Specimen 5
Total Readings per Fabric 25
Source Voltage 300 Volts

W* = White Fabric

O** = Orange Fabric

<u>Fabric Treatment</u>	<u>Average Resistivity (ohms)</u>	<u>Limits of Resistivities for Individual Tests</u>
30 - W	Out of Range	
31 - W	Out of Range	
32 - W	Out of Range	
33 - W	>6.12 x 10 ¹⁶	Minimum of 2.45 x 10 ¹⁶
34 - W	Out of Range	
35 - W	Out of Range	
36 - W	>6.12 x 10 ¹⁶	Minimum of 1.75 x 10 ¹⁶
37 - W	Out of Range	
38 - W	>6.12 x 10 ¹⁶	Minimum of 1.53 x 10 ¹⁶
39 - W	Out of Range	

TABLE 10

VARIATION IN TEST ATMOSPHERE MOISTURE CONTENTS

<u>Temp OF</u>	<u>RH %</u>	<u>Grains Water Vapor Per Pound Dry Air (Absolute Humidity)</u>	<u>Temp OF</u>	<u>RH %</u>	<u>Grains Water Vapor Per Pound Dry Air</u>
32	16	4.24	32	10	2.65
5	13	1.07	5	10	0.82
-4	12	0.66	-4	10	0.54
-15	11	0.35	-15	10	0.31
-25	11	0.21	-25	10	0.19
-30	10	0.14	-30	10	0.14

TABLE 11
RESISTIVITY MEASUREMENTS AND CALCULATIONS
(Hayek-Chromey Resistivity Meter; 70°F and 65% RH)

Anti-static Agent	Test Mean (ohms x 10 ⁵)	Test Variance (ohms x 10 ¹⁰)	Std. Error of Mean (per cent)	Estimated Population Limits for Individual Tests (ohms x 10 ⁵)
1 - W*	1680	366	0.16	1623 - 1737
2 - W	52800	26200	0.04	52314 - 53286
3 - W	48200	111300	0.10	47198 - 49202
5 - W	102000	23980000	0.68	87300 - 116700
6 - W	9180	4400	0.01	9157 - 9201
8 - W	644	14	0.08	632 - 656
9 - W	1360	307	0.18	1306 - 1414
10 - W	2710	1446	0.20	2596 - 2824
11 - W	14600	45100	0.21	13961 - 15239
12 - W	17200	89200	0.25	16300 - 18097
13 - W	1770	1965	0.36	1635 - 1905
16 - W	6740	77	0.02	6713 - 6767
17 - W	60200	11000	0.02	59885 - 60515
18 - W	43800	10700	0.11	42816 - 44784
1 - O**	5050	412	0.05	4990 - 5110
2 - O	176000	9110000	0.24	166940 - 185060
3 - O	58800	325500	0.14	57084 - 60516
5 - O	105000	46970000	0.93	84420 - 125560
6 - O	44100	9200	0.03	43812 - 44388
8 - O	547	3	0.05	541 - 553
9 - O	1810	411	0.16	1740 - 1870
10 - O	5570	697	0.07	5492 - 5648
11 - O	21800	366200	0.39	19982 - 23618
12 - O	32000	97400	0.14	31064 - 32936
13 - O	1840	4222	0.50	1645 - 2035
16 - O	298000	6260000	0.12	290470 - 305530
17 - O	123000	69250000	0.96	98010 - 147930
18 - O	53500	21600	0.04	53059 - 53941

* Treatment No. 1 in Table 1 on white nylon.

** Treatment No. 1 in Table 1 on orange nylon.

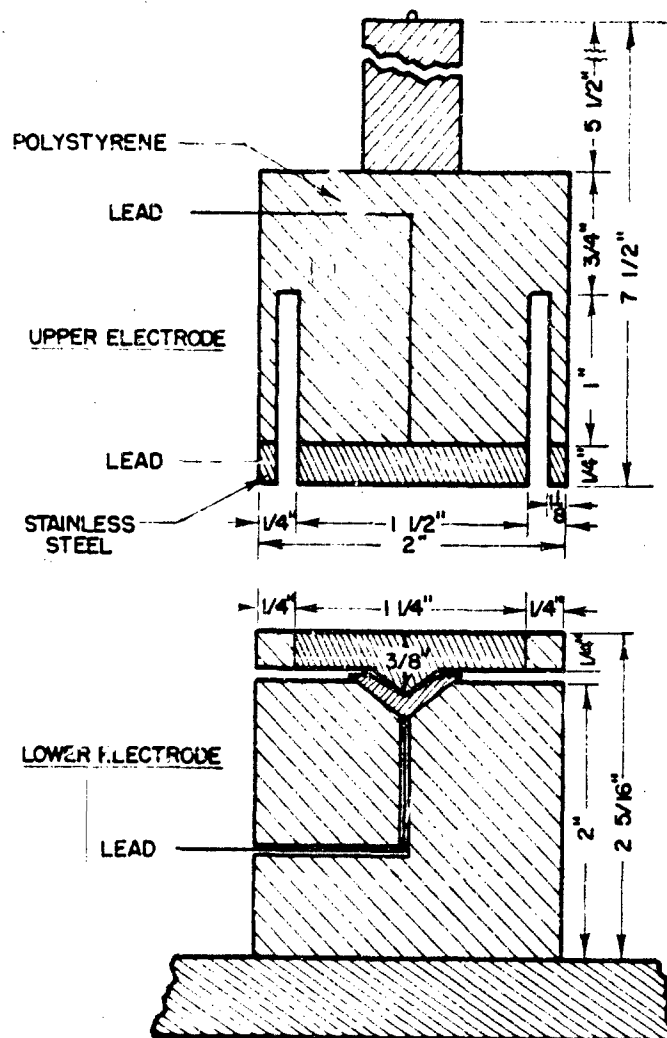


FIGURE 1

ELECTRODES

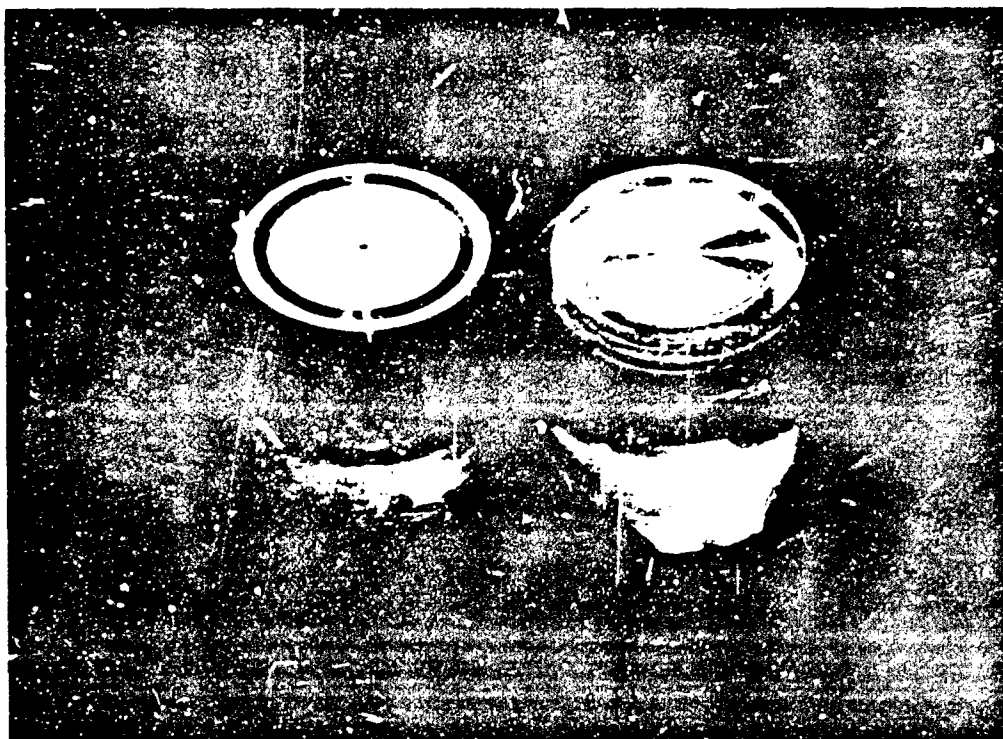


FIGURE 2
DISMOUNTED ELECTRODES

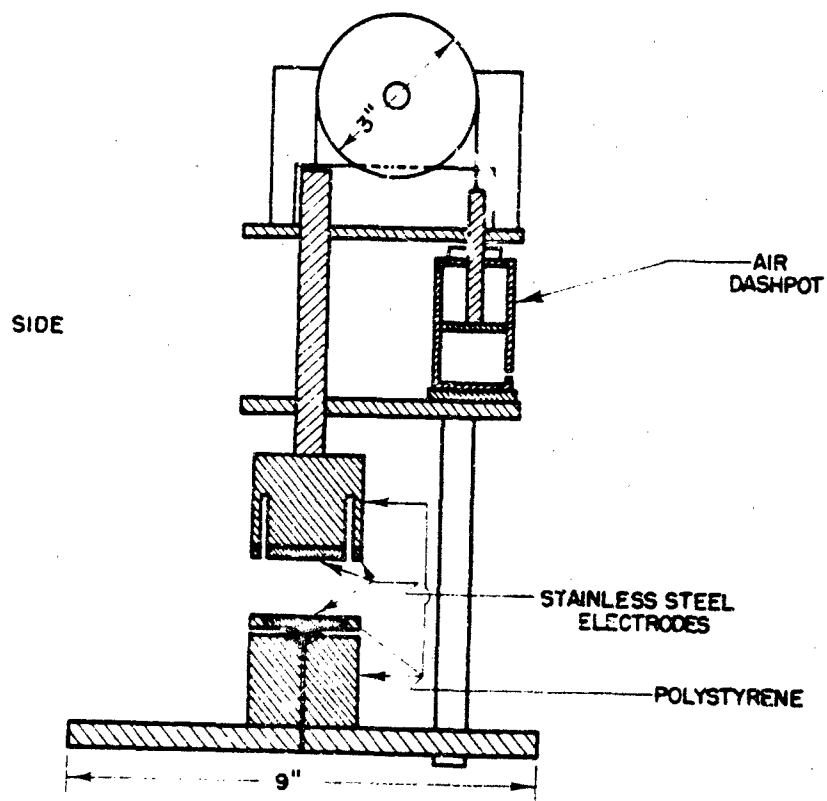


FIGURE 3
ELECTRODE ASSEMBLY

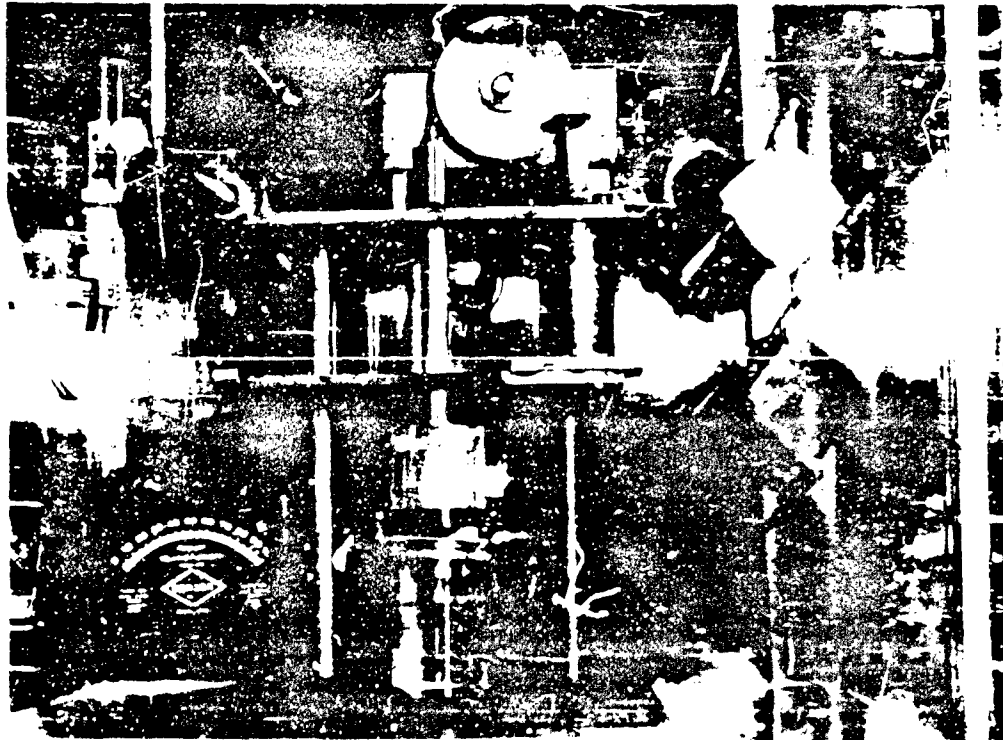
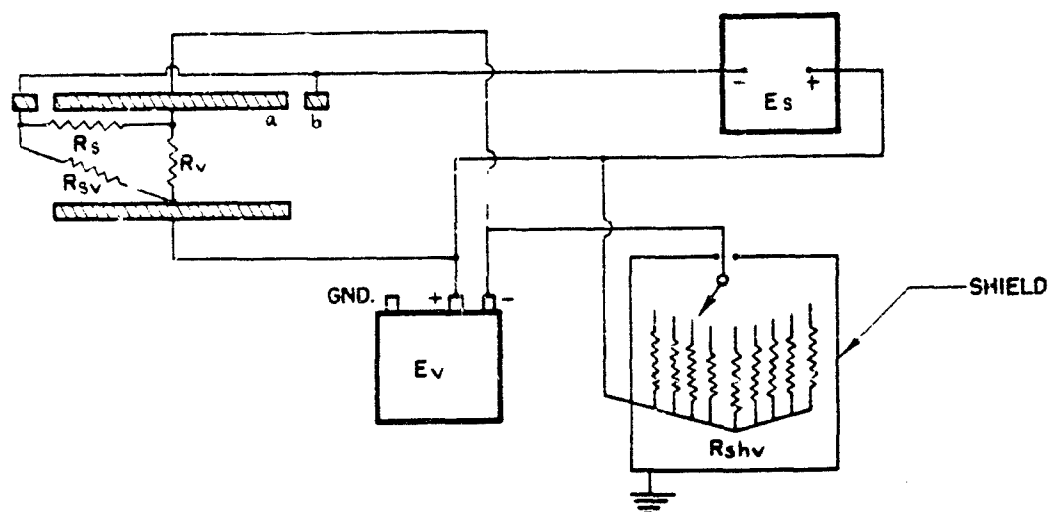


FIGURE 4
INTERNAL VIEW OF CHAMBER



- a = GUARDED ELECTRODE
- b = UNGUARDED ELECTRODE
- c = GUARD ELECTRODE
- E_s = SUPPLY VOLTAGE (300 V)
- E_v = CENCO ELECTROMETER
- R_{shv} = METER SHUNT (CALIBRATED RESISTORS)
- R_s = SURFACE RESISTANCE OF FABRIC
- R_v = VOLUME RESISTANCE OF FABRIC
- R_{sv} = LEAKAGE RESISTANCE FROM UNGUARDED ELECTRODE TO GUARD ELECTRODE

FIGURE 5

CIRCUIT FOR SURFACE RESISTANCE

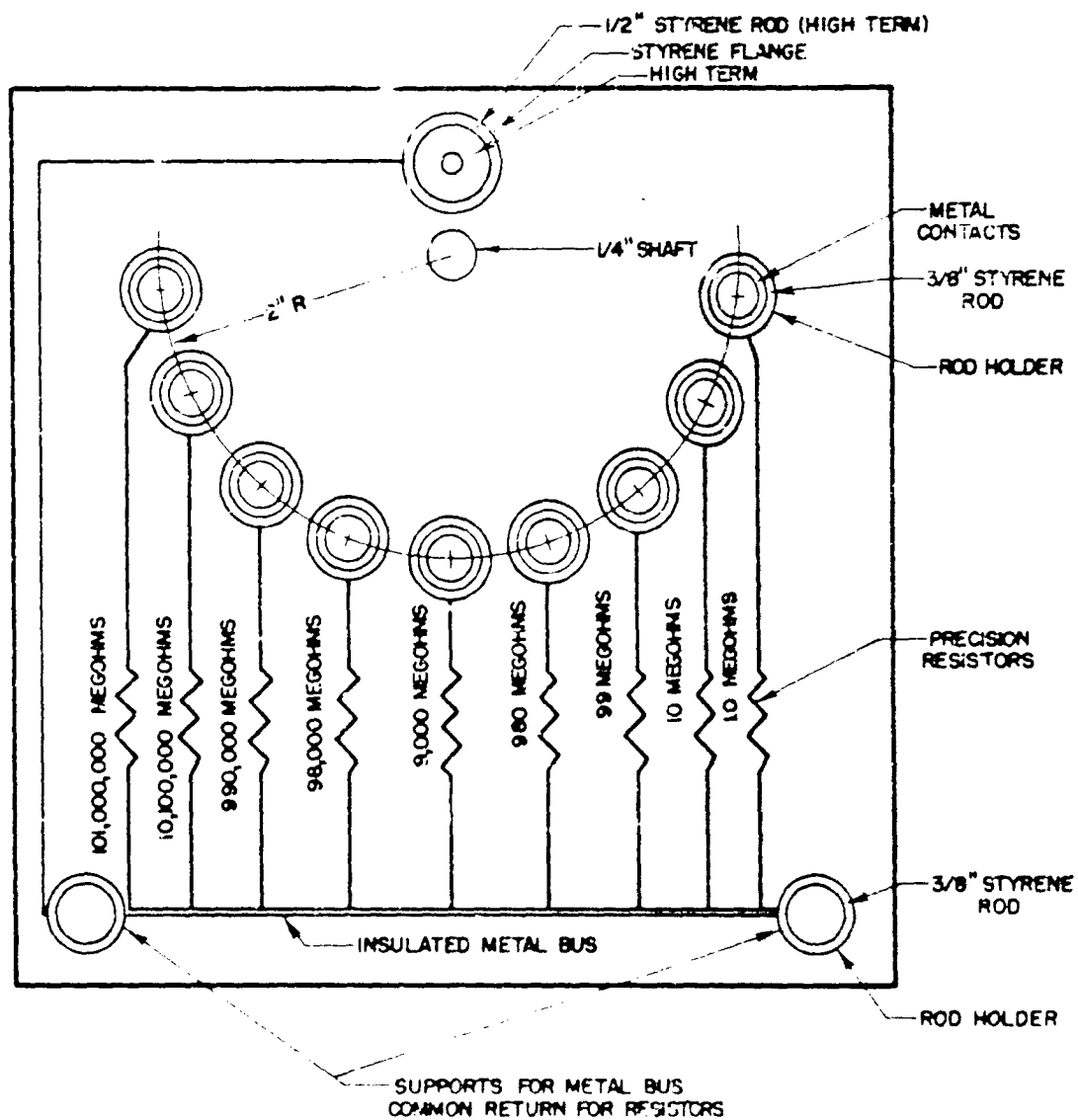


FIGURE 6

METER SHUNT, FRONT VIEW

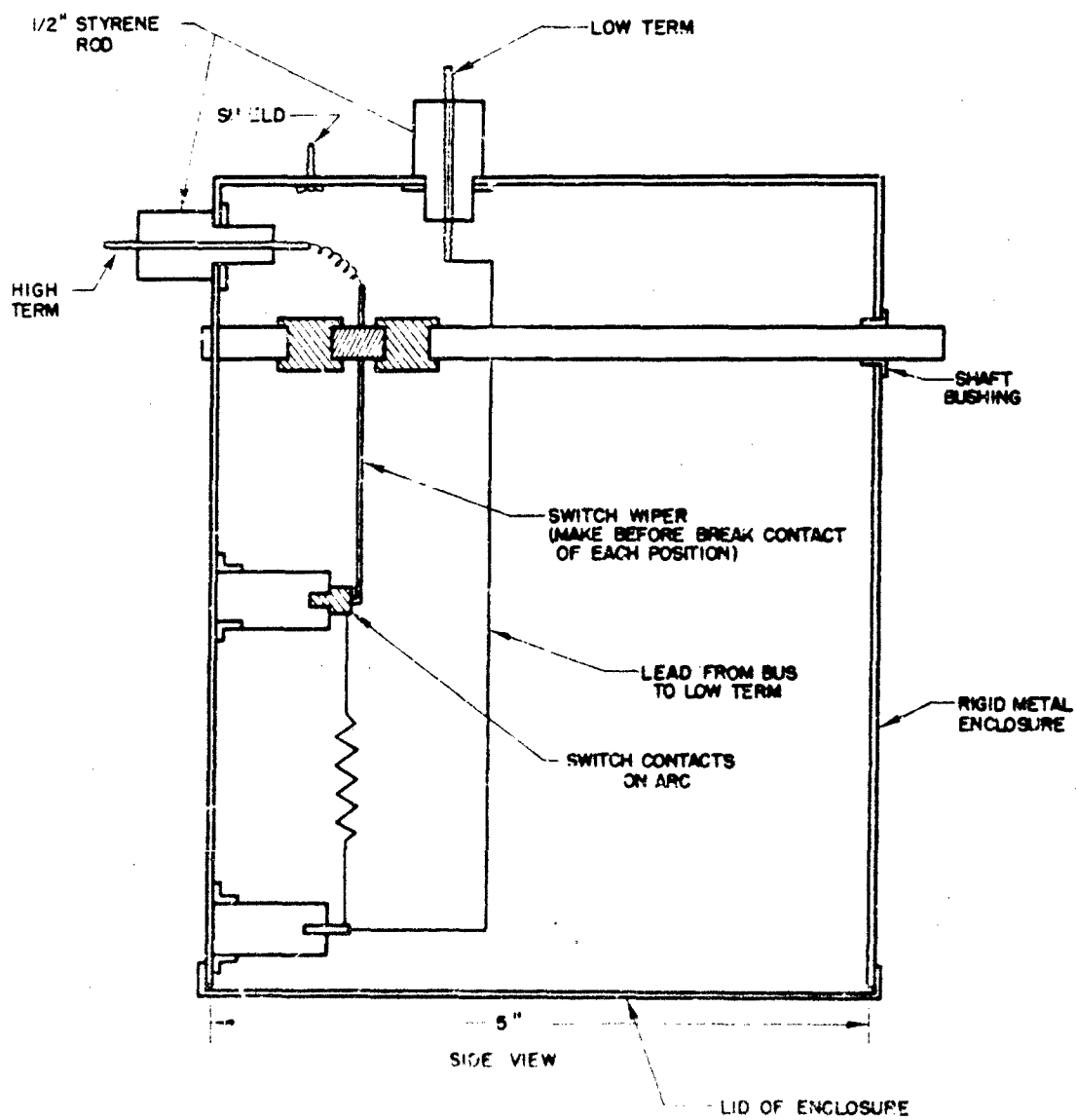


FIGURE 7

METER SHUNT, SIDE VIEW

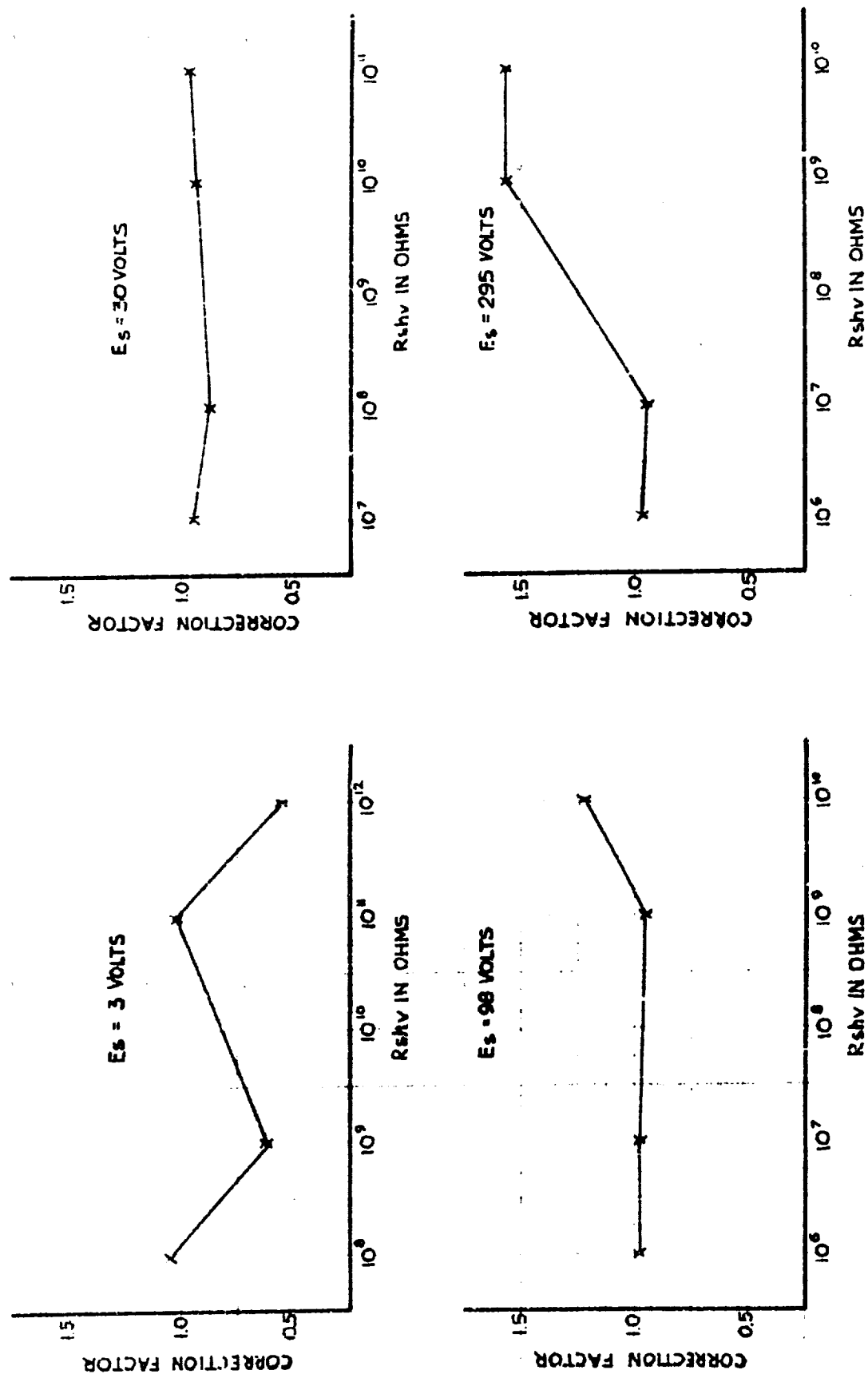


FIGURE 8
CORRECTION FACTOR $\frac{V_s}{V_e}$ R_{shv} VALUES
AT VARIOUS SUPPLY VOLTAGES

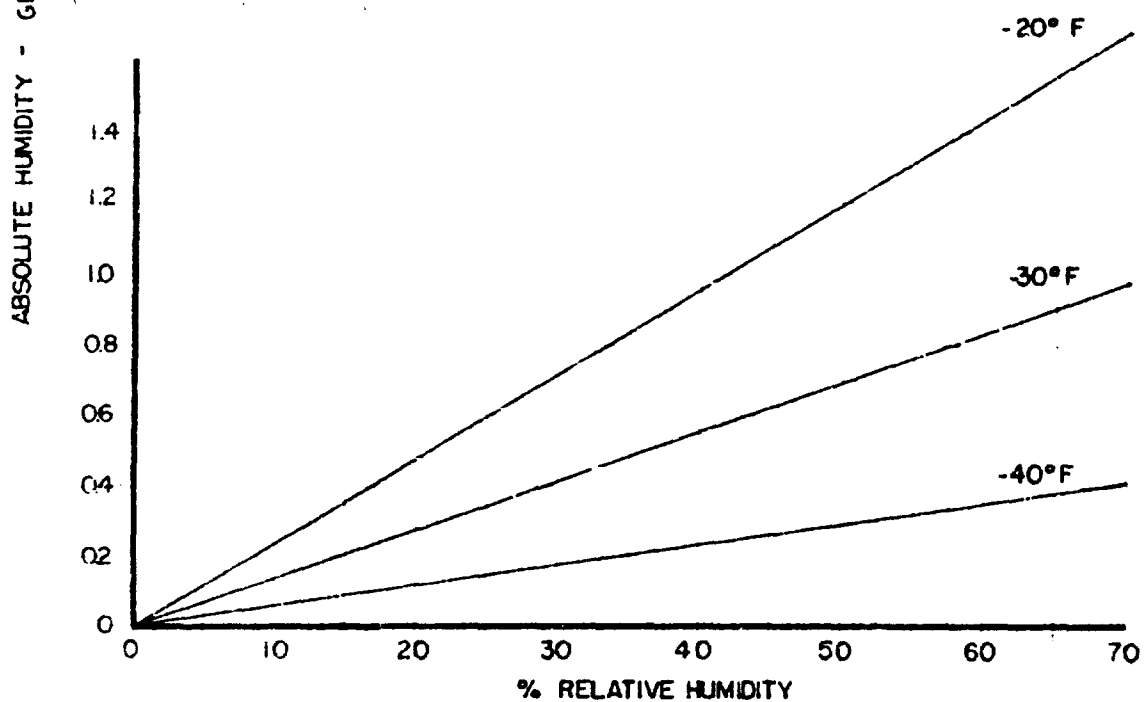
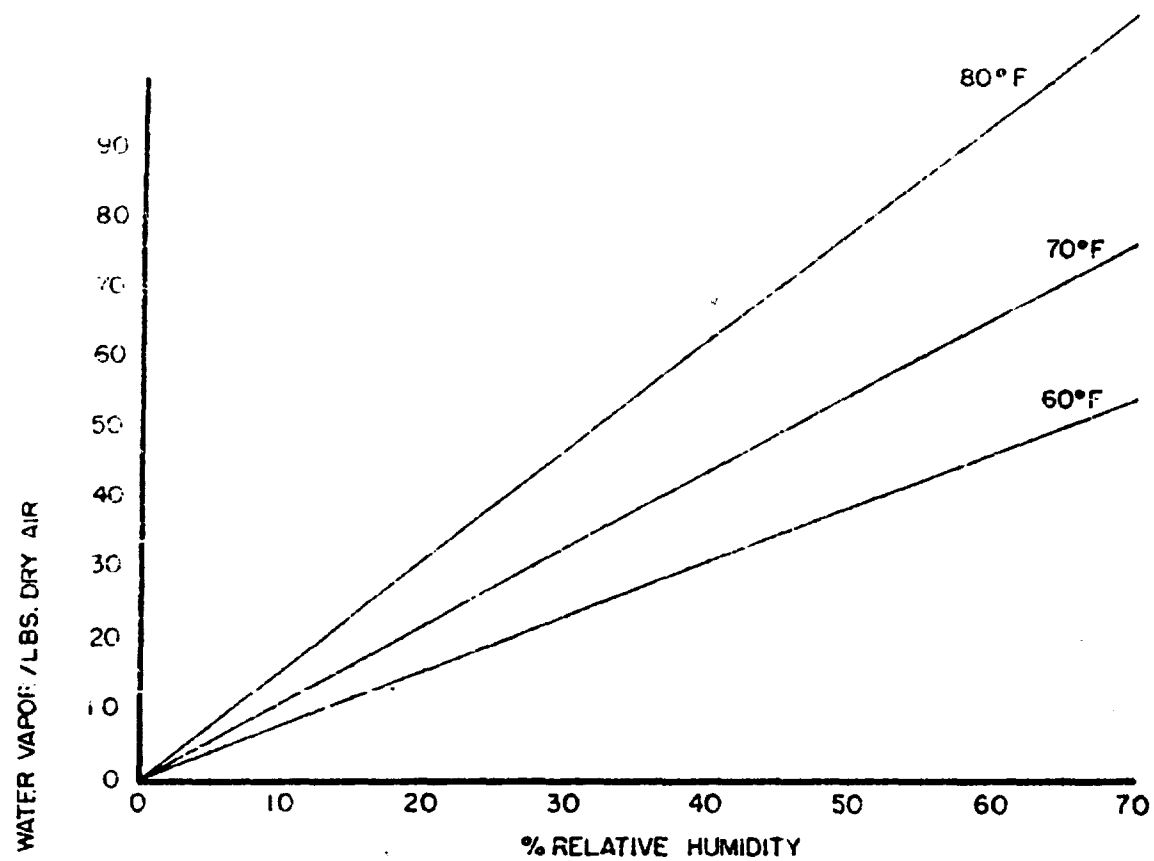


FIGURE 9
MOISTURE CONTENT Vs RELATIVE HUMIDITY

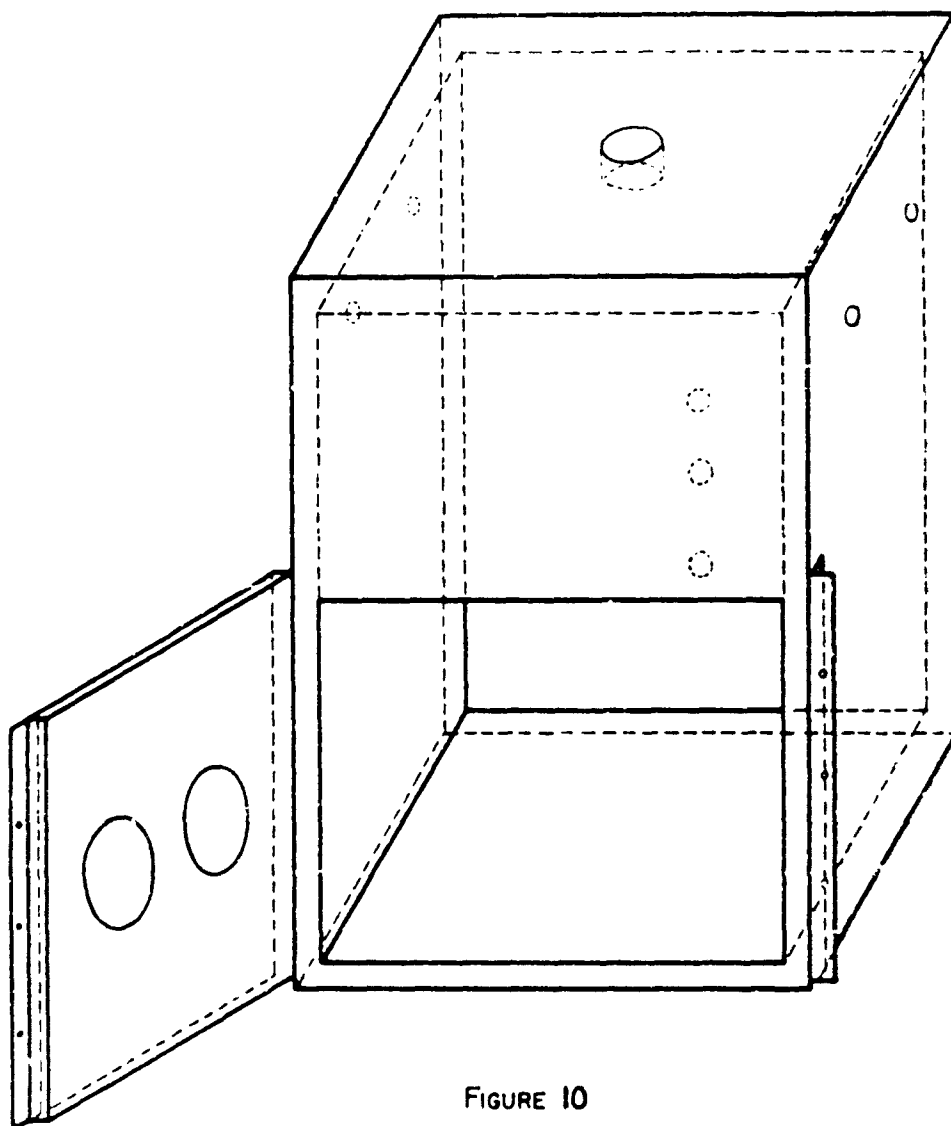


FIGURE 10

CONDITIONING AND TESTING CHAMBER

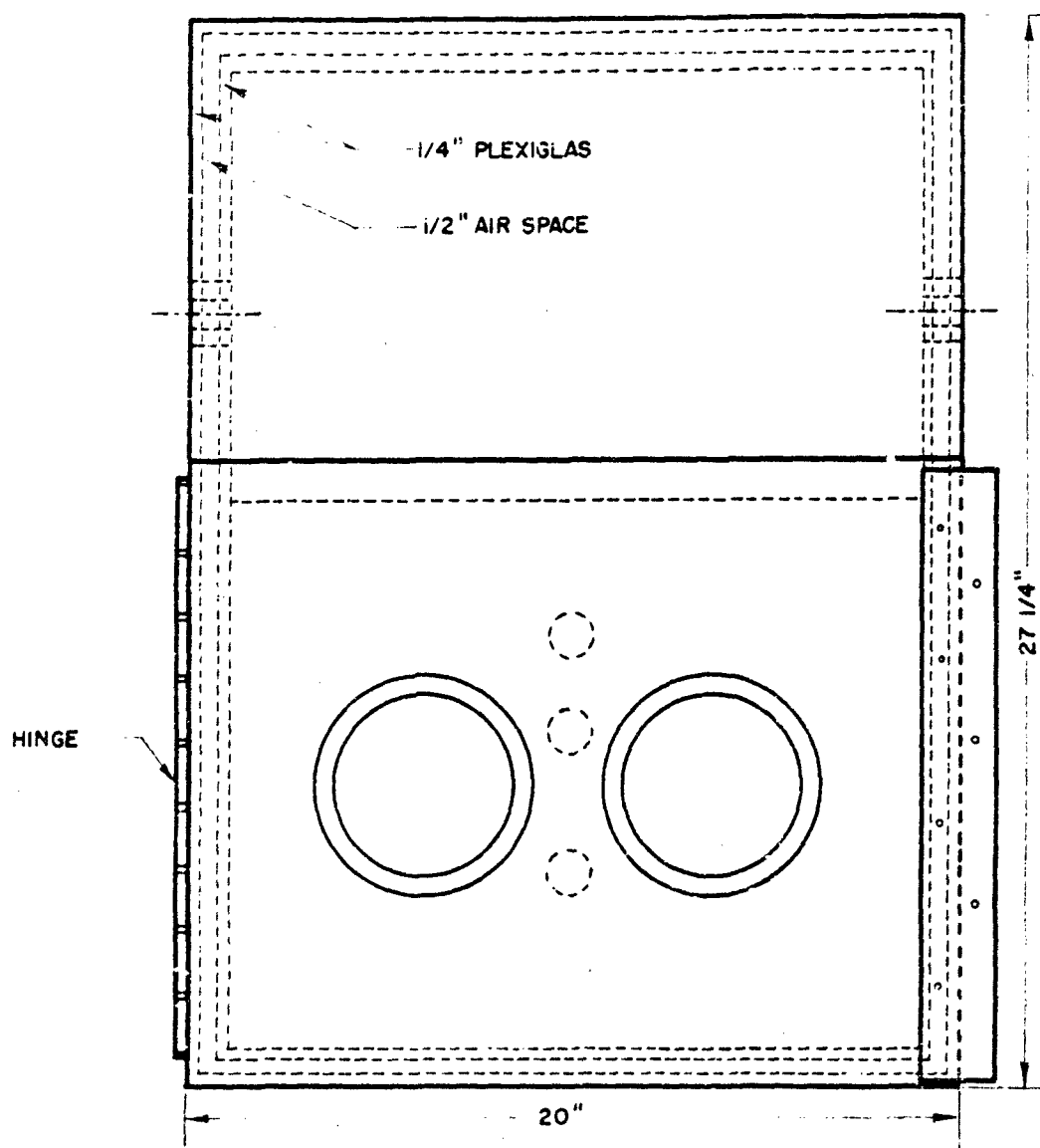


FIGURE 11

FRONT VIEW OF TESTING CHAMBER

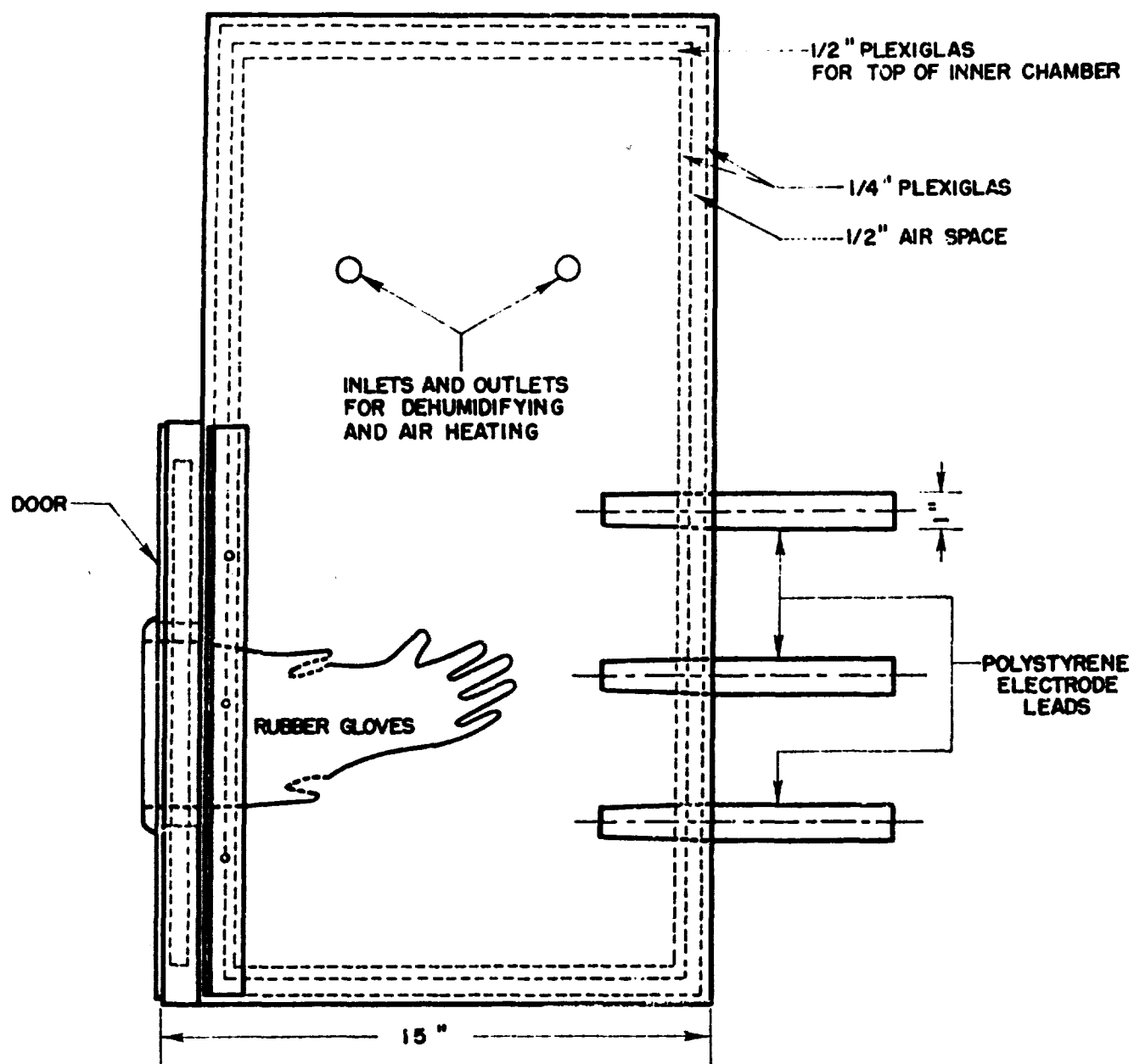


FIGURE 12

SIDE VIEW OF TESTING CHAMBER

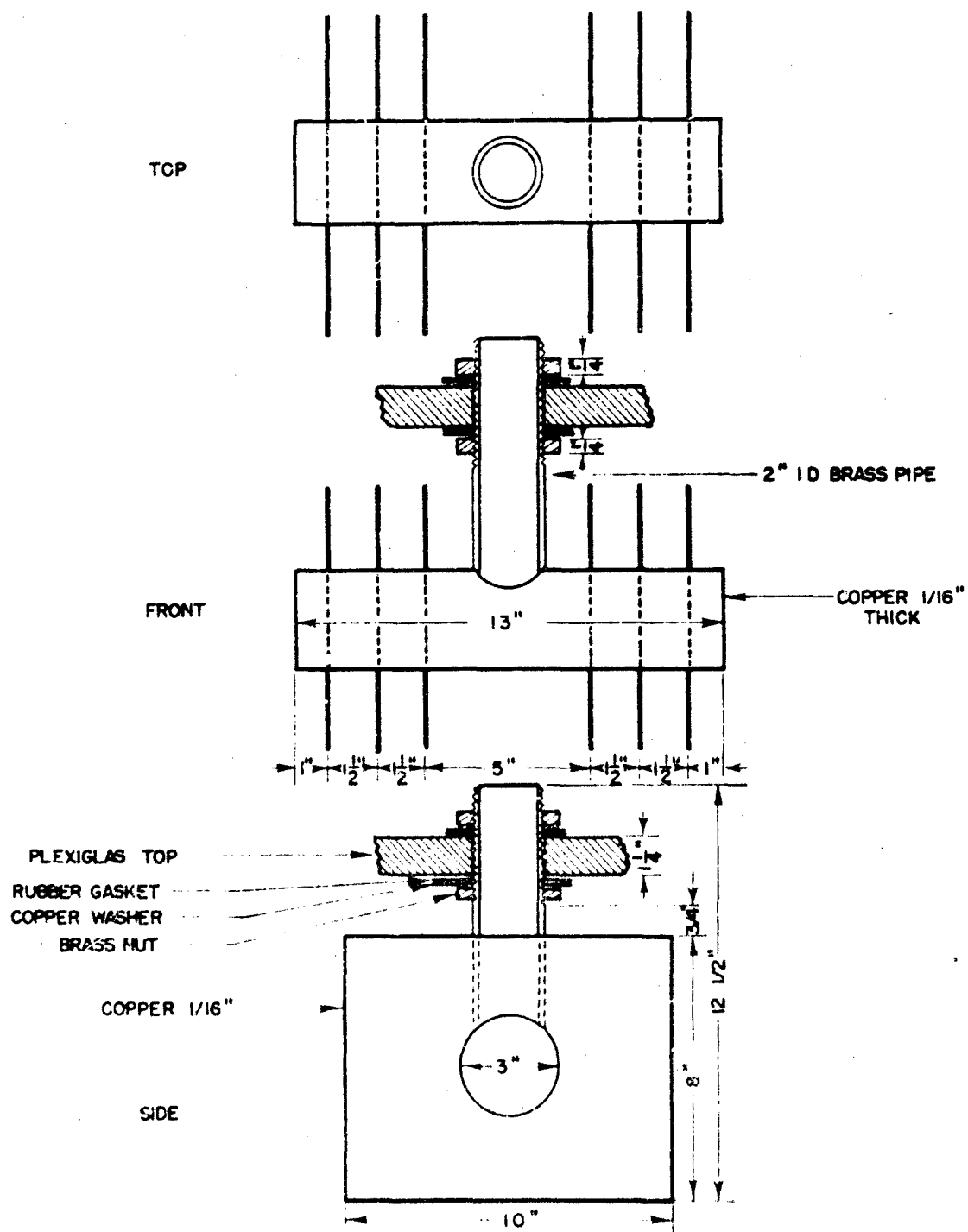


FIGURE 13
COOLING CHAMBER

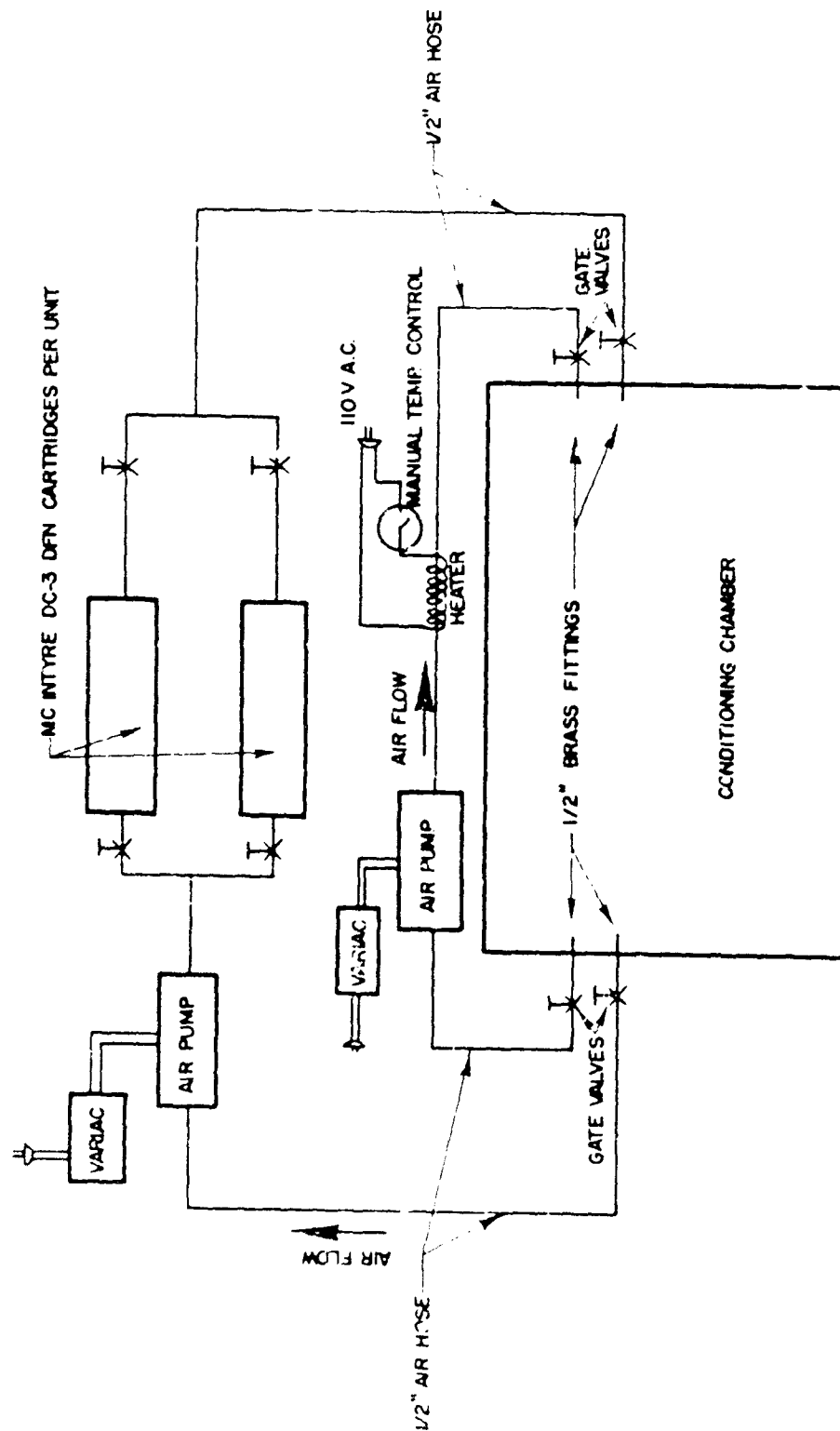


FIGURE 14
DEHUMIDIFYING AND HEATING SYSTEMS

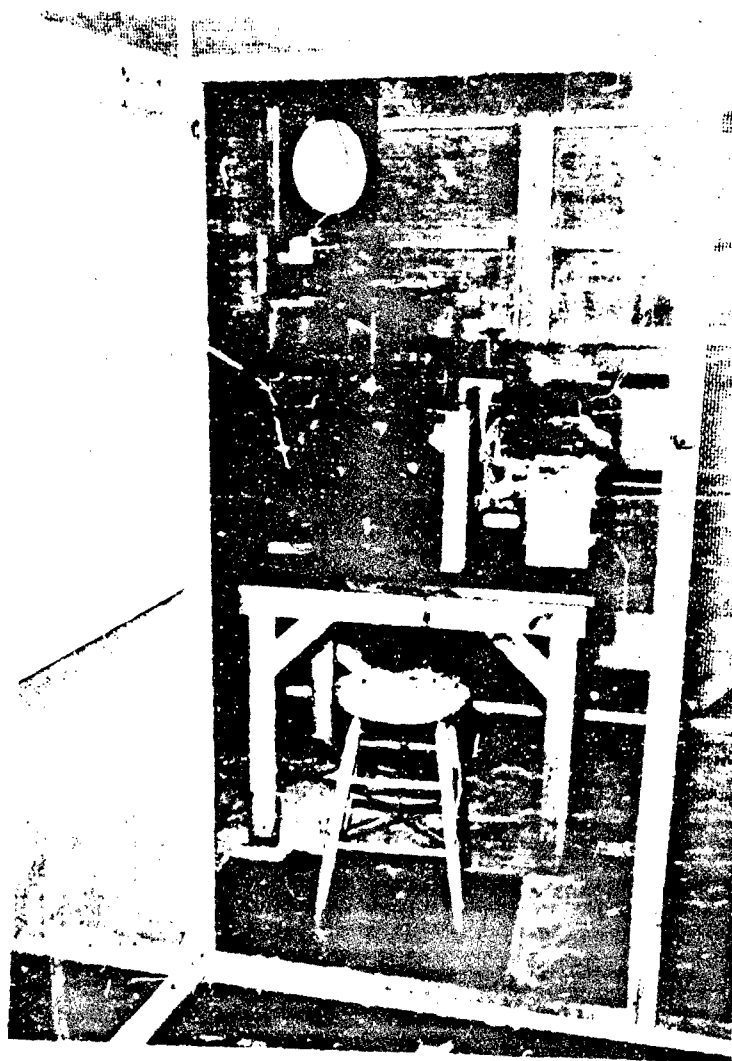


FIGURE 15
LTRF RESISTIVITY TESTER

WADC TR 54-513

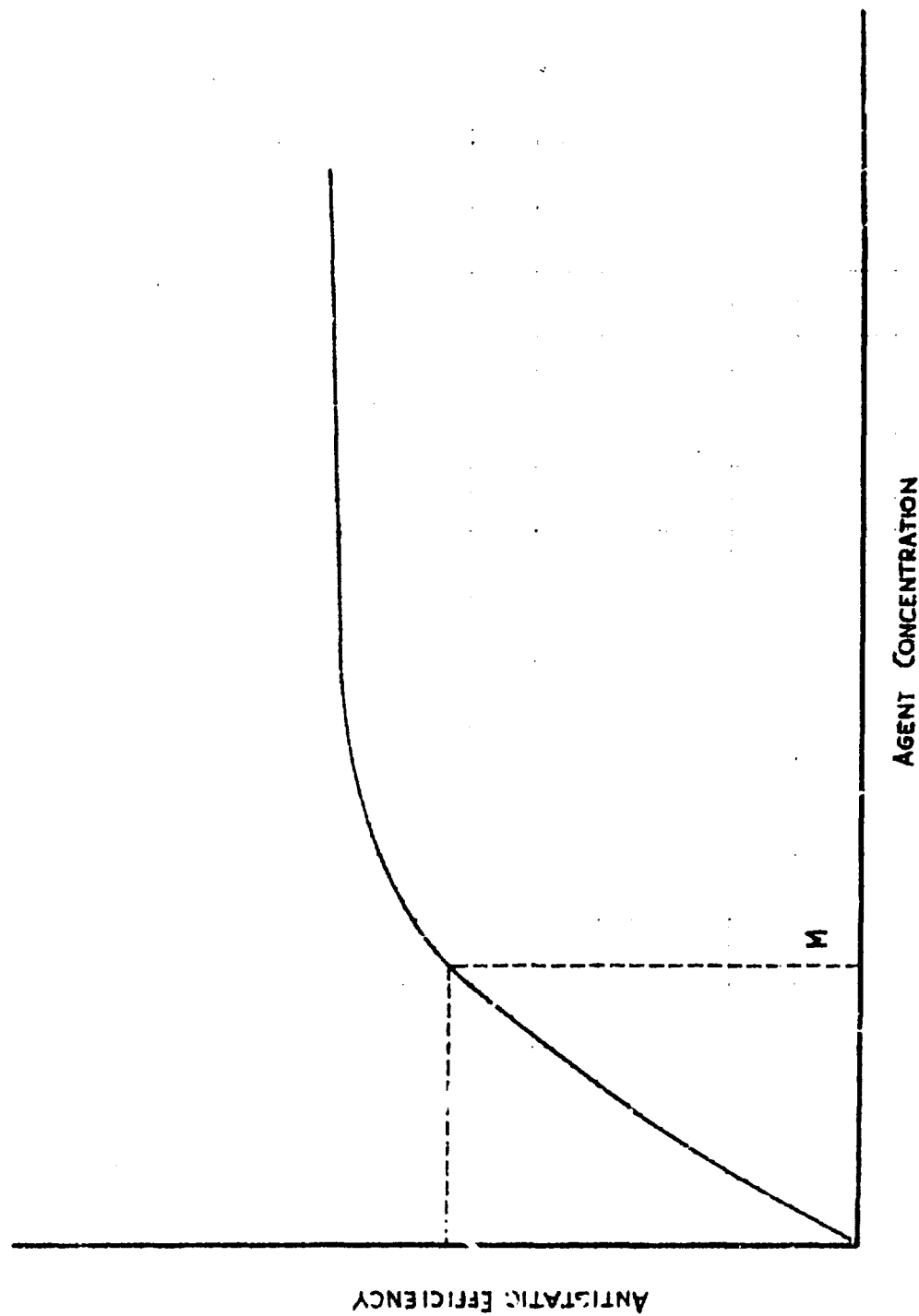


FIGURE 16
AGENT CONCENTRATION VS. ANTISTATIC EFFICIENCY

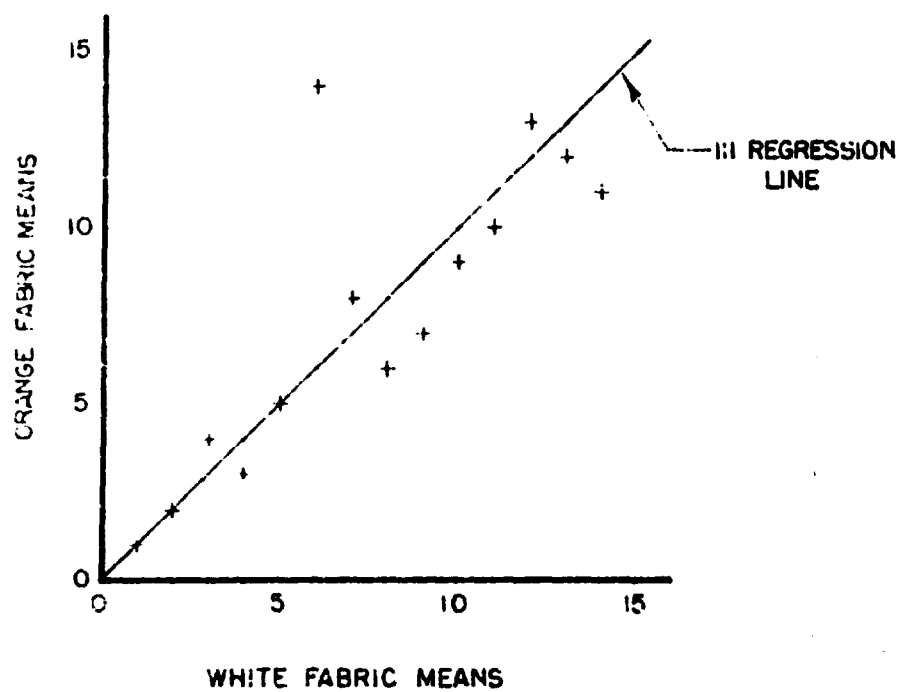


FIGURE 17

CORRELATION PLOT OF MEAN VALUE RANKINGS
FOR ORANGE AND WHITE NYLON PARACHUTE CLOTH

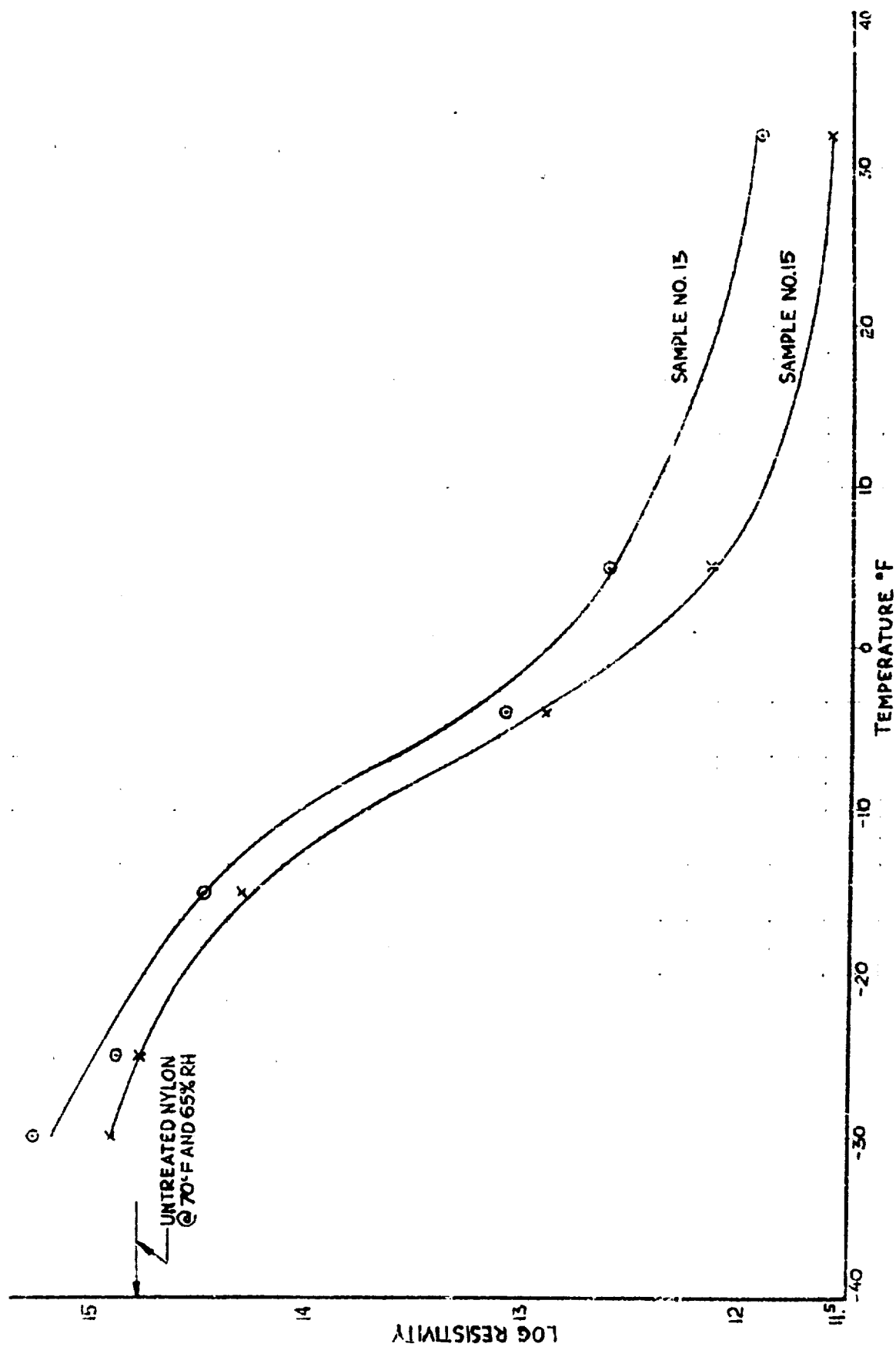


FIGURE 18
LOG RESISTIVITY VS TEMPERATURE
(CONSTANT HUMIDITY $13 \pm 5\% RH$)

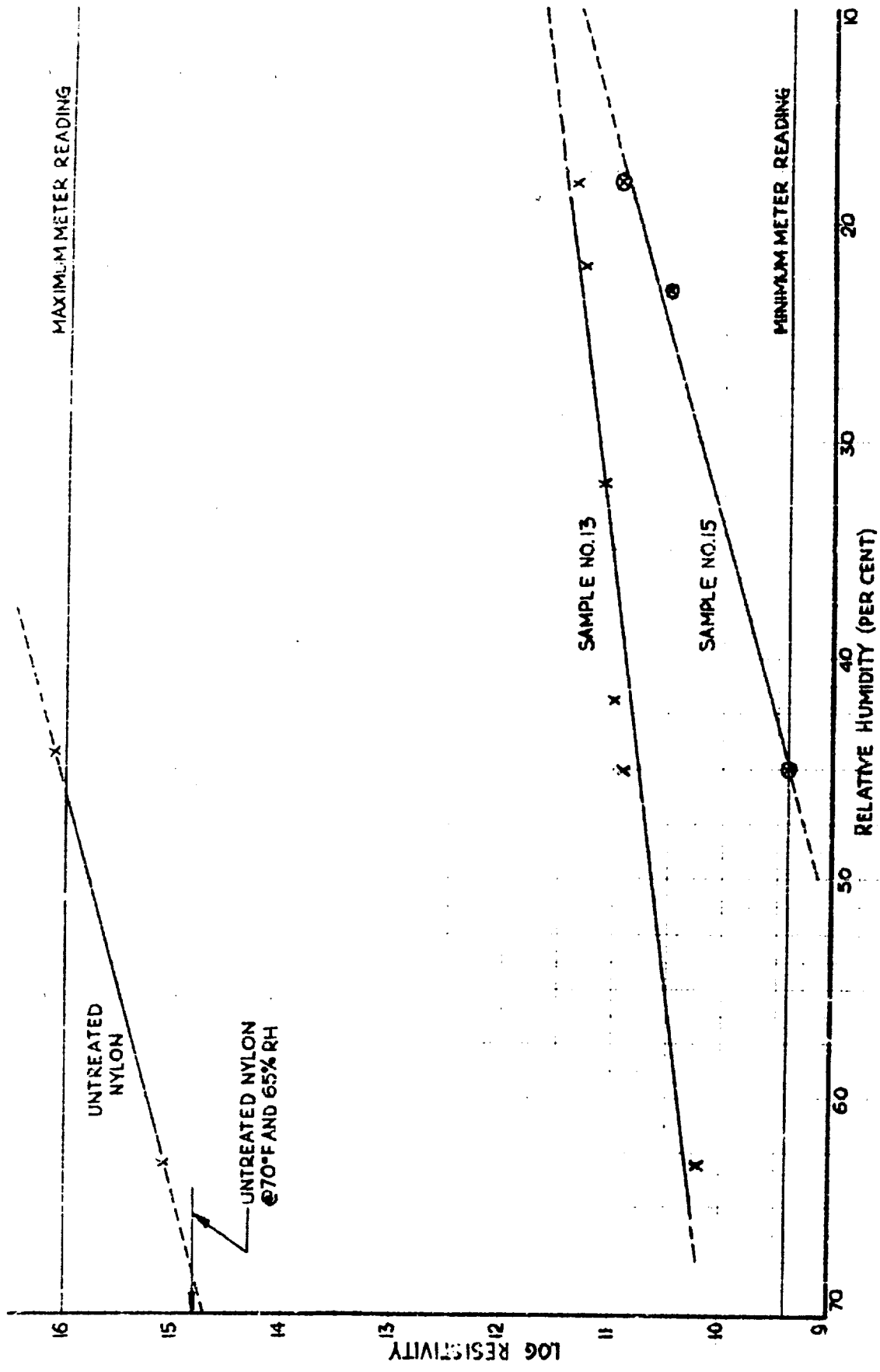


FIGURE 19
LOG RESISTIVITY VS RELATIVE HUMIDITY
AT CONSTANT TEMPERATURE : - 64° F

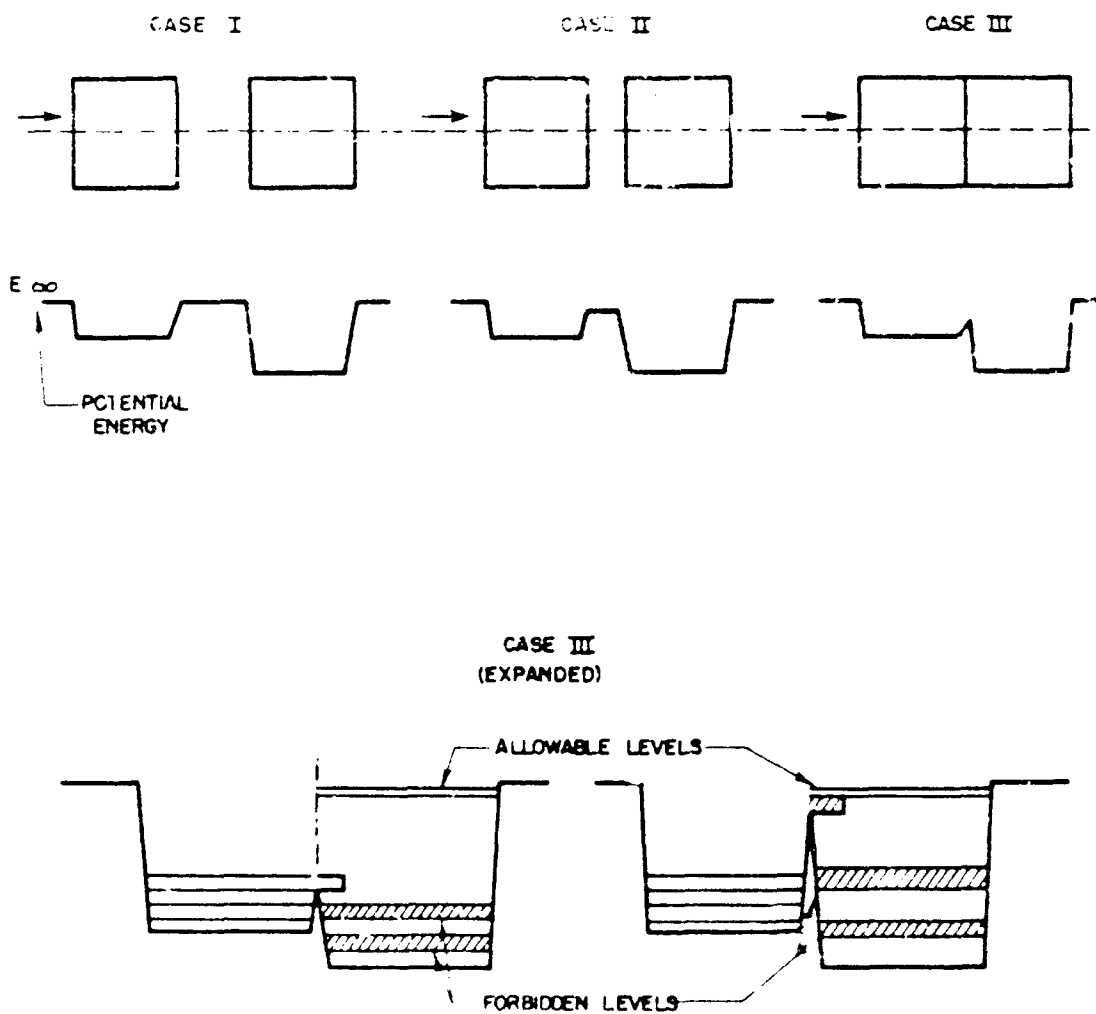
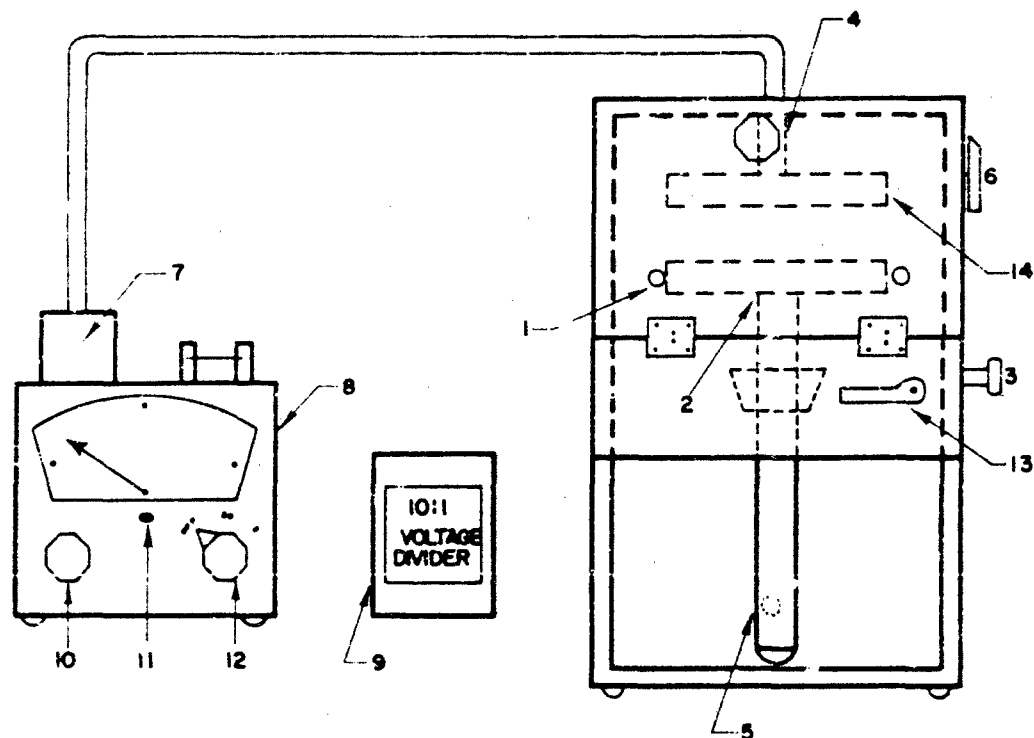


FIGURE 20

EXPLANATION FOR SOLID STATE PHYSICS INTERPRETATION
OF STATIC ELECTRICITY



1. Spring ring for securing cloth sample.
2. Lower plate and spindle.
3. Catch.
4. Threaded lead connection.
5. Ground connection.
6. Grounding switch.
7. Cap lead connection.
8. Keithly electrometer.
9. Voltage divider (10:1) given full scale reading of 200 volts when in place between (7) and (8).
10. Electrical zeroing knob.
11. Mechanical zeroing screw (adjusted only when Keithly is in "off" position).
12. Scale selector switch. Turn "off" when meter is not in use.
13. Trigger for dropping (2).
14. Upper plate.

FIGURE 21
FABRIC CONTACT POTENTIAL METER

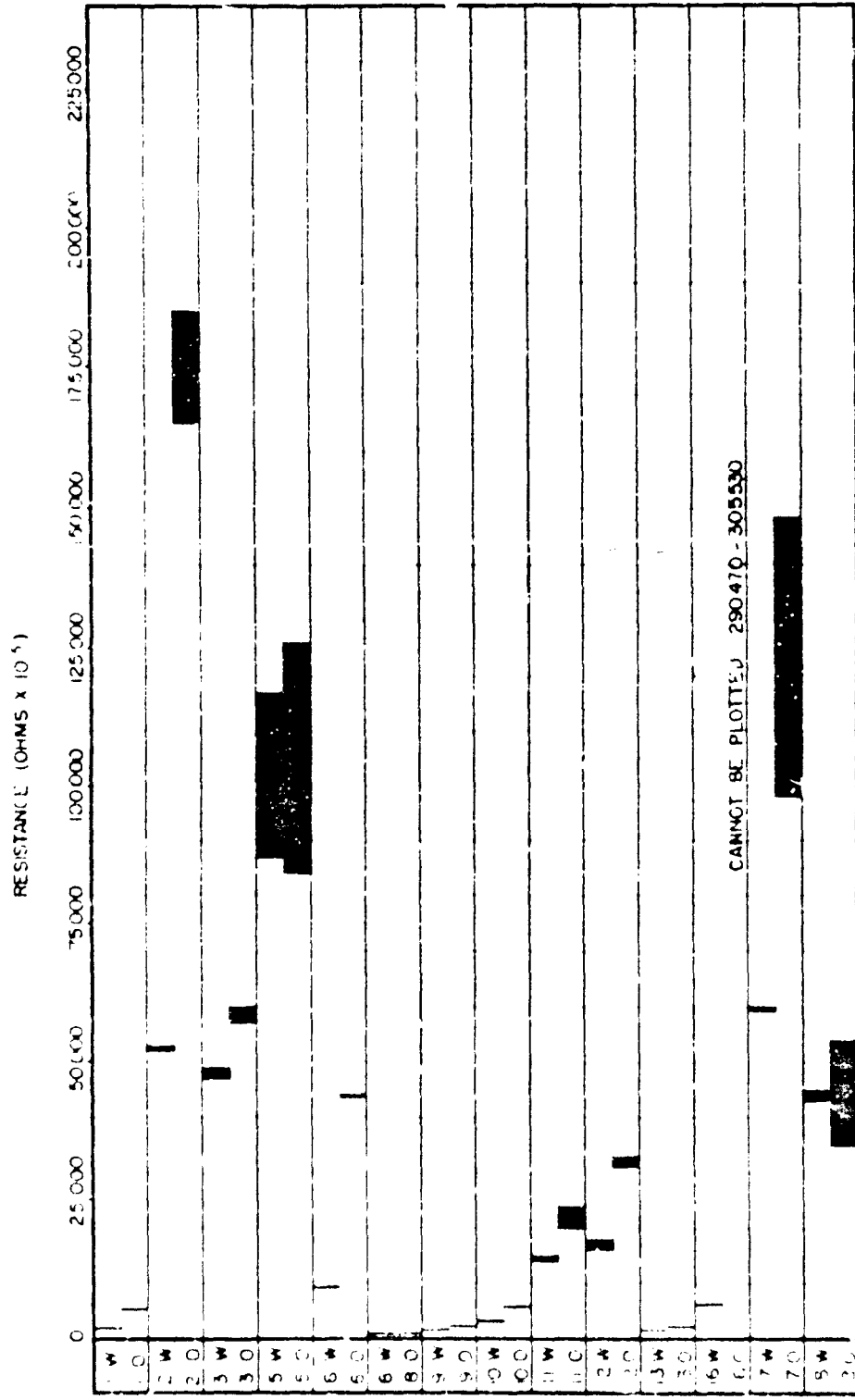


FIGURE 10
POPULATION LIMITS FOR INDIVIDUAL TEST RESULTS
(BASED ON TESTS ACTUALLY MADE)

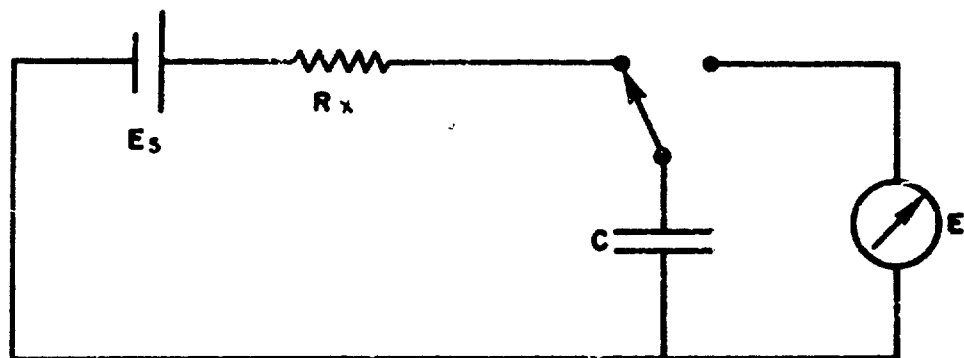


FIGURE 23

CIRCUIT FOR RESISTANCE MEASUREMENTS
(USING PRINCIPAL OF INTEGRATION)