PROPERTIES OF ELECTRICAL INSULATING MATERIALS OF THE LAMINATED PHENOL-METHYLENE TYPE

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ABSTRACT

The manufacture of phenolic synthetic resins as applied to the fabrication of electrical insulating material has only become commercially important within the last 20 years. Some of the older materials were not suited for particular purposes or were too expensive, and the phenolic type was developed to meet a real commercial need. The materials of this type may be broadly classified as laminated materials or molded materials.

This paper is concerned exclusively with materials of the laminated, phenol-methylene type, which are made by building up sheets of paper, fiber, or fabric which had been previously impregnated or coated with phenolic (synthetic) varnish to some desired thickness and then subjecting the stack to comparatively great pressure in a heated hydraulic press. This laminated type has been the subject of a comprehensive investigation at this Bureau. The varnishes used in the manufacture of the laminated materials whose properties have been investigated are Bakelite, Condensite, and Redmanol, manufactured, respectively, by the General Bakelite Co., Condensite Co. of America, and the Redmanol Chemical Products Co.

The companies who fabricate these laminated materials from the phenolic binder (varnish) and filler (paper, fiber, or fabric), with the grades on which data are given in this paper, are: Diamond State Fibre Co.—Condensite Celoron: Grade 10, fiber base; grade 15, fiber base; grade 20, fabric base. The Continental Fibre Co.—Bakelite Dilecto: Grade XX, paper base; grade X, paper base; grade CB, fabric base. The Formica Insulation Co.—Formica: Grade M, paper base; grade M-2, paper base; grade P, paper base; grade R, fabric base. Westinghouse Electric & Manufacturing Co.—Bakelite Micarta: Grade 32-X, paper base; grade 21-X, paper base; grade 323, paper base; grade 213, paper base; grade 21-D, fabric base.

The various properties or effects which have been determined for this type of material are listed below. Experimental data or other information are given relative to each of these properties. These tests cover radio-frequency phase difference or power loss, dielectric constant, and flash-over voltage, direct-current surface resistivity and volume resistivity, tensile strength, modulus of elasticity (tensile), proportional limit, modulus of rupture, modulus of elasticity (transverse), Brinell hardness, scleroscope hardness, impact strength, permanent distortion, density, moisture absorption, machining qualities, thermal expansivity, and the effects of heat, acid, and alkali.

The data on these properties have been arranged in such a manner as to be conveniently available for reference, either by a person desiring detailed information or by a person interested only in a general way in the more important properties. The methods of performing the various tests are also very fully described in a Bureau publication referred to in the text.

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I. INTRODUCTION

1. HISTORY OF SAMPLES

All of the data which the authors of this paper present were obtained on samples of laminated, phenolic insulating materials received by the Bureau between December 20, 1917, and August 24, 1919. Some observations made on a limited number of later samples have indicated that the various phenolic insulating materials have been more or less improved in their electrical and mechanical properties.

2. THE DEMAND FOR THE PHENOLIC INSULATING MATERIALS

Phenolic insulating materials have been introduced during the past few years for a wide variety of uses. In electrical work they are used for the same purposes for which hard rubber (sometimes called ebonite or vulcanite) has been used, namely, for the insulating parts of electrical instruments and apparatus. The ever-increasing demand for raw rubber in other industries has increased the tendency to load hard rubber with fillers or to use reclaimed rubber. Incorporation of reclaimed rubber and fillers does not necessarily cheapen the compound or lower its qualities. They are used to improve the material for certain uses. While hard rubber has a number of the properties desirable in an electrical insulating material, such as high electrical resistivity, very small power loss, and ease of machining, it has, on the other hand, certain undesirable qualities, such as low tensile strength, brittleness, high thermal expansivity, deterioration in sunlight, and because of a tendency to soften at moderate temperatures it shrinks and warps.

Composition materials using shellac, pitch, or similar compounds as a binding medium are used, but for most radio uses the more expensive materials using phenol condensation products as the binder have proved more satisfactory. The phenolic materials are described later in section II.

3. NEED FOR THIS RESEARCH

When the United States entered the war against Germany, the various Government departments and private manufacturers were making demands on a few manufacturers of laminated materials of the phenol-methylene type beyond the capacity of their manufacturing equipment. It was the practice in ordering insulating material for radio and other electrical apparatus to specify, more or less arbitrarily, the use of insulating material of a certain trade

name instead of specifying the qualities or properties required for the particular use in view. This condition led the War and Navy Departments and some of the manufacturers of phenolic insulating materials to seek data on the various properties of the materials. Some of the manufacturers began to inquire into the faults of their material with a view to correcting their processes, if possible, or choosing their basic materials so that their product would receive Government approval.

In October, 1917, the Formica Insulation Co. requested the Bureau of Standards to make measurements on the properties of Formica. Other companies whose products were included in the measurements that followed are given on page 501. The manufacturers had little idea concerning the nature of the tests necessary, but were willing to supply samples, information, and suggestions. Phenolic insulating material was being used by the Government in very large quantities for radio apparatus, and so the immediate aim was to obtain such data as would determine the suitability of the material for radio uses. The work soon broadened into a general research on the properties of these materials.

Prior to the time the Bureau of Standards started the tests on Formica there had been practically no measurements made of the properties of insulating materials at radio frequencies. This meant that the composition of the insulating materials using phenol varnish had to be studied, tests had to be devised, and apparatus designed and constructed for the measurement of various properties.

While much valuable information had been previously collected on these and other types of insulating material by manufacturers and testing laboratories, their work was confined largely to mechanical properties, 60-cycle puncture voltage, volume and surface resistivity, and dielectric constant. The data thus available from various sources are not related—that is, the electrical and mechanical data were seldom obtained from tests on the same sample. A reliable comparison of the several materials can not be made unless the properties are all measured on the same sample because of the very considerable variations from sample to sample. The work described herein has, consequently, been done with samples of such size that specimens for all tests on a particular grade of material could be cut from the same sheet.

The results of this work may therefore be of value to the manufacturers of these materials, to various departments of the Govern-

ment who buy such material in large quantities, and to manufacturers and users of electrical apparatus. It is shown that the properties of various samples of the same grade of material vary. A study of the several properties as found for the different makes and grades of material should lead to improved products as experience in the methods of manufacture increases and the needs of the consumer are better understood.

From the experience gained in this investigation it seems evident that there is no one insulating material of this type that could be cited to answer the broad question, "Which is the best insulating material?" The peculiar demands put upon the material when used in a particular place must be studied and a material chosen that has the best combination of properties to meet the need. As a rule, it may be stated that to obtain the best electrical properties the mechanical properties must be sacrificed to a certain extent. Other general conclusions are presented in section V, "Discussion of Results."

4. SCOPE OF THE WORK

To obtain comparative data on the various kinds and grades of laminated phenolic insulating materials, the following electrical, mechanical, and other properties have been measured for each grade and for several thicknesses of each grade where possible: Volume resistivity and surface resistivity, voltage effects at radio frequencies, phase difference or power factor and dielectric constant at radio frequencies, ultimate tensile strength, proportional limit and modulus of elasticity (tensile), modulus of rupture (transverse), proportional limit and modulus of elasticity (transverse), Brinell hardness, scleroscope hardness, impact strength, permanent distortion under dead weight, density, moisture absorption, machining qualities, thermal expansivity, heat effects, and effects of acid and alkali. The various tests made in this research are not necessarily the final word on the important properties requiring consideration. In fact, there are other tests that are now being considered for continued work on this same type of material. See section III-1 for the reasons why these properties were selected.

For every material the various properties were measured upon test specimens cut from the same sheet of insulating material. For reasons already stated principal emphasis was placed on measurements of radio properties.

Dielectric strength or puncture voltage at low frequencies has not been studied for two reasons: First, the significance of such measurements is somewhat doubtful and in particular is nil at radio frequencies, and, second, because the various manufacturers and some users of the materials have had many puncture voltage tests made at private testing laboratories. Other tests which were intentionally omitted are crushing strength and shear strength across and with the laminations. For the sake of comparison with the phenolic materials, in section V-23 is given a comprehensive comparison of laminated and molded phenolic materials, hard rubber, and vulcanized fiber. This paper deals primarily with the laminated and not the molded phenolic materials.

KIND OF SAMPLES AND SCHEME OF NUMBERING.—The test samples for measurement of the various properties were, in general, cut from standard-sized sheets of insulating material such as are furnished by the manufacturers to the trade. (They were slabs or sheets approximately 61 by 93 cm (24 by 36 inches) or 97 by 97 cm (38 by 38 inches) and in varying thicknesses, usually between 6 and 13 mm ($\frac{1}{4}$ to $\frac{1}{2}$ inch). Specimens for the measurements on all properties were cut from the same large sheet, so the results on the various properties are comparable.

Each sheet was assigned an arbitrary number when received, this number being the "B. S. Sample No." given in the tables of section IV. A record was made of this number, maker of sample, grade, color, thickness, size, nature of varnish and filler (base), and date of receipt.

When preparing test specimens cut from these large sheets, each of the several specimens cut for a particular test were assigned arbitrary numbers having no relation to the "B. S. Sample No." of the sheet. As an example, three tensile strength specimens might be cut from sample sheet No. 51 and be stamped A, 3C, and X. When these samples were mixed with many others of the same thickness, color, and finish, it would be difficult for the person doing the testing to check his own results from a knowledge of other results on similar materials.

INFORMATION NOT INCLUDED IN PRESENT PUBLICATION.—The description of the method of making the various tests is given in a separate publication entitled "Methods of Measurement of Properties of Electrical Insulating Materials." The bibliographies of periodicals and patents, etc., are also prepared separately as laboratory reports under the titles, "List of Books and Periodicals

on Tests, Properties, and Uses of Laminated Phenolic and Other Electrical Insulating Materials," and "List of the More Important United States Patents Covering Electrical Insulating Materials and Methods of Manufacture." A limited number of copies of these two reports are available at the radio laboratory of this Bureau.

5. COOPERATION IN THIS RESEARCH

The Bureau of Standards has had the hearty cooperation of the manufacturers at all stages of this work. The four manufacturers of laminated phenolic insulating materials mentioned above sent large numbers of samples of their products at the Bureau's request. The samples sent by these companies had a considerable money value. The companies not only sent samples willingly but contributed advice, experience, and discussion at various phases of the work. The following men representing these companies were particularly helpful to the Bureau in giving such assistance and cooperation: John A. Holmes and James McIntosh of the Diamond State Fibre Co.; W. C. Anderson and C. L. Bonham of the Continental Fibre Co.; D. J. O'Connor and W. W. Ryerson, eastern representative, of the Formica Insulation Co.; J. G. Miles and C. E. Skinner of the Westinghouse Electric & Manufacturing Co.

Besides the manufacturers of the laminated materials a number of the companies manufacturing the phenolic varnishes and molded phenolic materials took an interest in this work and assisted in its progress. The three companies which manufacture the phenolic varnishes were the Condensite Co. of America, the General Bakelite Co., and the Redmanol Chemical Products Co. The first two named also submitted samples of molded materials. The results of tests on molded insulating materials, built-up mica, and other materials are not included herein.

The measurements of the various properties described herein were made by the respective sections of the Bureau which specialize in those measurements. For the reasons stated, the general research was originally undertaken by the radio laboratory, and it was at the initiative of the radio laboratory that the several measurements were made. Besides measuring the radio-frequency properties the radio laboratory cut and prepared the test specimens for all measurements.

The work began in the latter half of 1917. Work on the methods of measurement was done by G. C. Southworth of the radio

laboratory, who also made many of the radio-frequency measurements and arranged for other tests. Credit for the results accomplished is due him. Measurements of phase difference were made by Miss H. H. Smith and E. L. Hall. The collecting and tabulating of the data and opinions on hard rubber, vulcanized fiber, and molded and laminated phenolic materials were done by E. L. Hall. Prof. H. W. Harmon and E. S. Purington were instrumental in developing the high-voltage radio-frequency testing set designed by G. C. Southworth. R. S. Ould prepared a bibliography of periodicals, etc., and an extensive patent list. Other members of the radio laboratory who have assisted directly in this work are F. E. Baldwin, H. B. Daniel, and N. Montgomery.

The following members of the Bureau of Standards staff cooperated by making the tests in which they had particularly specialized: Volume and surface resistivity, H. L. Curtis, C. N. Hickman, and C. M. Sparks; moisture absorption and density, E. L. Pfeffer; thermal expansivity, W. H. Souder and Peter Hidnert; effects of elevated temperature, E. F. Mueller and L. I. Dana; mechanical properties, H. L. Whittemore, H. A. Anderson, and G. M. Deming.

II. DESCRIPTION OF LAMINATED PHENOLIC INSULATING MATERIALS

1. DESCRIPTION OF THE COMMERCIAL GRADES

Data on the various grades of laminated, phenolic materials regularly manufactured by the various companies are given below. Further information on the particular grades can be found in the descriptive and advertising booklets furnished by the companies. Besides these standard grades the manufacturers sometimes make special grades to suit the particular requirements of a purchaser.

TABLE 1.—Description of Grades of Condensite Celoron Manufactured by Diamond State Fibre Co., Bridgeport, Pa.

Grade	Color	Finish	Base (filler)	Binder
15.....	Black.....	Polished or dull...	Vulcanized fiber..	Condensite phenol varnish
10.....	Natural.....	do.....	do.....	Do.
25.....	Black.....	do.....	Canvas.....	Do.
20.....	Natural.....	do.....	do.....	Do.
35.....	Black.....	do.....	Asbestos.....	Do.
30.....	Natural.....	do.....	do.....	Do.

TABLE 2.—Description of Grades of Bakelite-Dilecto and Continental-Bakelite Manufactured by the Continental Fibre Co., Newark, Del.

BAKELITE-DILECTO

Grade ^a	Color	Finish	Base (filler)	Binder
XX.....	Black or natural...	Polished or dull...	Paper.....	Bakelite phenol varnish
XXX.....	do.....	do.....	do.....	Do.
X.....	Natural.....	do.....	do.....	Do.
X (extra hard).....	do.....	do.....	do.....	Do.
G.....	Black or natural...	do.....	do.....	Do.
A.....	do.....	do.....	Asbestos.....	Do.
S.....	Black.....	do.....	Paper and hard rubber	Do.

CONTINENTAL-BAKELITE

CB.....	Black or natural...	Polished or dull...	Canvas.....	Bakelite phenol varnish
CBL.....	do.....	do.....	Light canvas.....	Do.

^a The X grade can also be furnished with the outer surfaces black.**TABLE 3.**—Description of Grades of Formica Manufactured by the Formica Insulation Co., 4614 Spring Grove Avenue, Cincinnati, Ohio

Grade	Color	Finish	Base (filler)	Binder
M.....	Black or natural...	Polished or dull...	Paper.....	Redmanol phenol varnish
M-2.....	do.....	do.....	do.....	Redmanol cresol varnish
P.....	Natural.....	Dull.....	do.....	Redmanol phenol varnish
R.....	do.....	do.....	Canvas.....	Do.

TABLE 4.—Description of grades of Bakelite Micarta Manufactured by Westinghouse Electric & Manufacturing Co., East Pittsburgh, Pa.

Grade	Color	Finish	Base (filler)	Binder
32-X.....	Black.....	Polished or dull...	Paper.....	Bakelite phenol varnish
21-X.....	Natural.....	do.....	do.....	Do.
323.....	Black.....	do.....	do.....	Do.
213.....	Natural.....	do.....	do.....	Do.
21-D.....	do.....	do.....	Canvas.....	Do.

2. DESCRIPTION OF MATERIAL AND METHOD OF MANUFACTURE

It is not within the scope of this paper to give a detailed description of the process of manufacture of this type of material. However, a general description may be of value to those not acquainted with the process. For those desiring a more complete understanding of the various processes the list of patent numbers and titles mentioned on page 507 will furnish a source of detailed information. The pamphlets listed in the bibliography mentioned on the same page will furnish some information also.

The two essential parts of this material are the base or filler and the binder. The base consists of sheets of paper, fabric, or fiber, and the binder is a phenol (carbolic acid) condensation product.

Bakelite-Dilecto, Continental-Bakelite, and Bakelite Micarta have as a binder a phenol varnish (condensation product) manufactured by the General Bakelite Co., Perth Amboy, N. J. The makers of Condensite Celoron use a phenol varnish manufactured by the Condensite Co. of America, Bloomfield, N. J., and the makers of Formica a phenol varnish manufactured by the Redmanol Chemical Products Co., 615 West Twenty-second Street, Chicago, Ill. The same type of phenol varnishes are used by many companies in making what are called molded materials, in which the base or filler consists usually of a powdered material instead of sheets, as in the laminated materials.

VARNISH.—The varnish referred to in this report as varnish or phenol condensation product used in the above insulating materials as a binder is, as the term designates, a varnish composed chiefly of phenol. In general, the varnish is the result of the chemical reaction of any suitable hydroxyl aromatic compound, such as phenol or its homologues and hexamethylenetetramine or a suitable equivalent active methylene body. The reaction, carried on in the presence of heat, may be stopped at any convenient point, so that the resulting resin may have any characteristic between a fusible, soluble resin and an almost infusible, insoluble resin. For use in this type of insulating material the reaction must be stopped while the resin is both fusible and soluble. The resin in this condition is then dissolved in a suitable solvent, such as alcohol or acetone, and is then ready for use as the varnish binder in the laminated insulating materials.

The foregoing description of the process of manufacture of phenol varnish is not meant to be an analysis for any one kind of phenol varnish. It is a general process. Further details may be found by reading the patents covering this class of materials (see p. 507). Neither does this description give a true idea of the complexity of the processes nor the probability of a nonuniform product.

LAMINATING.—Paper, fabric, or fiber may be more or less easily impregnated or coated with a phenol varnish. If sheets of paper have been so treated and dried at a low temperature, they are ready, then, to be built into a sheet of insulating material of any practical thickness. After a certain number of the impregnated sheets have been stacked together the stack is put in a hydraulic press and subjected to pressure and heat. This heating tends to complete the chemical reaction in the varnish, which was stopped

in the making of the resin to permit dissolving. The press heating tends to "turn-over" or convert the varnish to an insoluble, infusible state. The stack of impregnated sheets has now become a mechanically strong, dense sheet of insulating material.

GRAIN.—Since paper has a grain—that is, a unidirectional fibrous structure and a resulting greater strength with the grain—it is evident that if each sheet of paper is built into the stack in the same direction with reference to the grain, one should expect the resulting compressed insulating material to have a grain. This point will be raised again in the analysis of data on mechanical properties in section V, "Discussion of results."

FINISH.—The condition of the surface of the finished sheet of insulating material is dependent on the condition of the face plates of the hydraulic press, which are called platens. If these are polished, the sheet will have a polished surface; whereas if the platen faces were unpolished, the sheet will have a dull surface. A dull surface may be polished by buffing with oil and rouge, but such a method may affect the electrical properties of the surface of the insulating material.

COLOR.—At some stage in the manufacture or use of the phenol varnish a dye may be added, usually black. It is quite easy to recognize the various grades of laminated materials if natural colored samples only are considered, but to know each material and grade when all samples are black requires a thorough understanding of many details. The average user of the material would have much difficulty in checking his stock if the materials or grades were mixed by him or the jobber. Furthermore, some of the retailers of these laminated phenol-methylene insulating materials fail to appreciate or know any difference in grades of a particular kind of material, so the consumer may misjudge the material by not receiving the grade best suited to his needs. The manufacturers could assist by stamping the grade designation on each sheet, but the user must always take precautions to inform himself as to what grade of material he really has.

III. PROPERTIES MEASURED

1. REASONS FOR CHOICE OF PROPERTIES

(A) CHOICE OF ELECTRICAL PROPERTIES

PHASE DIFFERENCE OR POWER FACTOR.—The principal aim of the research being to determine the suitability of the materials for electrical uses, most attention was given to the electrical

properties. The limitations of an insulating material used in alternating-current apparatus are measured by the magnitude of the power loss caused by dielectric absorption. This is a phenomenon which causes the material to heat when a varying current flows in it. The amount of this property is given by a quantity called the phase difference, which is explained just below in section III-2. This property is measured at radio frequencies, (a) because it is more accurately measurable at radio frequencies than at low frequencies, (b) because this research has particularly in view the radio uses of insulating materials, (c) because the value of phase difference at radio frequencies largely determines the radio-frequency voltages the material will stand without injury, and (d) power loss in insulating parts introduces resistance into the circuit of radio apparatus and diminishes selectivity. A knowledge of phase difference or power factor sheds light on the basic theory of action of electrical insulating media.

DIELECTRIC CONSTANT.—The dielectric constant is an important property in an insulating material to be used in making up a condenser. It determines the amount of alternating current which flows when an alternating voltage is impressed on the condenser. It thus plays an important part in determining how much the condenser heats and the high-frequency voltage at which the insulating material is injured. This property is easily measured simultaneously with the measurement of phase difference. Both these properties are measured at radio frequencies. The dielectric constant is not greatly different at low frequencies and at radio frequencies.

VOLTAGE EFFECTS AT RADIO FREQUENCIES.—No measurements of the dielectric strength or puncture voltage at commercial frequencies were made, since, as already stated, the materials are seldom used where voltages are so high as to be destructive. Measurements of the effects of high voltage at radio frequencies have been included, however, because these materials are used as panels supporting the parts of generators of radio-frequency current in which fairly high voltages are present. The voltages required for destruction of the material at high frequencies used in radio are very much smaller than for low frequencies. The effects of voltage are discussed further in section V, "Discussion of results."

INSULATION RESISTANCE.—Generally speaking, the phenolic materials are used for insulating purposes at voltages which are

not so high as to threaten destruction of the material. For low-voltage work it is important to know how well the materials insulate. Hence, measurements were made to determine insulation resistance. Electricity leaks along the surface of an insulator as well as through its volume, and so it is necessary to determine both the surface resistivity and volume resistivity. These and the other properties are carefully defined later in section III.

(B) CHOICE OF MECHANICAL PROPERTIES

A material for any purpose must satisfy certain mechanical requirements or the most splendid electrical properties will be of no avail. For instance, it must be able to bear the weight it has to carry without breaking. Certain grades of the material are sold, primarily, for mechanical purposes. Such grades are usually very good for insulating purposes also, where only low-frequency currents are considered and the chief requirements are mechanical. Whether the chief requirements are electrical or mechanical, the mechanical properties must be known. Such data are necessary in the designing of electrical apparatus and for comparative information on the various kinds and grades of insulating material.

DENSITY AND MOISTURE ABSORPTION.—The absorption of moisture has an important effect on many of the properties. The reasons for measuring density and moisture absorption are analyzed elsewhere in this paper (sec. V-6). The percentage of moisture absorbed by a sample when immersed in water for a stated time is a measure of how thoroughly the phenol varnish has protected the cellulose fiber against moisture. Composite material, such as the laminated phenol-methylene type of insulation, is capable, therefore, of absorbing varying amounts of moisture from the atmosphere. Hard rubber also absorbs moisture but to a much smaller extent. The effect of this naturally absorbed moisture is shown by the data on the effect of season on phase difference (pp. 609 to 610) and on surface resistivity (p. 610) in section V, "Discussion of results."

TENSILE STRENGTH.—Tensile strength data furnish specific and comparative information to those designing electrical insulator parts which are under mechanical stress. The modulus of elasticity (tensile) shows a peculiarity of this type of material. Its modulus is very small in comparison with metals. The various makes of insulating materials differ somewhat in this respect, but

the greatest difference is between grades of the same kind of material. This difference is probably owing to the different percentages of varnish in the different grades. The proportional limit of the materials gives information as to the stress which can not be exceeded without gradual yielding taking place in the material.

TRANSVERSE STRENGTH.—Transverse or cross-bend strength data are equally important. The greater portion of the materials discussed in this report are of a laminated structure. When such laminated materials are subjected to a bending stress, there is a tendency for the laminations to shear owing to the different strain on the extreme (outer) layers. Tensile and transverse strength data give comparative knowledge of the strength of the different laminated materials and also furnish material for comparison with like data on hard rubber and other materials. In transverse strength tests modulus of rupture and modulus of elasticity have been considered. Modulus of elasticity values are missing for some materials listed in the tabulated data shown on pages 524 to 533. Some samples were tested without using a deflectometer, so there were not sufficient data to compute modulus of elasticity. A few measurements of proportional limit (transverse) were made. Some of these data are given on page 574 in connection with data on proportional limit (tensile).

HARDNESS.—Hardness of the various insulating materials has been measured for several reasons. The laminated phenolic materials are being substituted for hard rubber, the hardness of which varies considerably with temperature. Therefore, it has seemed fitting to measure the relative hardness of the various materials at different temperatures. Also, the hardness of the phenolic materials varies with the length of time the sheets have been cured. Hardness data are being accumulated with the hope that it will throw some light on other mechanical and electrical data.

IMPACT STRENGTH.—Impact tests determine the brittleness of a material or its ability to withstand a suddenly applied force. Such tests show differences in the various kinds of material, but chiefly in grades. Percentage of varnish, kind of filler, and length of curing influence the impact strength values.

PERMANENT DISTORTION.—Under the heading of distortion tests come measurements of permanent distortion (or warp under stress) and natural warp. The measurements of permanent dis-

tortion or warp under stress were made to compare one phenolic material with another and all such with hard rubber, since one of the chief difficulties with hard rubber is that it warps under stress. The warping of hard rubber increases when either stress is increased or heat is applied, but this paper will contain no data of comparative warp under stress and heat.

MACHINING QUALITIES.—Since this investigation was started to show how one laminated phenolic insulating material compared with another and how all such materials compared with hard rubber, practical considerations make it necessary to compare machining qualities. Hard rubber can be sawed, drilled, tapped, turned, threaded, and milled with comparative ease. Of course, hard rubber is brittle, but this can be provided against in the designing and machining of parts. The laminated insulating materials of the phenol-methylene type are comparatively tough, hard to machine, and dull the machine tools rapidly. The different kinds and grades of such material may differ in this respect. The extensive arbitrary test scheme outlined in a separate Bureau publication mentioned on page 506 was intended to approximate general simple machining operations, such as might be performed in the average shop using the various phenolic insulating materials, and to obtain statements from the Bureau of Standards machinists concerning their preferences of the various kinds and grades of insulating material for different operations, based on their own work.

(C) CHOICE OF THERMAL AND CHEMICAL PROPERTIES

THERMAL EXPANSIVITY.—The use of insulating materials of the phenol-methylene type on delicate instruments of varied types has made it necessary to know the thermal expansivity of the various kinds of material. If the delicate instruments whose construction includes such material are to be used where there are appreciable temperature changes, it is important to know whether any set of changes with temperature will be the same during a similar subsequent temperature cycle.

HEAT EFFECTS.—An attempt was made to analyze the effect of relatively high temperatures on the various laminated insulating materials. This test was used to determine, if possible, which materials were best adapted to the higher temperatures.

CHEMICAL EFFECTS.—Because of the multitude of uses to which the phenolic insulating materials are put it seemed necessary to determine some effects of acid and alkali on them. We have had numerous requests for such information. It is probable that such

tests are more important on the molded types of phenol-methylene materials because of the tendency to replace the more or less brittle hard-rubber containers for acids with the molded phenolic materials.

2. DEFINITIONS OF ELECTRICAL PROPERTIES

PHASE DIFFERENCE.—The property called phase difference is a quantity which gives a measure of the power loss accompanying production of heat in the material when an alternating current flows. In most materials this power loss or heating is caused by the phenomenon of dielectric absorption. This phenomenon is somewhat like viscosity in a liquid and is sometimes called "dielectric viscosity." The power loss can be caused by a very low

volume resistivity, but materials of such very low resistivity are hardly suitable for use as insulators.

The phase difference has a very simple relation to a more widely used quantity, the power factor. It is, in fact, equal to it in most cases. When alternating current flows in a condenser having a solid insulating material between the plates, the current is not exactly 90 degrees out of phase with

FIG. 1.—Diagram of phase relation of I and E

The phase difference (ψ) is magnified.

the impressed voltage, because of the existence of the heating or power loss. Instead of being exactly 90 degrees, the phase angle is some slightly smaller value and the cosine of this phase angle is called the power factor. The small difference between the phase angle and 90 degrees is called the phase difference. The power loss in the material is

$$P = EI \cos \theta,$$

where E is the voltage across the condenser, I the current, and θ the phase angle (see Fig. 1). The factor $\cos \theta$ is the power factor.

Letting $\psi =$ the phase difference or $90 \text{ degrees} - \theta$,

$$P = EI \sin \psi.$$

It follows that

$$\sin \psi = \cos \theta.$$

That is, the sine of the phase difference is equal to the power factor. In all except extremely poor condensers ψ is small, $\sin \psi$ is practically equal to ψ , and since $\sin \psi$ is equal to the power factor it follows that usually ψ (in radians) is equal to the power

factor. Phase difference is usually expressed in degrees, and power factor in per cent. Power factor in per cent is obtained by multiplying phase difference in degrees by 1.75.

Since the phase difference in radians is usually equal to power factor, therefore

$$\psi = \frac{P}{EI}. \quad (1)$$

In words, phase difference is the ratio of power dissipated as heat (P) to total power flowing (EI).

$$\psi \text{ in degrees} = \frac{0.1079 R \text{ ohms} \times C \mu\mu f}{\lambda \text{ meters}}. \quad (1a)$$

If one wishes to express this property of an insulating material in terms of watt loss (P),

$$\begin{aligned} P &= EI \psi \\ &= 2 \pi f \psi CE^2 \\ &= \frac{\text{constant} \times f(\psi K) SE^2}{T}, \end{aligned}$$

where E is the voltage across the condenser,

I is the current,

ψ is the phase difference in degrees,

f is the frequency in cycles per second,

K is the dielectric constant,

S is the area of one of the condenser plates in square centimeters,

T is the thickness of the dielectric in centimeters.

Also $P = RI^2$ where R is the equivalent resistance in ohms.

DIELECTRIC CONSTANT.—The dielectric constant of an insulating material is the property which characterizes the material in determining the capacity of a condenser employing it. It is the quantity K in

$$C = 0.0885 \frac{KS}{T}, \quad (2)$$

where C is the capacity of a flat-plate condenser in micromicrofarads, S is the area of one of the condenser plates in square centimeters, and T is the thickness of the insulating sheet in centimeters. The dielectric constant of air is 1 and the dielectric constant of most substances is between 1 and 10, except water, which has a dielectric constant of 81.

FLASH-OVER VOLTAGE.—Flash-over voltage is here defined as the effective radio-frequency voltage necessary to arc over the surface of an insulating material between skirted brass studs (diameter = 2.0 cm) placed with a distance of two centimeters between their nearest points.

$$E = \frac{1.6(10)^{11} I}{f C} = \frac{530\lambda I}{C}, \quad (3)$$

where f is frequency of the alternating current, λ is wave length in meters, C is the capacity in micromicrofarads, E is volts, and I is amperes. The definition of flash-over voltage is not complete without further specification of time and other factors. (See paper mentioned on p. 506 and sec. V-3 of this paper.)

ELECTRICAL RESISTIVITIES.—The current which flows between two conductors insulated from each other by a solid material is made up of two parts—that which flows through the insulator proper and that which flows through a film of moisture or other semiconducting material on the surface of the insulator. The relative importance of these depends on the resistance of the two paths. Since water, even if very pure, conducts much better than the ordinary solid insulators, a very thin film of water may have much less resistance than the insulator.

Volume Resistivity.—The volume resistivity ρ of a material is defined as the resistance between two opposite faces of a centimeter cube. For any specimen of cross section S and length l the resistance is

$$R = \frac{\rho l}{S} \text{ or } \rho = \frac{RS}{l}. \quad (4)$$

Surface Resistivity.—By analogy the surface resistivity is defined as the resistance between two opposite edges of a square surface film. If the film is uniform over a surface,

$$\sigma = \frac{R'b}{l}, \quad (5)$$

where σ is the surface resistivity and R' the resistance of a rectangle of the film of length l and breadth b . If the thickness of the film is t , the volume resistivity of the film will be

$$\rho' = \frac{R' b t}{l} = \sigma t.$$

or, $\sigma = \rho'/t$.

Since σ , the surface resistivity, depends upon the thickness of the film, it is not a property solely of the material of the film, and the term "resistivity," which is generally used to express the property of a material, can not strictly be applied. However, since both the thickness t and the volume resistivity ρ' of the surface film depend, under any given conditions, upon the material on which it is deposited, surface resistivity may be considered as a property of the material on which the film is deposited. Thus, we speak of the surface resistivity of glass, hard rubber, etc., though these materials only serve for condensing the moisture and do not carry any of the current.

For a more complete explanation of volume and surface resistivity, see B. S. Sci. Papers, No. 234, by H. L. Curtis, entitled "Insulating Properties of Solid Dielectrics."

3. DEFINITIONS OF MECHANICAL PROPERTIES

DENSITY.—The density of a substance is its mass per unit volume. In the cgs system density values are expressed numerically either by the number of grams per milliliter or grams per cubic centimeter. Since it is customary among engineers to speak of density in terms of grams per cubic centimeter, all the tables giving Bureau of Standards density data are headed "grams per cubic centimeter." This is slightly in error, but values expressed in g/ml and g/cc differ by only 27 parts in 1 000 000.

MOISTURE ABSORPTION.—Moisture absorption is here given the arbitrary definition: The percentage by weight of water absorbed by a sample (cut 5 by 10 cm by the natural thickness of the material) when immersed in water at room temperature for 24 hours. Results obtained on samples of any other size or shape are not comparable with moisture absorption as here defined.

ULTIMATE STRENGTH.—Ultimate strength (tensile) of a material is the pulling force, in pounds, necessary to break a given sample, divided by the area of the cross section in square inches.

MODULUS OF ELASTICITY.—Modulus of elasticity (tensile) is the ratio of the magnitude of the stress to that of the accompanying unit elongation produced.

$$\text{Modulus of elasticity (tensile)} = \frac{P L}{b d l}, \quad (6)$$

where P = load in pounds, L = distance in inches between gage marks, l = elongation in inches, b = width of sample in inches at reduced section, d = thickness of sample in inches.

Where cylindrical samples are used, modulus of elasticity (tensile) = $\frac{PL}{al}$, where a = area of reduced section in inches, bd is equivalent to a . The formula $\frac{PL}{al}$ may be written $\frac{\frac{P}{a}}{\frac{l}{L}}$,

$\frac{P}{a}$ being the stress per unit area or the measure of stress, and $\frac{l}{L}$ is the strain per unit length or the measure of strain.

The formula $\frac{PL}{al}$ or $\frac{PL}{bd\ l}$ is then a ratio of stress to the accompanying strain, this ratio being constant within the limits of elasticity.

PROPORTIONAL LIMIT.—Proportional limit (abbreviated P-limit) is the stress at which deformations cease to be proportional to the load. This point is determined by plotting a stress-strain or load-deformation curve. This definition holds both for tensile and transverse strength measurements.

MODULUS OF RUPTURE.—Modulus of rupture is the maximum stress in the extreme fiber—that is, outer surface—of a specimen tested to rupture by a transverse force, as computed by the empirical application of the flexure formula to stresses above the transverse proportional limit.

Modulus of rupture (sometimes called maximum fiber stress) =

$$\frac{3}{2} \frac{P L}{b d^2}, \quad (7)$$

where the letters refer to the same terms as below.

MODULUS OF ELASTICITY.—Modulus of elasticity (transverse) is the ratio of unit stress within the proportional limit to the corresponding unit strain.

$$\text{Modulus of elasticity (transverse)} = \frac{L^3 S}{6df}, \quad (8)$$

$$= \frac{PL^3}{4bd^3f},$$

where P = load in pounds (concentrated at center),

b = width of sample in inches,

d = thickness of sample in inches,

f = deflection at center in inches,

S = unit stress,

L = length of span in inches.

BRINELL HARDNESS NUMERAL.—Brinell hardness numeral (abbreviated B. h. n.) is the ratio of the pressure on a sphere used to indent the material to be tested to the area of the spherical indentation produced. The standard sphere used is a 10 mm diameter hardened steel ball. The pressures as chosen for tests on these materials are 500 kg for the harder materials and 250 kg for softer materials, and the time of application of pressure is 30 seconds. Five hundred (500) kilogram pressure was used in all regular tests recorded in this paper.

$$\text{B. h. n.} = P \div \pi tD = P \div [\pi D (D/2 - \sqrt{D^2/4 - d^2/4})] \quad (9)$$

P = pressure in kilograms,
 t = depth of indentation,
 D = diameter of ball,
 d = diameter of indentation,

all dimensions being expressed in millimeters.

SHORE SCLEROSCOPE HARDNESS.—Shore scleroscope hardness is the height of rebound of a diamond-pointed hammer falling by its own weight on the object to be tested for hardness. The value is measured on an empirical scale on which the average hardness of martensitic high-carbon steel equals 100. On very soft materials a “magnifier” hammer is used in place of the commonly used “universal” hammer, and values may be converted to the corresponding “universal” value by multiplying the reading by 4/7. The scleroscope hardness when accurately determined is an index of the tensile elastic limit of the material tested.

IMPACT STRENGTH.—Impact strength is defined as the mechanical energy absorbed by a standard test piece during fracture by a blow from a pendulum hammer.

PERMANENT DISTORTION.—Permanent distortion is here defined as the permanent set or distortion due to a certain dead weight centrally suspended from a sample of known dimensions supported by V blocks with a definite separation. The natural distortion or warp of a few sheets of insulating material has been considered under this head.

MACHINING QUALITIES.—Machining qualities are not capable of rigorous definition. In this work they are considered to be given by the ease of machining, surface finish of machined samples, effect on machine tools for specimens sawed, turned, machine and

die threaded, tapped, drilled, and shaped, according to the arbitrary tests outlined in the Bureau publication mentioned on page 506. The results of such tests are largely determined by the personal judgment of the machinist.

4. DEFINITIONS OF THERMAL AND CHEMICAL PROPERTIES

THERMAL EXPANSIVITY.—Thermal expansivity of a solid material is the increase in length per unit length per degree centigrade rise in temperature.

HEAT EFFECTS.—The heat effects determined here were merely the effects of the application of heat over a range of 100 to 500° C. The approximate temperature at which blistering, cracking, and charring begin was recorded.

EFFECTS OF CHEMICALS.—The chemical effects determined in this work were the effects on 5 by 10 by 1.27 cm samples of laminated phenolic insulating materials when immersed in a 22 per cent (by weight) solution of sulphuric acid or a 17 per cent (by weight) solution of sodium hydroxide (caustic soda) for 48 hours. The following effects were considered: Visible effects (swelling, splitting, etc.), increase or decrease in weight, and change in hardness.

IV. TABULATION OF RESULTS

1. PRINCIPAL ELECTRICAL AND MECHANICAL PROPERTIES

The four ensuing data sheets give in a condensed form the results of many determinations. The methods of securing the data are given in a separate publication entitled "Methods of Measurement of Properties of Electrical Insulating Materials" and the final results are analyzed below. The arrangement and abbreviations have been explained in part. The notes collected below, however, make the four data tables independently complete.

Column 1 specifies material, grade, color, and surface finish.

Column 2 gives the identification number assigned the sample when received.

Column 5 gives the dates on which the phase difference (ψ°) and dielectric constant (K) determinations were made.

Columns 6–11, inclusive, give values of phase difference and dielectric constant at the lower and maximum wave lengths used on that day. Usually such determinations were made at five or more different wave lengths. The temperature and relative humidity of the air near the sample was measured. The values are on record in the radio laboratory and have not been given here.

The statement, "sample baked (date)," appears several times in these columns. The average time of baking was 96 hours and the temperature about 80° C.

Columns 13 and 14 are somewhat irregular, in that some measurements of surface resistivity were made at 34 per cent relative humidity instead of 25 per cent and some at 42 per cent instead of 50 per cent.

Column 17. These values were determined on samples 5 by 10 cm by the thickness stated in columns 3 and 4 (see pp. 524 to 533).

Columns 18 and 20. Where x and y appear with values of ultimate strength or modulus of rupture, it means that one value was obtained on a sample cut out the way of the grain and the other in a direction 90 degrees from the first. It is to be pointed out that where more than two values of tensile strength are given for test pieces cut from one sample one test piece marked x of any pair may not have been cut in the same direction as a test piece marked x in another pair. The test specimens marked x in the tensile strength column are not necessarily cut in the same direction as a modulus of rupture test specimen marked x.

Columns 22 and 23. The letters B and S refer to Brinell method and Shore scleroscope method, respectively. A and B refers to side of sample tested. Values of the A side only are given unless the A and B values differ appreciably. Thus, B-42-A means Brinell hardness numeral of 42 on side A.

The results condensed into these four large tables are given more fully in the graphs and tables of data on particular properties that follow.

TABLE 5.—Detailed Electrical and Mechanical Data on 20 Samples of Bakelite-Dilecto, Grades XX, X, and CB

Grade, color, and surface	B. S. sample number	Approximate thickness		Date of test	Wave length (λ_m)	Phase difference (ϕ)	Dielectric constant (K)	Wave length (λ_m)	Phase difference (ϕ)	Dielectric constant (K)	Volume resistivity	Surface resistivity at relative humidity of—			Density	Moisture absorbed	Tensile strength		Transverse strength		Hardness numbers for specimens tested at—	
		cm	In.									25 or 34 per cent a	42 or 50 per cent b	84 per cent			Ultimate strength	Modulus of elasticity	Modulus of rupture	Modulus of elasticity +1000	20–30° C	50° C
1	2			5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	10	0.32	$\frac{1}{8}$	Mar. 14, 1918	Met- 779	Deg. 2.0	4.5	Met- 792	Deg. 1.8	4.6	Ohm- cu $\times 10^8$	Ohms $\times 10^8$	Ohms $\times 10^8$	Ohms $\times 10^8$	Ohms $\times 10^8$	Per cent	Lbs./in. ²	Lbs./in. ²	Lbs./in. ²	Lbs./in. ²		
XX. Blk., pol.	11	.64	$\frac{1}{4}$	Apr. 30, 1919	1265	1.9	5.1	4170	1.7	5.0	5.2	7 700	11 000	6 400	3	1.35	0.44	15 200	15 400	1290		
	11	.64	$\frac{1}{4}$	Mar. 14, 1918	414	2.2	4.9	1375	1.9	5.0	3 000	680	230	10			15 500					
XX. Nat., pol.	56	.64	$\frac{1}{4}$	Apr. 10, 1919	1004	1.9	5.3	3365	1.6	5.4	200	4 200	700	9			13 900	1510	19 000	1290		
	56-0	.64	$\frac{1}{4}$	Apr. 16, 1919	5320	1.5	5.4															
XX. Blk., pol.	57	.64	$\frac{1}{4}$	May 3, 1919	952	1.7	5.3	3135	1.4	5.4	70 000	430 000	67 000	8	1.34	.25						
	162	.64	$\frac{1}{4}$	Nov. 5, 1918	654	2.4	5.3	3188	2.4	5.5												
	12	.95	$\frac{3}{8}$	Apr. 1, 1919	979	2.5	5.3	3225	2.5	5.4	10 000	380	65	12	1.35	.32	11 100y	14 300	15 600y	1340		
	14	.95	$\frac{3}{8}$	Mar. 15, 1918	550	2.2	5.2	1140	2.0	5.3												
	13	1.27	$\frac{1}{2}$	Mar. 15, 1918	495	2.5	5.4	1450	2.4	5.6	2 000	17 000	13 000	140	1.35	.10	10 600z	11 000y	16 000	1340	B-37-A	B-37-A
	59	1.27	$\frac{1}{2}$	Mar. 16, 1918	557	2.1	5.3	1142	1.9	5.4	18 000	32 000	9 000	16	1.34	.17	11 000z	13 000	15 600y	1340	S-82-A	S-82-A
XX. Nat., po.	163	1.27	$\frac{1}{2}$	Oct. 15, 1918	541	2.3	5.2	1930	2.3	5.4	5 000	20 000	67 500	11			12 600y				B-37-A	B-37-A
	59	1.27	$\frac{1}{2}$	Mar. 15, 1918	495	2.5	5.4	1450	2.4	5.6	2 000	17 000	13 000	140	1.35	.10	10 600z	11 000y	16 000	1340	S-85-A	S-85-A
XX. Blk., pol.	251	1.27	$\frac{1}{2}$	Apr. 23, 1919	729	2.5	5.7	2394	2.3	5.9	1 000	3 600	1 800	120	1.34	.22	9 600y	11 900	16 000		B-40-A	B-39-A
	163	1.27	$\frac{1}{2}$	Mar. 27, 1919	726	2.0	5.5	2364	1.6	5.6	80 000	18 000	1 400	200	1.36	.14	14 400z	11 900	17 300y		S-87-A	S-87-A
XX. Blk., pol.	251	1.27	$\frac{1}{2}$	June 10, 1919	721	2.1	5.6	1714	2.0	5.7	20 000	13 000	2 100	26	1.37	.19						
	251	1.27	$\frac{1}{2}$	June 10, 1919	721	2.1	5.6	1714	2.0	5.7	20 000	13 000	2 100	26	1.37	.19						

^a All values marked *a* are at 34 per cent; all others at 25 per cent.
^b All values marked *b* are at 42 per cent; all others at 50 per cent.
^c Sample baked Dec. 17, 1918.
^d Sample baked Nov. 13, 1918.

TABLE 6.—Detailed Electrical and Mechanical Data on 25 Samples of Bakelite Micarta, Grades 32-X, 21-X, 323, 213, and 21-D

Grade, color, and surface	B. S. sample number	Approximate thickness	Date of test	Wave length (λ_m)	Phase difference (ψ)		Dielectric constant (K)	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Volume resistivity	Surface resistivity at relative humidity of —			Density	Moisture absorbed	Tensile strength		Transverse strength		Hardness numbers for specimens tested at—				
					Deg.	cm						Ohms. $\times 10^8$	25 per cent	42 or 50 per cent a			84 per cent	Ultimate strength	Modulus of elasticity $\times 1000$	Lbs./in. ²		Lbs./in. ²	Modulus of elasticity $\times 1000$	Lbs./in. ²	Lbs./in. ²
32-X. Blk., pol.	18	0.32 $\frac{1}{8}$	Mar. 24, 1918	655	2.7	5.2	2.7	1510	2.5	5.3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	50° C			
	19	.64 $\frac{1}{4}$	May 1, 1919	1377	2.8	5.4	4335	3.0	5.6	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	20-30° C			
	19	.64 $\frac{1}{4}$	Mar. 18, 1919	774	2.9	5.6	1894	2.9	5.8	200	460	340	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....			
	146	.64 $\frac{1}{4}$	Oct. 21, 1918	696	4.3	6.0	3482	5.3	6.5	40	300	120	28	1.35	.36	9 700x	11 400y	14 200x	19 000y	16 000	1470	.....			
	147	.64 $\frac{1}{4}$	Mar. 4, 1919	1376	3.7	6.0	3420	3.9	6.2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....			
32-X. Blk., dull.	252	.64 $\frac{1}{4}$	Mar. 11, 1919	1264	2.2	4.9	3097	2.1	5.0	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....			
	253	1.27 $\frac{1}{2}$	Aug. 2, 1919	677	2.8	5.5	1842	2.8	5.7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....			
	21	1.27 $\frac{1}{2}$	Aug. 2, 1919	3326	2.8	5.8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....			
	147	.64 $\frac{1}{4}$	Mar. 21, 1919	1370	3.2	5.8	3370	3.3	5.9	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....			
	252	.64 $\frac{1}{4}$	Aug. 1, 1919	832	2.0	5.7	1860	1.9	5.8	37 000	21 000	5300	44	1.35	.54	.....	.....	.....	.....	.....	.....	.....			
32-X. Blk., pol.	20	.95 $\frac{3}{8}$	Mar. 23, 1918	595	2.9	5.7	1190	3.1	5.8	45 000	2 600	820	21	.....	.....	.....	.....	.....	.....	.....	.....	.....			
	148	.95 $\frac{3}{8}$	Apr. 2, 1919	850	3.8	5.8	2845	4.3	6.1	30	60	16	4	1.34	.38	11 800x	13 300y	17 300y	14 400	1050	.....	.....			
	253	1.27 $\frac{1}{2}$	June 11, 1919	728	2.2	5.8	1736	2.1	6.0	1 000	3 600	680	15	.....	.....	.....	.....	.....	.....	.....	.....	.....			
	21	1.27 $\frac{1}{2}$	Mar. 18, 1919	750	2.8	6.2	1840	2.8	6.3	1 200	1 200	600	6	1.36	.28	8 800x	12 200y	.....	.....	.....	.....	.....			
	149	1.27 $\frac{1}{2}$	Mar. 31, 1919	740	2.7	5.8	2440	2.5	6.0	200	1 600	1 000	70	1.35	.19	9 800x	16 800y	.....	.....	.....	.....	.....			

2. All values marked (a) are at 42 per cent; all others at 50 per cent.

TABLE 7.—Detailed Electrical and Mechanical Data on 16 Samples of Condensite Celoron, Grades 10, 15, and 20

Grade, color, and surface	B. S. sample number	Approximate thickness		Date of test	Wave length (λ_m)		Phase difference (ϕ)		Dielectric constant (K)	Volume resistivity	Surface resistivity at relative humidity of—			Density	Moisture absorbed	Tensile strength		Transverse strength		Hardness numbers for specimens tested at—	
		cm.	$\frac{1}{16}$		Meters	Deg.	Meters	Deg.			Ohms $\times 10^8$	Ohms $\times 10^8$	Ohms $\times 10^8$			Ultimate strength	Modulus of elasticity	Modulus of rupture	Modulus of elasticity	20-30° C	50° C
1. Blk., pol.	141	0.32	$\frac{1}{16}$	Apr. 24, 1918	1435	2.2	5.8	2.0	5.9	Ohms $\times 10^8$	Ohms $\times 10^8$	Ohms $\times 10^8$	Ohms $\times 10^8$	g/cm	Per cent	Lbs./in. ²	Lbs./in. ²	Lbs./in. ²	Lbs./in. ²	22	23
	142	.64	$\frac{1}{8}$	Apr. 28, 1919	870	2.2	6.0	1.9	6.0	10 000	25 000	360	40	1.39	0.35	12 500x	13 000	13 000	12 500		
	143	.64	$\frac{1}{8}$	Oct. 8, 1919	700	2.5	6.0	2.3	6.1	6.1	6.1	6.1	6.1	6.1	6.1	7 900y	7 900y	12 500	12 500		
	144	.64	$\frac{1}{8}$	Oct. 8, 1919	2410	2.3	6.2	2.1	6.2	6.2	6.2	6.2	6.2	6.2	6.2	11 800x	11 800x	19 000	19 000		
10. Nat., pol.	160	.64	$\frac{1}{8}$	Oct. 18, 1918	694	3.2	5.8	3.4	6.2	200	7 000	1 200	150	1.40	.36	10 100	12 300	12 300	21 400x		
	186	.64	$\frac{1}{8}$	Dec. 20, 1918	1720	2.6	5.6	3.963	5.8	4 500	6 200	1 200	14	1.41	.32	16 500x	21 400x	15 100y	15 100y		
10. Nat., pol.	187	.64	$\frac{1}{8}$	Mar. 29, 1919	1037	2.5	6.2	3.425	6.3	3 100	18 000	1 800	33	1.41	.24	9 100y	9 100y	9 900x	9 900x		
	106	.64	$\frac{1}{8}$	Aug. 12, 1918	1205	3.3	7.0	2.795	7.2	7.2	7.2	7.2	7.2	7.2	7.2	15 100x	17 600y	17 000y	17 000y		
15. Blk., pol.	273b	.64	$\frac{1}{8}$	Jan. 22, 1920	508	4.7	7.2	3.545	7.9	7.9	7.9	7.9	7.9	7.9	7.9	14 600x	14 600x	17 000y	17 000y		
	143	.95	$\frac{3}{8}$	Apr. 28, 1919	853	2.4	6.0	2.800	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6 600y	6 600y	9 900x	9 900x		
15. Blk., pol.	188	.95	$\frac{3}{8}$	Dec. 20, 1918	1495	1.9	5.8	3.462	1.9	6.2	6.2	6.2	6.2	6.2	6.2	14 500y	14 500y	11 800x	11 800x		
	189	.95	$\frac{3}{8}$	Oct. 7, 1919	623	3.1	6.8	3.800	7.1	7.1	7.1	7.1	7.1	7.1	7.1	14 900y	14 900y	18 600y	18 600y		

1441.1.27	1/2	Aug. 5, 1919	753	2.5	6.4	2613	2.4	6.6	9 000	8 000	6 000	220	1.38	.26	8 500y 13 800x 8 000y 14 500x	11 600 8 200 11 500	B-34-A B-36-B B-39-B S-82-A S-85-A S-86-B
10. Nat., pol.	161.1.27	1/2	Mar. 31, 1919	744	2.7	5.9	2465	2.5	6.2	60	700	70	1.41	.20	8 400 13 000		
15. Blk., pol.	272.1.27	1/2	Jan. 22, 1920	678	4.7	7.9	2869	5.2	8.2								
	189.1.27	1/2	Mar. 29, 1919	768	2.6	6.3	2485	2.2	6.5	68 000	25 000	4 400	50	1.42	.18 16 200x 9 400y 22 100x 22 800x		
10. Nat., pol.	145.3.02	1 1/8													17 300x 17 300x 18 500 18 500		
20. Nat., pol.	218.64	1/4	Jan. 15, 1919	1665	5.8	6.4	4075	6.9	7.0	100 27	280 270	25 2	1.34	.32	7 900x 8 500y 7 800x 7 200y	12 000 12 000 12 000 8 400	B-34-A B-32-A B-42-B B-33-B S-88-A S-84-A S-87-B
	219.1.27	1/2											1.35	.46			

TABLE 8.—Detailed Electrical and Mechanical Data on 38 Samples of Formica, Grades M, M-2, P, and R—Continued.

Grade, color, and surface	B. S. sample number			Approximate thickness		Date of test	Wave length (λ _m)	Phase difference (ψ)	Dielectric constant (K)	Volume resistivity	Surface resistivity at relative humidity of—			Density	Moisture absorbed	Tensile strength		Transverse strength		Hardness num- erals for speci- mens tested at—	
	2	3	4	cm	In.						25 per cent	42 or 50 per cent	84 per cent			Ultimate strength	Modulus of elas- ticity +1000	Modulus of rup- ture	Modulus of elas- ticity +1000		
M-2. Blk., pol.....	118	1.27	½	Mar. 25, 1919	1017	3.8	6.0	2485	4.3	6.3	Ohm- cm × 10 ⁸	Ohms × 10 ⁸	Ohms × 10 ⁸	g/cm ³	Per cent	Lbs./ in. ²	Lbs./ in. ²	Lbs./ in. ²	Lbs./ in. ²	20-30°C	50°C
	216	1.27	½	Mar. 26, 1919	737	3.6	5.8	2444	3.8	6.1	470	1000	250	6	1.36	.23	14 100x	16 000x	16 900	16 900	
	53	2.54	1																		
P. Nat., dull.....	103	.64	¼	Sept. 13, 1918 Nov. 4, 1918	482 684	3.2 3.4	5.5 5.9	2500 3412	3.6 3.7	6.3 6.2	90	600	200	50	1.38	.77	24 900x	17 800	12 100x	19 200	
	104	.95	⅜	Mar. 11, 1919	868	2.7	5.7	2745	2.4	5.8	600	220	65	3	1.41	.53	25 600x	29 900x	24 900x	19 400	
R. Nat.....	55	1.27	½	June 19, 1918	1707	2.2	5.6	.....	.....	.....	2000	1200	640	50	1.34	.28	15 000x	13 100x	1520	1410	
	215	1.27	½	Mar. 27, 1919	705	2.7	5.4	2275	2.7	5.6	.....	.....	.....	.....	1.36	.76	17 700x	27 000x	23 000x	27 000x	
	172	.64	¼	Mar. 5, 1919	1400	4.2	6.4	3450	4.7	6.5	60	340	220	80	1.38	1.47	9 700x	13 300	12 200x	15 200x	

2. PHASE DIFFERENCE AND DIELECTRIC CONSTANT

The results of the measurements of phase difference and dielectric constant on representative samples are shown graphically in the following Figs. Nos. 2 to 27.

FIG. 2.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade XX, 0.35 cm thick

FIG. 3.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade XX, 0.63 cm thick

FIG. 4.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade XX, 0.96 cm thick

FIG. 5.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency of Bakelite-Dilecto, grade XX, 1.27 cm thick

FIG. 6.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade X, 0.60 cm thick

FIG. 7.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade X, 0.96 cm thick

FIG. 8.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade X, 1.28 cm thick

FIG. 9.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 32-X, 0.32 cm thick

FIG. 10.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 32-X, 1.27 cm thick

FIG. 11.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 21-X, 1.27 cm thick

FIG. 12.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 323, 1.25 cm thick

FIG. 13.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 213, 0.64 cm thick

FIG. 14.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 21-D, 0.65 cm thick

FIG. 15.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Condensite Celoron, grade 15, 0.31 cm thick

FIG. 16.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Condensite Celoron, grade 15, 0.63 cm thick

FIG. 17.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Condensite Celoron, grade 15, 0.96 cm thick

FIG. 18.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Condensite Celoron, grade 15, 1.31 cm thick

FIG. 19.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M, 0.65 cm thick

FIG. 20.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M, 0.94 cm thick

FIG. 21.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M, 1.29 cm thick

FIG. 22.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M, 1.63 cm thick

FIG. 23.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M-2, 0.65 cm thick

FIG. 24.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M-2, 1.24 cm thick

FIG. 25.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade P, 0.98 cm thick

FIG. 26.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade R, 0.64 cm thick

FIG. 27.—Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of hard rubber, 0.50 cm thick, sample taken from stock, grade unknown

3. FLASH-OVER VOLTAGE AT RADIO FREQUENCIES

TABLE 9.—Suddenly Applied Radio-Frequency Voltage Necessary to Arc the Surface of the Several Grades of Phenolic Electrical Insulation between Two 2-cm Skirted Brass Studs Placed 2 cm Apart

Material	Grade	Color	Finish	B. S. sample number	Date of test	Flash-over voltage suddenly applied (E_f)
Bakelite-dilecto	XX	Black	Polished	11	July 23, 1918	17 700
	XX	do.	do.	11	Apr. 10, 1919	21 400
	XX	Natural	do.	56-0	July 26, 1918	17 300
	XX	do.	do.	56-0	Feb. 12, 1919	20 000
	XX	Black	do.	57	Feb. 11, 1919	22 200
	XX	do.	do.	162	Jan. 8, 1919	20 200
	X	Natural	do.	60	July 29, 1918	17 900
	X	do.	do.	60	Jan. 18, 1919	20 600
	X	do.	do.	164	Feb. 17, 1919	21 000
Continental bakelite.	CB	do.	do.	166	Jan. 18, 1919	19 800
	CB	do.	do.	166	Feb. 11, 1919	22 400
Bakelite micarta.....	32-X	Black	do.	19	July 25, 1918	17 600
	32-X	do.	do.	19	Jan. 18, 1919	19 900
	32-X	do.	do.	19	Apr. 8, 1919	20 300
	32-X	do.	do.	146	Jan. 7, 1919	19 900
	32-X	do.	do.	146	Feb. 4, 1919	20 700
	32-X	do.	Dull	147	Feb. 11, 1919	21 800
	32-X	do.	Polished	25	June 24, 1918	17 100
	323	do.	do.	150	Feb. 8, 1919	21 400
	323	do.	Dull	151	Jan. 8, 1919	19 400
	323	do.	do.	151	Feb. 7, 1919	21 800
Bakelite micarta (purchased in open market).	Probably 213	Natural	Polished	15	Aug. 13, 1918	18 600
	do.	do.	do.	15	Jan. 17, 1919	19 300
	do.	do.	do.	15	Jan. 18, 1919	20 800
	21-D	do.	do.	182	Feb. 11, 1919	22 100
Condensite celoron...	10	do.	do.	160	Feb. 17, 1919	21 500
	15	Black	do.	186	Jan. 7, 1919	19 100
	15	do.	do.	186	Feb. 8, 1919	21 100
	10	Natural	do.	187	Feb. 11, 1919	21 600
	20	do.	do.	218	Feb. 14, 1919	27 800
Formica.....	M	Black	do.	5	July 23, 1918	16 300
	M	do.	do.	5	Jan. 18, 1919	21 500
	M	do.	Dull	212	Feb. 5, 1919	20 800
	M	do.	do.	168	Feb. 5, 1919	20 700
	M	do.	Polished	101	Aug. 28, 1918	18 500
	M	do.	do.	101	Jan. 14, 1919	19 000
	M	do.	do.	101	Feb. 5, 1919	21 000
	M-2	do.	do.	50	July 27, 1918	17 200
	M-2	do.	do.	50	Jan. 8, 1919	21 800
	M-2	do.	do.	50	Apr. 8, 1919	20 800
	M-2	do.	do.	116	Feb. 4, 1919	21 000
	M-2	Natural	Dull	140	Feb. 8, 1919	22 300
	P	do.	do.	103	Aug. 13, 1918	18 400
	R	do.	do.	172	Feb. 11, 1919	21 000
Hard rubber.....	Not known	Black	Polished		July 31, 1918	20 600
	do.	do.	do.		Jan. 7, 1919	19 800

4. SURFACE RESISTIVITY

The results of the measurements of surface resistivity on representative samples are shown graphically in the following Figs. Nos. 28 to 39.

FIG. 28.—Change of surface resistivity with humidity, of Bakelite-Dilecto, grades XX and X

FIG. 30.—Change of surface resistivity with humidity, of Bakelite-Dilecto, grades XX and CB

FIG. 31.—Change of surface resistivity with humidity, of Bakelite Micarta, grades 32-X, 213, 323, and 21-D

FIG. 32.—Change of surface resistivity with humidity, of Bakelite Micarta, grades 21-X, 213, and 323

FIG. 34.—Change of surface resistivity with humidity, of Condensite Celoron, grades 10, 15, and 20

FIG. 35.—Change of surface resistivity with humidity, of Formica, grade M

FIG. 36.—Change of surface resistivity with humidity, of Formica, grades P, M-2, and R

FIG. 37.—Change of surface resistivity with humidity, of Formica, grade M-2

FIG. 38.—Change of surface resistivity with humidity, of Formica, grade M

FIG. 39.—Change of surface resistivity with humidity, of hard rubber, sample taken from stock, grade not known

5. TENSILE AND TRANSVERSE STRENGTH

The results of the measurements of tensile and transverse strength on representative samples are shown graphically in the following Figs. Nos. 40 to 51.

FIG. 40.—Stress-strain curves, tensile strength tests on Bakelite-Dilecto and Bakelite Micarta, showing the tensile proportional limit

FIG. 41.—Stress-deflection curves, transverse strength tests on Bakelite-Dilecto, Bakelite Micarta, and Formica, showing the transverse brobortional limit

FIG. 42.—Load-deflection curves, transverse strength tests on Condensite Celoron, grade 10

Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

FIG. 43.—Load-deflection curves, transverse strength tests on Bakelite-Dilecto, Bakelite Micarta, Condensite Celoron, and Formica

^a Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

FIG. 45.—Load-deflection curves, transverse strength tests on Bakelite Micarta, Condensite Celoron, and Continental-Bakelite

Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

FIG. 47.—Load-deflection curves, transverse strength tests on Bakelite-Dilecto and Condensite Celoron

All samples approximately 1 inch wide. Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

FIG. 50.—Load-deflection curves, transverse strength tests on Condensite Celoron and Formica

All samples approximately 1 inch wide. Tested in apparatus described in paper mentioned on page 566. Fo: results computed to pounds per square inch of cross section, see pages 524 to 533.

TABLE 10.—Showing the Relation between Transverse and Tensile Proportional Limit Data Gathered from Tests on Bakelite Dilecto and Formica

Material	Grade	B. S. sample number	Thick-ness	Transverse P-limit	Average tensile P-limit
			Inch	Lbs./in. ²	Lbs./in. ²
Bakelite-Dilecto	XX	56	0.23	7 200	3 500
	X	61	.37	15 000	4 700
	X	62	.50	6 500	5 300
	X				
Formica	M	47	.25	8 500	4 400
	M	48	.24	9 100	4 800
	M	49	.25	12 000	4 900
	M-2	50	.25	9 100	8 000
	M-2	52	.52	14 000	3 600
	M-2	54	.50	13 000	4 300
	P	55	.52	9 400	4 500
	P				

6. IMPACT STRENGTH**TABLE 11.**—Average Resistance to Impact of the Several Grades of Phenolic Electrical Insulation and Hard Rubber, Using Standard Test Specimens

B. S. sample number	Material	Grade	Average impact strength	Base
			Ft.-lbs.	
59	Bakelite-Dilecto	XX	0.7	Paper.
62	do.	X	.9	Do.
175	Continental-Bakelite	CB	a 1.5 x 1.0 y	Canvas.
21	Bakelite Micarta	32-X	.2	Paper.
153	do.	213	.8	Do.
169	do.	21-D	2.1	Canvas.
144	Condensite Celoron	15	.4	Fiber.
161	do.	10	.4	Do.
219	do.	20	1.0	Canvas.
8-0	Formica	M	.3	Paper.
118	do.	M-2	.3	Do.
55	do.	P	1.5	Do.
174	do.	R	2.9	Canvas.
	Hard rubber	Not known	.1	

^a x and y are used merely to indicate that specimen x is cut at right angles to specimen y.

7. PERMANENT DISTORTION
TABLE 12.—Summary of Permanent Distortion Data on the Several Grades of Phenolic Electrical Insulating Materials Using Samples 14 Inches Long and Loaded over a Span of 12 Inches

[X following slab number means sample cut one way of grain; Y, cut opposite way of grain]

B. S. sample number	Thick- ness in inches	Material	Grade	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set
162.....	1/4	Bakelite-Di- lecto.	XX.....	Lbs. 25	Inch 0.063	Lbs. 40	Inch 0.137	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch
162.....	1/4	do.	XX.....	5 1/2	0.008	34	0.133	40	.189	50	0.010	150	0.071	150	0.046	150	0.071
163.....	1/2	do.	XX.....	11	.010					50	.009	100	0.018	150	.046	150	.046
163.....	1/2	do.	XX.....							50	(a)						
164.....	1/4	do.	X.....							51	.007	100	0.114	150	(a)	150	(a)
164.....	1/4	do.	X.....							50	.017			150	.056	150	.056
62.....	1/2	do.	X.....							50	.009	(b)	(b)	(b)	(b)	(b)	(b)
166.....	1/4	Continental- Bakelite	CB.....	22	.169	40	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
166.....	1/4	do.	CB.....	25	.139	40	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
175.....	1/4	do.	CB.....							50	.003	100	.077	150	(a)	150	(a)
175.....	1/4	do.	CB.....							51	.016						
146.....	1/4	Bakelite Mj- carta	32-X.....	33	.125	40	(a)										
146.....	1/4	do.	32-X.....	33	.147	40	(a)										
149.....	1/4	do.	21-X.....							50	.012	100	.029	150	.094	150	.094
149.....	1/4	do.	21-X.....							51	.010	100	.144				
150.....	1/4	do.	323.....	25	.076	40	.185										
150.....	1/4	do.	323.....	10 1/2	.012	22 1/2	.049	33	.120	50	.000	100	.025	150	.138	150	.138
150.....	1/4	do.	213.....							45	.016	100	.025	150	.059	150	.059
153.....	1/4	do.	213.....														
182X.....	1/4	do.	21-D.....	5	.009	22	.146										
182Y.....	1/4	do.	21-D.....	5 1/2	.016												
184Y.....	1/4	do.	21-D.....	15	.005					51	.012	150	.372	150	(a)	150	(a)
184X.....	1/4	do.	21-D.....	17 1/2	.008					51	.024						
187.....	1/4	Condensite Celoron	10.....	5 1/2	.011												

a Broke.

b Slipped under extreme distortion.

TABLE 12.—Summary of Permanent Distortion Data on the Several Grades of Phenolic Electrical Insulating Materials Using Samples 14 Inches Long and Loaded over a Span of 12 Inches—Continued

[X following slab number means sample cut out one way of grain; Y, cut opposite way of grain.]

B. S. sample number	Thick- ness in inches	Material	Grade	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set
187.	1/4	do.	10.	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch
144.	1/2	do.	15.	25	.048			40	(c)	51	.007	100	.114	100	.114	150	(c)
144.	1/2	do.	15.	25	.000			40		50	.003	100	.015	100	.015	150	(c)
218Y	1/8	do.	20.	25	.108			40	.283			100		100		150	(c)
219X	3/8	do.	20.														
168.	1/4	Formica	M.			33	.038										
168.	1/4	do.	M.	25	(c)			40	.129								
108.	1/4	do.	M.	25	.062			40	.131							150	.053
108.	1/4	do.	M.	25	.079												
107.	1/2	do.	M.							50	.025						
107.	1/2	do.	M.	15	.000			35	.004							150	.043
116.	1/4	do.	M-2.	25	.115			40	.230								
116.	1/4	do.	M-2.	25	.066			40	.233								
103.	1/4	do.	P.			33	.045	40	.074								
103.	1/4	do.	P.	25	.024			40	.080								
104.	3/8	do.	P.					43	.003			78	0.017	100	.020	125	(c)
104.	3/8	do.	P.	104						50	.006			100	.032	125	(c)
215.	1/2	do.	P.							50	.012					150	.066
215.	1/2	do.	P.							50	.015					150	.066
172.	1/4	do.	R.	11	.044												
172.	1/4	do.	R.	5	.012												
174.	1/2	do.	R.					22 1/2	.169								
174.	1/2	do.	R.							51	.029			100	.102	150	.461

a Broke.

PERMANENT DISTORTION OF PANELS.—Two irregular permanent distortion tests were made on panels of the phenolic insulating materials. The test was made at room temperature of 23° C, using an Emery dead-weight testing machine. The panel was supported by 2 V-blocks set 22 inches between centers and the load applied through a V-block mounted at the center of the span. Progressive load increments of 50 pounds were used, and all load was removed after the application of each 50 pounds increment in order to note the permanent set that was developed during loading. At intervals during loading the load was allowed to stand for 24 hours and then was removed so as to determine whether any increase in permanent set had occurred. One sample panel measured 18 by 24 inches by ½ inch thick.

Up to a load of 597.5 pounds this panel seemed perfectly elastic. This load caused a deflection of 0.5 inch and was allowed to remain on for 24 hours, after which time the load was removed and it was found that a permanent set of 0.0938 inch had developed. The load was then reapplied to a total of 797.5 pounds, at which load the deflection was 0.8 inch. This load was also allowed to remain on the panel for a 24-hour period. On removal of the load it was found that the permanent set had increased to 0.1563 inch.

The second sample measured 18 by 24 inches by ¾ inch thick. The above method was followed in this test except in regard to time of loading and the number of Ames dials used. Deflections are measured by means of two Ames dials set at either end of the center V-block. Up to a load of 397 pounds the panel seemed perfectly elastic. This load was allowed to remain on the panel for a 44-hour period, and upon removal of the load it was found that a permanent set of 0.25 inch had developed. The results of this test are given below in tabulated form.

TABLE 13.—Temporary and Permanent Distortion Data Taken on One Sheet of Phenolic Electrical Insulating Material, 18 by 24 by ¾ inch. The Method is Described Above

Load (pounds)			Load (pounds)		
Dial No. 1		Dial No. 2	Dial No. 1		Dial No. 2
Increasing loads:			Decreasing loads after 44-hour applied load:		
Pan ^a	Inch	Inch	Pan + 300.....	Inch	Inch
Pan + 50.....	0.00380	0.00387	Pan + 250.....	0.00909	0.00950
Pan + 100.....	.00459	.00484	Pan + 200.....	.00901	.00950
Pan + 150.....	.00531	.00562	Pan + 150.....	.00850	.00907
Pan + 200.....	.00604	.00703	Pan + 100.....	.00778	.00832
Pan + 250.....	.00685	.00799	Pan + 50.....	.00696	.00730
Pan + 300.....	.00800	.00869	Pan.....	.00612	.00635
	.00871	.00935		.00528	.00540

^a Weight of pan approximately 97 pounds.

NATURAL DISTORTION OR WARP.—Some difficulty has been experienced by the various apparatus manufacturers using the laminated phenolic materials with sheets of the insulating material having a large natural warp. This property of the various materials has not been systematically considered in this investigation. Judging from the samples we have received, all the laminated phenolic materials are liable to have a certain amount of natural warp. Whether this warping increases with time we are not able to state, for no measurements have been made.

One sample which seemed to be warped the worst was selected from each kind of material and the maximum sag measured. The sag was measured by placing a rigid meter bar diagonally across the sheet and observing the distance the sheet sagged from the center of the straight bar 1 meter long.

TABLE 14.—Observations on the Natural Warp of Four Standard Sheets of Phenolic Electrical Insulating Material

Material	Grade	Approximate thickness		Average sag
		cm	Inch	cm
Continental-Bakelite.....	CB.....	0.64	$\frac{1}{4}$	1.1
Bakelite Micarta.....	32-X.....	.95	$\frac{3}{8}$	2.1
Condensite Celoron.....	15.....	.64	$\frac{1}{4}$	.4
Formica.....	M.....	.95	$\frac{3}{8}$	.7

8. MACHINING QUALITIES

A description of the method of determining the machining qualities of the laminated phenolic materials is given in the Bureau publication mentioned on page 506. A discussion of the results follows this discussion on pages 605 to 607. Both of these references are needed for an understanding of the following tabulated results:

TABLE 15.—Results of Sawing Tests (Test No. 1)

[Used 12-inch hollow-ground circular saw; no set; speed, 1830 revolutions per minute; cutting teeth per second, 6780; speed of travel, 5750 feet per minute]

Material	Grade	Saws		Phenol odor	
		Fairly easily	Easily	Faint	Strong
Bakelite-Dilecto	XX	x		x	
	X		x	x	
Continental-Bakelite	CB	x		x	
Bakelite Micarta	32-X	x			x
	323	x			x
	21-D		x	x	
Condensite Celoron	15	x			x
	20		x		x
Formica	M		x	x	
	M-2	x		x	
	P		x	x	
	R	x			x

Notes on tests Nos. 2 to 9, inclusive, Table 16. Test numbers refer to the method as outlined in the Bureau publication mentioned on page 506; b-1, b-2, and b-3 refer to the questions stated in the same paper. L and R refer to the machinists making the tests, Messrs. Lund and Rheinbold.

Column 5 is given because in some cases it was very hard to choose one material which was best in respect to questions b-1 and b-2. As an example, operator L decided that in test No. 2 Grades XX, 323, 15, and M-2 worked very similarly to 32-X, X, and P, but dulled the lathe tool a little more rapidly.

GRADES.—Only the grade numbers of material are put in the data table. This is done for compactness. The meaning of XX, X, CB, etc., are given on pages 508 and 509. The names of the companies manufacturing these grades are given on pages 508 and 509.

MEANING AND ORDER OF ENTRIES IN TABLE.—The grades given in the table below are those which showed noticeable superiority in the particular quality and kind of test indicated. Thus, under column 2 and test No. 2, the grades 32-X and R appear. This means that 32-X and R exhibited superior ease of machining in test No. 2. The entries in column 4 are the grades which had least effect on the machine tool. In all cases where more than one grade appears in the same group the order of arrangement is the arbitrary alphabetical arrangement used elsewhere in this paper and indicates no preference. That is, the order is X, P, for instance, because those letters represent Bakelite-Dilecto, grade X, and Formica, grade P.

TABLE 16.—Materials Which Showed Superiority in the Various Machining Tests

1	2		3		4		5	6
Test number and description	Ease of machining b-1		Quantity of machined surface b-2		Effect on machine tool b-3		Similarity in general working to the better materials under b-1 and b-2	Notes
	L	R	L	R	L	R		
2, lathe turning, to determine quality of machined surface	32-X R.....	CB.....	X..... R..... M.....	CB..... X..... 32-X..	32-X.. R.....	X..... CB..... 32X... 323... 21-D.. M..... P..... R.....	XX..... 323... 323... 15..... M-2....	All samples difficult to die thread
3, lathe turning, to determine effect on tool	32-X.. 21-D..	X.....	X.....	X..... CB..... 21-D.. R.....	32-X.. X..... CB..... 21-D.. R.....	X..... CB..... 21-D.. R.....	XX..... 323... M..... M-2....	
4, ability to take a die-cut thread, $\frac{1}{2}$ inch, 20-thread	XX.....	XX.....	M-2....	XX..... M.....	XX..... M-2....	XX.....	32-X.. 323... 15..... M.....	
5, ability to take a machine thread, $\frac{1}{2}$ inch, 20-thread	323... M.....	.....	CB..... 32-X..	XX..... CB..... 32-X.. M.....	.....	.....	.....	
6, drilling, nature of hole and effect on drill	XX..... 32-X..	R..... (a)	XX..... 32-X.. M-2....	XX..... 32-X.. 15..... M..... M-2....	20.....	R.....	X..... CB..... 21-D.. 20..... P.....	
7, screw thread tapping, $\frac{1}{2}$ inch, 20-thread	R.....	.....	XX.....	(b)	R.....	.....	(b)	
8, splitting, drilling and tapping parallel to laminations	(b)	XX..... 323... M-2.... 20.....	323....	.....	(b)	.....	(b)	
9, planing, to determine degree of splitting	20.....	CB.....	CB.....	CB..... 21-D.. R.....	20.....	(b)	(b)	

^a Others about equal.^b All about equal.

9. THERMAL EXPANSIVITY

An extended study was made of these materials with a view to determining their applicability for use in instruments of high precision which may be subjected to temperature variations.

The accompanying representative curves (Figs. 52 and 53) are self-explanatory and in general show the tendency of contraction at constant temperature (above 60° C) of any of the materials dealt with in this paper. Similar curves are given for many other samples of laminated phenolic materials in Bureau of Standards Scientific Paper No. 352, "Thermal Expansion of Insulating Materials," by Wilmer H. Souder and Peter Hidnert. In most

FIG. 52.—Expansion of Bakelite-Dilecto, grade XX

FIG. 53.—Expansion of hard rubber

cases, after cooling to room temperature, these materials show a marked diminution in length. The numbers near the circles represent the order of the observations. The time elapsing between consecutive observations is indicated. When the time is less than one hour (except at critical temperatures) it is not indicated.

TABLE 17.—Summary of the Coefficients of Expansion Obtained on Various Samples of Phenolic Electrical Insulating Material

B. S. number	Material	Sample heated in—	Average coefficients $\times 10^6$
S446.....	Bakelite-Dilecto (black, XX grade).....	Air furnace.....	22 between 20 and 60° C
S447.....	do.....	Oil bath.....	36 between 30 and 100° C
S448.....	Bakelite-Dilecto (natural, XX grade).....	Air furnace.....	26 between 25 and 60° C
S449.....	do.....	Oil bath.....	28 between 30 and 100° C
S439.....	Bakelite-Dilecto (XX grade).....	Air furnace.....	21 between 25 and 50° C
S440.....	Bakelite Micarta (32-X grade).....	do.....	33 between 25 and 50° C
S441.....	Bakelite Micarta (323 grade).....	do.....	29 between 25 and 50° C
S451.....	Continental-Bakelite (CB grade).....	do.....	(a)
S450.....	do.....	Oil bath.....	31 between 25 and 60° C
S432.....	Formica (grade M) ^b	do.....	33 between 20 and 60° C
S433.....	do. ^b	Air furnace.....	30 between 20 and 60° C
S434.....	do. ^b	Oil bath.....	20 between 20 and 60° C
S435.....	do. ^b	Air furnace.....	14 between 20 and 60° C
S508.....	Hard rubber (rod).....	do.....	80 between 20 and 60° C

^a Expansion very irregular.

^b Nos. S432 and S433 were cut perpendicular to Nos. S434 and S435.

Most of these materials when kept at some constant temperature above 60° C shrink in length and lose weight (give off vapors). When the temperature of the material increases, it expands; but when kept at a constant temperature above 60° C it contracts.

The following table gives the maximum temperatures to which the specimens were heated and the changes in weight and in length after the test. The plus (+) sign indicates a gain in weight or length and the minus (−) sign a diminution in weight or length.

TABLE 18.—Showing the Percentage of Change in Weight and Length of 14 Samples of Phenolic Electrical Insulating Material When Surrounded with Heated Air or Oil

B. S. number	Material	Sample heated in—	Maximum temperature	Change in weight after test	Change in length after test
			° C	Per cent	Per cent
S446.	Bakelite-Dilecto (black, XX grade).....	Air furnace.....	172	-6.3	-0.4
S447.	do.....	Oil bath.....	147	-0.1	-0.2
S448.	Bakelite-Dilecto (natural, XX grade).....	Air furnace.....	191	-2.8	-0.2
S449.	do.....	Oil bath.....	175	-0.3	-0.2
S439.	Bakelite-Dilecto (XX grade) ^a	Air furnace.....	253	-20.4	-1.5
S440.	Bakelite Micarta (32-X grade).....	do.....	195	-2.7	-0.4
S441.	Bakelite Micarta (323 grade) ^a	do.....	246	-27.6	-4.0
S451.	Continental-Bakelite (CB grade).....	do.....	170	-2.0	-0.1
S450.	do.....	Oil bath.....	160	+0.1	-0.2
S432.	Formica (grade M).....	do.....	60	+0.2	-0.01
S433.	do.....	Air furnace.....	79	-0.6	-0.14
S434.	do.....	Oil bath.....	61	+0.2	0.00
S435.	do.....	Air furnace.....	66	-0.3	-0.03
S508.	Hard rubber.....	do.....	100	-0.1	-0.8

^a After test, specimen was found warped, cracked on sides, and blistered on upper and lower surfaces.

From a study of the work on these materials it is evident that the length is a function of the temperature, medium in which the material is heated (air or oil), time, rapidity of heating or cooling, etc.

10. EFFECTS OF CHEMICALS

TABLE 19.—Change in Weight and Surface Hardness Owing to Submerging Phenolic Electrical Insulating Material in a 22 Per Cent (by Weight) Solution of Sulphuric Acid for 48 Hours

B. S. sample number	Material	Grade	Weight in air before submerging in solution	Weight in air after 24 hours out of solution	Change in weight	Weight in air after 48 hours out of solution	Change in weight	Final change in weight	Surface hardness (Bri- nell, pressure, 500 kg)	
									Before immersion	After immersion
59.....	Bakelite-Dilecto.....	XX.....	Grams 84.212	Grams 84.319	Grams 0.107	Grams 84.321	Grams 0.109	Per cent 0.129	41.0	36.0
251.....	do.....	XX.....	85.835	85.964	.129	85.964	.129	.146	37.0	37.0
163.....	do.....	XX.....	84.504	84.607	.103	84.614	.110	.130	39.0	38.0
62.....	do.....	X.....	83.536	84.334	.798	84.326	.790	.947	24.9	18.6
175.....	Continental-Bakelite.....	CB.....	78.336	79.670	1.334	79.669	1.333	1.700	30.4	31.2
21.....	Bakelite Micarta.....	32-X.....	87.577	87.700	.123	87.700	.123	.1405	38.0	38.0
253.....	do.....	32-X.....	84.376	84.481	.105	84.481	.105	.1240	37.0	37.0
149.....	do.....	21-X.....	82.962	83.108	.126	83.109	.127	.1530	34.5	34.5
27.....	do.....	323.....	87.950	88.403	.453	88.389	.439	.5000	37.0	19.3
255.....	do.....	323.....	83.752	84.006	.254	83.998	.246	.2940	37.0	32.6
153.....	do.....	213.....	85.420	85.649	.229	85.647	.227	.2660	37.0	34.5
184.....	do.....	21-D.....	90.698	91.129	.431	91.122	.424	.4670	32.6	33.6
189.....	Condensite Celoron.....	15.....	86.611	88.839	.228	88.839	.228	.257	38.0	36.0
144.....	do.....	15.....	89.250	89.379	.129	89.379	.129	.144	34.5	35.0
219.....	do.....	10.....	106.235	106.954	.719	106.942	.707	.666	30.4	28.4
161.....	do.....	10.....	97.570	97.724	.154	97.723	.153	.157	32.6	32.6
8-0.....	Formica.....	M.....	88.812	88.955	.143	88.957	.145	.163	38.0	36.0
214.....	do.....	M.....	85.520	85.638	.118	85.639	.119	.139	40.0	36.0
107.....	do.....	M.....	83.434	83.524	.090	83.526	.092	.110	45.0	40.0
115.....	do.....	M.....	85.354	85.475	.121	85.477	.123	.144	36.0	35.0
243.....	do.....	M.....	83.728	83.820	.092	83.822	.094	.112	48.0	46.0
216.....	do.....	M-2.....	83.105	83.279	.174	83.279	.174	.210	37.0	34.5
118.....	do.....	M-2.....	84.169	84.221	.052	84.222	.053	.063	49.0	49.0
54.....	do.....	M-2.....	86.202	86.279	.077	86.279	.077	.089	46.0	46.0
52.....	do.....	M-2.....	87.904	88.035	.131	88.038	.134	.152	44.0	43.0
215.....	do.....	P.....	88.759	89.286	.527	89.273	.514	.580	37.0	29.1
55.....	do.....	P.....	90.990	91.587	.597	91.575	.585	.644	38.0	22.3
174.....	do.....	R.....	86.722	87.066	.344	87.053	.331	.382	35.0	35.0

TABLE 20.—Change in Weight and Surface Hardness Owing to Submerging Phenolic Electrical Insulating Material in a 17 Per cent (by Weight) Solution of Sodium Hydroxide for 48 Hours

B. S. sample number	Material	Grade	Weight in air before submerg- ing in solution	Weight in air after 24 hours out of solution	Change in weight Grams	Weight in air after 48 hours out of solution	Change in weight Grams	Final change in weight Per cent	Surface hardness	
									Before immersion (Brinell, 500 kg. pressure)	After immersion (Brinell, 250 kg. pressure)
59.....	Bakelite-Dilecto.....	XX.....	84.661	87.880	3.219	87.438	2.777	3.28	40.0	20.00
251.....	do.....	XX.....	85.184	87.824	2.640	87.746	2.562	3.00	36.0	18.00
163.....	do.....	XX.....	83.234	85.046	1.812	84.951	1.717	2.06	41.0	20.50
62.....	do.....	X.....	83.573	91.230	7.757	90.273	6.700	8.02	28.5	14.25
175.....	Continental-Bakelite.....	CB.....	78.928	87.814	8.986	82.887	3.959	5.01	30.1	15.05
21.....	Bakelite Micarta.....	32-X.....	87.052	90.561	3.509	90.443	3.391	3.89	38.0	19.50
253.....	do.....	37-X.....	82.821	87.247	5.426	87.130	4.309	5.20	34.5	17.25
149.....	do.....	21-X.....	85.460	88.751	3.291	88.568	3.208	3.75	38.0	19.00
27.....	do.....	323.....	87.573	96.151	8.578	95.998	7.525	8.60	37.0	18.00
255.....	do.....	323.....	83.802	91.948	8.146	90.633	6.831	8.13	36.0	18.00
153.....	do.....	213.....	85.225	88.770	3.545	88.561	3.436	4.03	37.0	18.00
184.....	do.....	21-D.....	89.396	93.354	3.958	93.365	3.969	4.71	29.1	14.55
144.....	Condensite Celoron.....	15.....	90.397	93.087	2.690	92.641	2.244	2.48	37.0	18.5
189.....	do.....	15.....	89.660	93.110	3.450	92.769	3.109	3.56	36.0	18.0
219.....	do.....	10.....	106.088	107.543	1.455	107.467	1.379	1.29	29.1	14.5
161.....	do.....	10.....	95.873	98.869	2.996	98.755	2.882	3.01	28.4	14.2
8-0.....	Formica.....	M.....	88.669	92.583	3.914	92.112	3.443	3.88	37.0	18.5
214.....	do.....	M.....	84.015	88.079	4.064	87.819	3.804	4.53	45.0	22.5
107.....	do.....	M.....	83.870	85.789	1.919	85.768	1.898	2.26	45.0	22.5
115.....	do.....	M.....	82.906	87.955	5.049	87.161	4.255	5.13	37.0	18.5
243.....	do.....	M.....	84.080	87.084	3.004	87.534	3.454	4.07	48.0	24.0
216.....	do.....	M-2.....	83.080	89.112	6.032	88.136	5.056	6.04	38.0	19.0
118.....	do.....	M-2.....	84.043	90.206	6.163	89.529	5.486	6.51	49.0	24.5
54.....	do.....	M-2.....	85.953	89.470	3.517	89.163	3.210	3.74	46.0	23.0
52.....	do.....	M-2.....	87.870	91.436	3.560	91.076	3.206	3.65	27.2	13.6
215.....	do.....	P.....	88.815	94.076	5.261	93.808	4.993	5.51	37.0	18.5
55.....	do.....	P.....	90.611	96.067	5.456	95.472	4.861	5.36	38.0	19.0
174.....	do.....	R.....	86.522	89.941	3.419	89.742	3.220	3.72	36.6	13.3

11. SUMMARIES OF PROPERTIES

The following summaries are obtained as averages of the data on the various properties of the laminated phenolic materials as given in section IV-1. This separates the various properties recorded on pages 524 to 533 and shows the average of data on each property as determined at the Bureau of Standards. Since the properties of most of the laminated phenolic materials vary from sample to sample, the average value would be more practical for general use. In some of the data tables a column of per cent variation appears. These values are obtained by computing the average per cent variation from the average.

TABLE 21.—Average Values of Volume Resistivity of 15 Grades of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Volume resistivity ohm-cm $\times 10^8$
		Inch	cm	
Bakelite-Dilecto.....	XX.....	$\frac{1}{4}$	0.64	18 000
		$\frac{3}{8}$	.95	12 000
		$\frac{1}{2}$	1.27	26 000
	X.....	$\frac{1}{4}$	.64	130 000
		$\frac{3}{8}$	.95	790 000
		$\frac{1}{2}$	1.27	640 000
Continental-Bakelite.....	CB.....	$\frac{1}{4}$	.64	200
Bakelite Micarta.....	32-X and 21-X.....	$\frac{1}{4}$	.64	12 000
		$\frac{3}{8}$	.95	15 000
		$\frac{1}{2}$	1.27	990
	323 and 213.....	$\frac{1}{4}$	.64	48 000
		$\frac{3}{8}$	.95	530
	21-D.....	$\frac{1}{2}$	1.27	41 000
Condensite Celoron.....	10 and 15.....	$\frac{1}{4}$	.64	4 400
		$\frac{1}{2}$	1.27	26 000
	20.....	$\frac{1}{4}$	.64	63
Formica.....	M.....	$\frac{1}{4}$	.64	5 000
		$\frac{3}{8}$	.95	270
		$\frac{1}{2}$	1.27	1 300
	M-2.....	$\frac{1}{4}$	.64	25
		$\frac{3}{8}$	.95	20
		$\frac{1}{2}$	1.27	710
	P.....	$\frac{1}{4}$	.64	90
		$\frac{3}{8}$	.95	600
	R.....	$\frac{1}{2}$	1.27	2 000
		$\frac{1}{4}$	.64	60

TABLE 22.—Average Values of Surface Resistivity at three Humidities of 15 Grades of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Surface resistivity at relative humidity of—		
				24 per cent	50 per cent	84 per cent
		Inch.	cm	Ohms ×10 ⁸	Ohms ×10 ⁸	Ohms ×10 ⁸
Bakelite-Dilecto.....	XX.....	1/4	0.64	89 000	2400	8
		5/8	.95	14 600	4700	14
		1/2	1.27	13 000	4600	120
	X.....	1/4	.64	4 300	2900	6
		5/8	.95	840 000	6600	9
		1/2	1.27	490 000	2600	4
Continental-Bakelite.....	CB.....	1/4	.64	100	9	1
Bakelite Micarta.....	32-X and 21-X.....	1/4	.64	7 100	1900	37
		5/8	.95	1 000	300	9
		1/2	1.27	1 900	520	21
	323 and 213.....	1/4	.64	14 000	4000	16
		5/8	.95	6 500	100	2
		1/2	1.27	11 000	4100	71
Condensite Celoron.....	21-D.....	1/4	1.27	580	130	3
		1/4	.64	14 000	1100	59
		1/2	1.27	11 000	3500	96
Formica.....	20.....	1/4	.64	1 800	280	13
	M.....	1/4	.64	980	270	16
		5/8	.95	260	98	3
		1/2	1.27	560	120	10
	M-2.....	1/4	.64	100	15	2
		5/8	.95	240	71	3
		1/2	1.27	690	280	11
	P.....	1/4	.64	600	200	50
		5/8	.95	220	65	3
		1/2	1.27	1 200	640	50
	R.....	1/4	.64	340	220	80
		1/4	.64			

TABLE 23.—Showing the Effective Voltage Necessary to Arc Over the Surface of a Sample of Phenolic Electrical Insulating Material Between Two 2-cm Brass-Skirted Studs Bolted Through the Sample 2 cm Apart

Material	Grade	Thickness		Volts
		Inch	cm	
Bakelite-Dilecto.....	XX.....	1/4	0.64	19 800
	X.....	1/2	.64	19 800
Continental-Bakelite.....	CB.....	1/4	.64	21 100
Bakelite Micarta.....	32-X and 21-X.....	1/4	.64	20 000
	323 and 213.....	1/4	.64	19 700
	21-D.....	1/4	.64	22 000
Condensite Celoron.....	10 and 15.....	1/4	.64	21 000
	20.....	1/4	.64	27 800
Formica.....	M.....	1/4	.64	19 700
	M-2.....	1/4	.64	20 600
	P.....	1/4	.64	18 400
	R.....	1/4	.64	21 000

TABLE 24.—Average Values of Phase Difference and Power Factor at Radio Frequencies of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Phase difference (ψ)	Power factor
		Inch	cm	Degrees	Per cent
Bakelite-Dilecto.....	XX.....	$\frac{1}{8}$	0.32	2.0	3.4
		$\frac{1}{4}$	.64	2.0	3.6
		$\frac{3}{8}$	.95	2.1	3.7
		$\frac{1}{2}$	1.27	2.2	3.8
	X.....	$\frac{1}{4}$	.64	1.8	3.2
		$\frac{3}{8}$	.95	1.9	3.3
		$\frac{1}{2}$	1.27	1.9	3.3
Continental-Bakelite.....	CB.....	$\frac{1}{4}$	.64	3.8	6.6
Bakelite Micarta.....	32-X and 21-X.....	$\frac{1}{8}$	.32	2.8	4.8
		$\frac{1}{4}$	.64	3.0	5.2
		$\frac{3}{8}$	.95	3.5	6.1
		$\frac{1}{2}$	1.27	2.5	4.4
	323 and 213.....	$\frac{1}{8}$	.32	2.2	3.8
		$\frac{1}{4}$	.64	3.0	5.3
		$\frac{3}{8}$	.95	2.4	4.2
		$\frac{1}{2}$	1.27	2.1	3.5
	21-D.....	$\frac{1}{4}$	.64	5.4	9.5
		$\frac{3}{8}$	.95	4.8	8.4
		$\frac{1}{2}$	1.27	6.7	11.7
Condensite Celoron.....	10 and 15.....	$\frac{1}{8}$	.32	2.1	3.6
		$\frac{1}{4}$	.64	3.6	6.3
		$\frac{3}{8}$	.95	2.3	4.1
		$\frac{1}{2}$	1.27	3.7	6.5
	20.....	$\frac{1}{4}$	.64	6.3	11.0
Formica.....	M.....	$\frac{1}{8}$	.16	2.5	4.4
		$\frac{1}{8}$	.32	3.2	5.6
		$\frac{1}{4}$	.64	2.7	4.7
		$\frac{3}{8}$	.95	3.2	5.7
		$\frac{1}{2}$	1.27	3.2	5.6
		1	2.54	3.4	6.0
	M-2.....	$\frac{1}{4}$	.64	4.6	8.0
		$\frac{3}{8}$	.95	3.1	9.1
		$\frac{1}{2}$	1.27	3.4	5.9
	P.....	$\frac{1}{4}$	.64	3.7	6.5
		$\frac{3}{8}$	.95	2.6	4.5
		$\frac{1}{2}$	1.27	2.4	4.2
	R.....	$\frac{1}{2}$	1.27	2.4	4.2
		$\frac{1}{4}$	.64	4.5	7.9

TABLE 25.—Comparison of Average Phase Difference and Per Cent Power Factor of First Samples and More Recent Samples of Formica

Samples received	Approximate thickness		Average phase difference (ψ)	Average power factor
	Inch	cm	Degrees	Per cent
Early (1917-18).....	$\frac{1}{4}$	0.64	6.4	11.2
Do.....	$\frac{1}{2}$	1.27	3.6	6.3
Recently (1919).....	$\frac{1}{4}$	.64	2.5	4.4
Do.....	$\frac{1}{2}$	1.27	2.6	4.5

TABLE 26.—Average Values of Dielectric Constant at Radio Frequencies of Phenolic
Electrical Insulating Material

Material	Grade	Thickness		Dielectric constant (K)
		Inch	cm	
Bakelite-Dilecto.....	XX.....	$\frac{1}{8}$	0.32	4.5
		$\frac{1}{4}$	.64	5.3
		$\frac{3}{8}$	.95	5.3
		$\frac{1}{2}$	1.27	5.6
	X.....	$\frac{1}{4}$	.64	5.3
		$\frac{3}{8}$	.95	5.5
		$\frac{1}{2}$	1.27	5.6
Continental-Bakelite.....	CB.....	$\frac{1}{4}$	.64	5.3
Bakelite Micarta.....	32-X and 21-X.....	$\frac{1}{8}$	.32	5.4
		$\frac{1}{4}$	.64	5.8
		$\frac{3}{8}$	.95	5.9
		$\frac{1}{2}$	1.27	6.0
	323 and 213.....	$\frac{1}{8}$	.32	5.5
		$\frac{1}{4}$	.64	6.2
		$\frac{3}{8}$	.95	6.0
		$\frac{1}{2}$	1.27	6.0
	21-D.....	$\frac{1}{4}$	.64	6.6
		$\frac{3}{8}$	.95	6.7
		$\frac{1}{2}$	1.27	6.1
Condensite Celoron.....	10 and 15.....	$\frac{1}{8}$	.32	5.9
		$\frac{1}{4}$	.64	6.9
		$\frac{3}{8}$	.95	6.4
		$\frac{1}{2}$	1.27	7.2
	20.....	$\frac{1}{4}$	.64	6.8
Formica.....	M.....	$\frac{1}{8}$	.16	5.7
		$\frac{1}{4}$	.32	5.2
		$\frac{1}{4}$	.64	5.1
		$\frac{3}{8}$	.95	5.6
		$\frac{1}{2}$	1.27	5.8
		1	2.54	6.1
	M-2.....	$\frac{1}{4}$	.64	5.7
		$\frac{3}{8}$	.95	6.1
		$\frac{1}{2}$	1.27	5.5
	P.....	$\frac{1}{4}$	.64	6.0
		$\frac{3}{8}$	.95	5.8
	R.....	$\frac{1}{2}$	1.27	5.6
		$\frac{3}{4}$	.64	6.5

TABLE 27.—Average Values of Ultimate Strength and Modulus of Elasticity (Tensile) of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Ultimate strength	Vari- ation	Modu- lus of elas- ticity +1000	Vari- ation
		Inch	cm	Lbs./in. ²	Per cent	Lbs./in. ²	Per cent
Bakelite-Dilecto.....	XX.....	$\frac{1}{4}$	0.64	13 800	9	1510	
		$\frac{3}{8}$	.95	12 700	7		
		$\frac{1}{2}$	1.27	11 900	15		
		$\frac{3}{4}$	.64	15 500	25		
	X.....	$\frac{3}{8}$	.95	18 600	30	2120	26
		$\frac{1}{2}$	1.27	18 600	23	2120	41
		$\frac{3}{4}$	2.54	18 400	21	2060	32
		1					
Continental-Bakelite.....	CB.....	$\frac{1}{4}$	.64	9 400	8		
		$\frac{1}{2}$	1.27	8 000	1		
Bakelite Micarta.....	32-X and 21-X.....	$\frac{1}{4}$	.64	10 800	13		
		$\frac{3}{8}$	.95	11 000	12		
		$\frac{1}{2}$	1.27	10 900	14		
		$\frac{3}{4}$	.64	16 400	20		
	323 and 213.....	$\frac{3}{8}$	.95	16 500	16		
		$\frac{1}{2}$	1.27	16 800	11		
		$\frac{3}{4}$	.64	8 300	15		
	21-D.....	$\frac{1}{2}$	1.27	9 500	3		
		$\frac{3}{4}$					
		1					
Condensite Celoron.....	10 and 15.....	$\frac{1}{8}$	.32	11 200	33		
		$\frac{1}{4}$	.64	10 700	23		
		$\frac{3}{8}$	.95	11 100	34		
		$\frac{1}{2}$	1.27	11 500	25		
		$\frac{3}{4}$	3.02	17 300	0		
	20.....	$\frac{1}{4}$	.64	8 200	4		
		$\frac{1}{2}$	1.27	7 500	4		
		$\frac{3}{4}$					
		1					
Formica.....	M.....	$\frac{1}{4}$	.64	11 400	9		
		$\frac{3}{8}$	.95	14 200	4		
		$\frac{1}{2}$	1.27	12 200	11		
		$\frac{3}{4}$	.64	13 900	16	1720	
	M-2.....	$\frac{3}{8}$	.95	12 700	20		
		$\frac{1}{2}$	1.27	12 400	17	1730	4
		$\frac{3}{4}$	2.54	13 800	10	2410	17
		1					
	P.....	$\frac{1}{4}$	.64	18 300	35		
		$\frac{3}{8}$	.95	19 300	32		
		$\frac{1}{2}$	1.27	17 000	36	2260	33
		$\frac{3}{4}$	.64	10 400	4		
	R.....	$\frac{3}{8}$	.95	8 900	12		
		$\frac{1}{2}$	1.27	10 400	2		
		$\frac{3}{4}$					
		1					

TABLE 28.—Average Values of Modulus of Rupture and Modulus of Elasticity (Transverse) of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Modulus of rupture	Variation	Modulus of elasticity ÷ 1000	Variation	
		Inch	cm					
Bakelite-Dilecto	XX	$\frac{1}{4}$	0.64	16 600	7	1290	.....	
		$\frac{3}{8}$	.95	20 700	.....	1340	.....	
		$\frac{1}{2}$	1.27	16 600	4	.....	.....	
	X	$\frac{1}{4}$	.64	22 000	30	.....	.....	
		$\frac{3}{8}$	.95	24 500	26	2370	.....	
		$\frac{1}{2}$	1.27	21 600	.....	1440	.....	
Continental-Bakelite	CB	$\frac{1}{4}$	.64	13 800	2	.....	.....	
		$\frac{1}{2}$	1.27	13 500	.....	.....	.....	
Bakelite Micarta	32-X and 21-X	$\frac{1}{4}$	.64	16 200	10	1470	.....	
		$\frac{3}{8}$	.95	15 000	10	1050	.....	
		$\frac{1}{2}$	1.27	17 400	3	.....	.....	
	323 and 213	$\frac{1}{4}$	.64	20 600	14	2060	.....	
		$\frac{3}{8}$	.95	18 000	6	1150	.....	
		$\frac{1}{2}$	1.27	25 800	20	.....	.....	
	21-D	$\frac{1}{4}$	.64	14 100	2	.....	.....	
		$\frac{1}{2}$	1.27	13 700	6	.....	.....	
	Condensite Celoron	10 and 15	$\frac{1}{4}$	.64	15 500	20		
			$\frac{3}{8}$	.95	15 000	22		
$\frac{1}{2}$			1.27	15 200	38	.....	.....	
20		$\frac{1}{4}$	3.02	17 700	6	.....	.....	
		$\frac{1}{2}$	.64	12 000	0	.....	.....	
		$\frac{1}{2}$	1.27	10 200	18	.....	.....	
Formica	M	$\frac{1}{4}$	.64	16 800	9	1120	.....	
		$\frac{3}{8}$	.95	18 300	12	1420	.....	
		$\frac{1}{2}$	1.27	18 100	3	.....	.....	
	M-2	$\frac{1}{4}$	.64	17 000	15	1480	.....	
		$\frac{1}{2}$	1.27	17 700	16	1380	5	
	P	$\frac{1}{4}$	.64	18 800	4	.....	.....	
		$\frac{3}{8}$	.95	24 300	23	.....	.....	
		$\frac{1}{2}$	1.27	21 100	28	1410	.....	
	R	$\frac{1}{4}$	.64	14 000	5	.....	.....	
		$\frac{3}{8}$	.95	14 500	9	.....	.....	
		$\frac{1}{2}$	1.27	16 800	4	.....	.....	

TABLE 29.—Average Values of Brinell Hardness Numerals of Phenolic Electrical Insulating Material Tested at Two Temperatures

Material	Grade	Thickness		Brinell hardness numerals tested at—	
				20-30° C	50° C
Bakelite-Dilecto.....	XX.....	Inch	cm		
		$\frac{3}{8}$	0.95	42	37
	X.....	$\frac{1}{2}$	1.27	40	39
		$\frac{3}{8}$	.95	34	31
Continental-Bakelite.....	CB.....	$\frac{1}{2}$	1.27	23	20
		$\frac{1}{2}$	1.27	32	30
Bakelite Micarta.....	32-X and 21-X.....	$\frac{3}{8}$	.95	39	34
		$\frac{1}{2}$	1.27	39	34
	323 and 213.....	$\frac{3}{8}$	.95	35	33
		$\frac{1}{2}$	1.27	34	30
Condensite Celoron.....	21-D.....	$\frac{1}{2}$	1.27	37	32
		$\frac{1}{2}$	1.27	38	35
	10 and 15.....	$\frac{1}{2}$	1.27	38	32
		$\frac{1}{2}$	1.27	38	32
Formica.....	M.....	$\frac{3}{8}$	.95	35	33
		$\frac{1}{2}$	1.27	37	34
	M-2.....	$\frac{3}{8}$	.95	44	40
		$\frac{1}{2}$	1.27	45	42
	P.....	$\frac{1}{2}$	1.27	38	34
		$\frac{1}{2}$	1.27	39	34
	R.....	$\frac{1}{2}$	1.27	39	34
		$\frac{1}{2}$	1.27	39	34

TABLE 30.—Average Values of Scleroscope Hardness of Phenolic Electrical Insulating Material Tested at Two Temperatures

Material	Grade	Thickness		Scleroscope hardness tested at—	
				20–30° C	50° C
		Inch	cm		
Bakelite-Dilecto.....	XX.....	$\frac{3}{8}$	0.95	88	83
		$\frac{1}{2}$	1.27	87	83
	X.....	$\frac{3}{8}$	.95	73	65
Continental-Bakelite.....		$\frac{1}{2}$	1.27	64	63
	CB.....	$\frac{1}{2}$	1.27	58	58
Bakelite Micarta.....	32-X and 21-X.....	$\frac{1}{2}$	1.27	83	80
	323 and 213.....	$\frac{3}{8}$	.95	83	78
		$\frac{1}{2}$	1.27	79	75
	21-D.....	$\frac{1}{2}$	1.27	75	70
Condensite Celoron.....	10 and 15.....	$\frac{1}{2}$	1.27	86	82
	20.....	$\frac{1}{2}$	1.27	87	82
	30.....	$\frac{3}{4}$	.64	75	74
Formica.....	M.....	$\frac{3}{8}$	.95	84	80
		$\frac{1}{2}$	1.27	85	79
	M-2.....	$\frac{3}{8}$	.95	94	93
		$\frac{1}{2}$	1.27	86	85
	P.....	$\frac{1}{2}$	1.27	86	82
	R.....	$\frac{1}{2}$	1.27	70	64

TABLE 31.—Average Values of Resistance to Impact, Expressed in Foot-Pounds, of Phenolic Electrical Insulating Material as Determined by the Use of Standard, Square, Notched Specimens

Material	Grade	Thickness		Impact strength
		Inch	cm	Ft.-lbs.
Bakelite-Dilecto.....	XX.....	$\frac{1}{2}$	1.27	0.7
	X.....	$\frac{1}{2}$	1.27	.9
Continental-Bakelite.....	CB.....	$\frac{1}{2}$	1.27	1.2
Bakelite Micarta.....	32-X and 21-X.....	$\frac{1}{2}$	1.27	.2
	323 and 213.....	$\frac{1}{2}$	1.27	.8
	21-D.....	$\frac{1}{2}$	1.27	2.1
Condensite Celoron.....	10 and 15.....	$\frac{1}{2}$	1.27	.4
	20.....	$\frac{1}{2}$	1.27	1.0
Formica.....	M.....	$\frac{1}{2}$	1.27	.3
	M-2.....	$\frac{1}{2}$	1.27	.3
	P.....	$\frac{1}{2}$	1.27	1.5
		$\frac{1}{2}$	1.27	2.9
	R.....	$\frac{1}{2}$	1.27	2.9

TABLE 32.—Average Value of density of and Percentage by Weight of Moisture Absorbed in 24 Hours by Phenolic Electrical Insulating Material

Material	Grade	Thickness		Density	Water absorbed in 24 hours
		Inch	cm		Percent- age by weight
Bakelite-Dilecto	XX.....	$\frac{1}{4}$	0.64	1.34	0.30
		$\frac{3}{8}$	.95	1.34	.17
		$\frac{1}{2}$	1.27	1.36	.16
	X.....	$\frac{1}{4}$	.64	1.34	2.35
		$\frac{3}{8}$	.95	1.37	.74
		$\frac{1}{2}$	1.27	1.31	2.20
Continental-Bakelite.....	CB.....	$\frac{1}{4}$	.64	1.32	.46
		$\frac{1}{2}$	1.27	1.29	.52
Bakelite Micarta.....	32-X and 21-X.....	$\frac{1}{4}$	.64	1.36	.38
		$\frac{3}{8}$	.95	1.34	.38
		$\frac{1}{2}$	1.27	1.36	.24
	323 and 213.....	$\frac{1}{4}$	.64	1.37	1.09
		$\frac{3}{8}$	.95	1.37	.89
		$\frac{1}{2}$	1.27	1.37	.67
Condensite Celoron.....	21-D.....	$\frac{1}{4}$	.64	1.36	1.09
		$\frac{3}{8}$	.95	1.36	.74
		$\frac{1}{2}$	1.27	1.36	
	10 and 15.....	$\frac{1}{4}$	.64	1.40	.32
		$\frac{3}{8}$	.95	1.43	.24
		$\frac{1}{2}$	1.27	1.41	.22
Formica.....	20.....	$\frac{1}{4}$	.64	1.34	.32
		$\frac{3}{8}$	.95	1.35	.46
		$\frac{1}{2}$	1.27	1.35	
	M.....	$\frac{1}{4}$	.64	1.36	.39
		$\frac{3}{8}$	.95	1.37	.21
		$\frac{1}{2}$	1.27	1.35	.19
	M-2.....	$\frac{1}{4}$	.64	1.34	.52
		$\frac{3}{8}$	.95	1.33	.76
		$\frac{1}{2}$	1.27	1.36	.20
	P.....	$\frac{1}{4}$	.64	1.38	.77
		$\frac{3}{8}$	.95	1.41	.53
		$\frac{1}{2}$	1.27	1.35	.52
	R.....	$\frac{1}{4}$	.64	1.38	1.47
		$\frac{3}{8}$	.95	1.37	1.38
		$\frac{1}{2}$	1.27	1.39	.81

V. DISCUSSION OF RESULTS

1. UNIFORMITY OF PROPERTIES

SAMPLE TO SAMPLE.—Variations in electrical and other properties of materials of the same manufacture and grades are clearly shown in the tabulated data on pages 524 to 533. In some cases these variations are by no means unimportant. The causes of these variations are not easily traced. Variations in electrical and other properties of these insulating materials may be due to variations in the phenolic varnish, the paper, the atmospheric conditions at the time of manufacture, or the way the material is handled during manufacture.

SAMPLES SUBMITTED VS. SAMPLES PURCHASED.—It has been gratifying to find that, in general, the samples of laminated phenolic materials purchased in the open market have checked quite closely in electrical and other properties the samples submitted by the various companies. In one instance a sheet of

laminated material was purchased from a Washington firm, who sold the sheet as Bakelite Micarta, grade 21-X. Our tests showed quite clearly that this sheet was grade 213 Bakelite Micarta. This emphasizes the fact previously pointed out that the purchaser can not determine the grade of the material from appearance.

Sheets of Formica, grade M, which were purchased for laboratory use about this Bureau, have, in general, shown electrical properties rather better than the samples furnished by the manufacturer for testing.

UNIFORMITY OF SHEET.—Tests of the uniformity of a sheet of material were made by measuring the volume resistivity of pieces cut from various parts of the sheet. The results are given on page 598. Similar tests were made on phase difference. This was measured for a piece taken from the center and opposite corners of a sheet taken from stock, B. S. No. 20-256, Formica M. Pieces 25 by 31 cm (10 by 12 inches) were cut from sheet 61 by 92 cm (24 by 36 inches).

TABLE 33.—Phase Difference and Dielectric Constant of Three Portions of a Standard Size (24 by 36 inches) Sheet of Formica, Grade M

Portion of sheet from which sample was taken	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)
	Meters	Degrees	
Center.....	1021	1.77	4.71
	1395	1.73	4.74
	1925	1.70	4.77
Corner.....	1015	1.77	4.67
	1388	1.79	4.70
	1919	1.70	4.74
Diagonally opposite corner.....	1017	1.83	4.68
	1390	1.84	4.70
	1920	1.79	4.74

The variations are somewhat greater than the limit of error of the measurement.

2. PHASE DIFFERENCE

On page 512 several reasons were shown why power factor or phase difference at radio frequencies was given special emphasis among the properties measured. To one interested in the development or correct use of an insulating material to be subjected to radio-frequency voltages, the phase difference probably furnishes the best single basis for judgment of such material.

Because all measures of phase difference have been made on a temporarily constructed condenser using the insulating material as a solid dielectric, it is not to be inferred that such materials are actually used for radio condensers or recommended for such use. However, when a solid insulating material is used as a

means of supporting and insulating binding posts, contacts, or wires carrying alternating current, there is in reality a condenser or series of condensers between these conducting pieces with the insulating material as the dielectric. A relatively poor insulating material for radio use is a material that adds resistance to a circuit and causes power loss. For this reason it is of value to have experimental data that will determine the relative superiority of materials in respect to power loss.

In the equation $P=RI^2$, the equivalent resistance (R) of a sample is equal to the watt loss (P) per ampere. However, (R) is not a constant of the material, since it varies with frequency and with the size and shape of the specimen.

Phase difference or power factor assists also in an understanding of some other radio properties of an insulating material. Formula 1 states that phase difference may be expressed as a ratio of the power dissipated in the form of heat to the total power flowing. The effect of the energy lost as heat is cumulative. The initial heating lowers the electrical resistance of the insulating material, this causing greater current conduction and increased heating. Thus, when high voltage are used, the insulating material gradually becomes conductive and a flash-over or breakdown occurs. The phase difference, a property which expresses the heating of the material, is the most important single property in determining the radio-frequency current and voltage that an insulating specimen will stand. It indicates in a comparative way which material should stand longest under high electrical stress. This is discussed further in section V-3, "Voltage effects at radio frequencies."

EFFECT OF METAL PARTICLES IN MATERIAL.—In comparing some values of phase difference obtained on three samples of laminated phenolic insulating materials of the same grade received at the same time surprising differences of properties in the different thicknesses were observed. The following is a statement of results on the three samples:

TABLE 34.—Effect of Metal Particles in Material

Approximate thickness		Average phase difference (ψ)
cm	Inch	Degrees
0.34	$\frac{1}{8}$	3.6
.65	$\frac{1}{4}$	2.2
.98	$\frac{3}{8}$	2.1

It seemed strange that the first two samples should differ so much, in view of the fact that they were the same grade, made under same conditions, and presumably differed in thickness only. Ordinarily the thinner sheets show a lower phase difference or power loss. After close inspection, however, it was found that many small metallic particles had found their way into the material. It seemed probable that these were sufficient to cause the unusually high phase difference. They may have been present in the particular batch of paper used in making up this sheet of material.

3. VOLTAGE EFFECTS AT RADIO FREQUENCIES

The methods of measuring the radio-frequency flash-over voltage and other voltage effects at radio frequencies upon the various insulating materials have not been worked out as completely as the method of measuring phase difference. It is hoped that more work can be done at this in the future. The results given on page 549 show some differences, although not great, in the makes and grades of material. The data also show a difference in flash-over voltage with time of test. This seems to be another effect of surface-absorbed moisture.

Flash-over voltage is dependent upon the nature of the material, character of the surface, and the shape, size, and spacing of the contacts. Besides the measurements of flash-over voltage, the materials were tested for endurance voltage, as described in a Bureau publication mentioned on page 506. As explained there, the measurements of endurance voltage can not be so readily presented nor interpreted as the flash-over voltage, and hence are not included in this paper. The results run quite parallel to those in flash-over voltage and are a fairly good index of the voltage properties in general.

Measurements of breakdown voltage at radio frequencies were not made in any systematic way. This occurs at very much lower voltages than for low frequencies. The breakdown voltage is of less practical importance than flash-over voltage, since the metal parts on insulating panels in radio apparatus are usually so placed that high voltage will produce failure across the surface rather than through the material.

Breakdown voltages, and to a somewhat smaller extent all the voltage effects at radio frequencies, are a function of the heating of the insulating material. The failure of the insulation is usually not a definite puncture but is instead a loss of insulating and

dielectric properties. That is, the material heats up and becomes a conductor, so that it no longer functions as a dielectric. This research has shown that a simple statement of voltage for breakdown or any other effect at radio frequencies is meaningless without accompanying specification of a number of other factors. The experiments made indeed indicate that the phase difference is fully as good a criterion of the breakdown point as a single value of voltage. The fact is that the phenomenon of breakdown depends on the dielectric constant, phase difference, thermal conductivity, specific heat, temperature at which material carbonizes, disintegrates, and melts, as well as frequency, voltage, and time of application. The breakdown voltage differs for different shape and size of sample, shape, size, and location of electrodes, frequency, time of application of voltage, and characteristics of the source supplying the voltage. It depends very largely upon the phase difference, because for a given voltage the heat produced in the material is greater the greater the phase difference, and consequently the more rapidly does the material heat and a failure occur for a given applied voltage. Materials which have high phase difference generally show low values in the voltage tests.

4. VOLUME RESISTIVITY

The values of volume resistivity of the laminated phenolic insulating materials vary widely also—that is, different samples of the same grade in some cases vary by a factor of about 100 in volume resistivity values. Rather wide variations were also found when measurements were made at different places on a comparatively large sample. The sketch and results below show this:

FIG. 54.—Diagram of places where volume resistivity measurements were made on a sample 25 by 31 cm

TABLE 35.—Volume Resistivity Values^a at Five Positions on a 25 by 31 cm sample of Phenolic Electrical Insulating Material

Position	Volume resistivity
	Ohm-cm ×10 ⁸
1.....	500
2.....	130
3.....	130
4.....	680
5.....	300

^a All volume resistivity measurements were made at room temperature and humidity.

5. SURFACE RESISTIVITY

The curves shown on pages 550 to 561 were plotted from the data given in the summary tables on pages 524 to 533. The dates of tests recorded in column 5 apply only to the data in columns 6 to 11, inclusive. However, the resistivity data in the table are recorded chronologically. That is to say, where two or more resistivity measurements have been made on the same sample, the values appear in the summary table in chronological order.

Only a few of the first curves shown will be discussed here. The curves for B. S. sample No. 164 (Fig. 29, p. 551) are rather uniform. Two test samples (A and B) were cut from the same sheet and tested twice (about 50 days apart). The earlier data are represented by the two upper curves. The curves for B. S. samples Nos. 61 and 62 (Fig. 28, p. 550) represent data taken about one year apart, the upper curves being for the earlier data. In fact, in all cases where the same sample has been tested twice, the earlier surface resistivity values are the higher. This can be ascertained by comparing the curves and the data on pages 524 to 533.

By comparing the upper curves (Fig. 28, p. 550) for B. S. samples Nos. 61 and 62 it might appear that Bakelite-Dilecto, grade X, was equivalent to hard rubber (see Fig. 39, p. 561) in surface resistivity. However, if the average values of surface resistivity of hard rubber at a 25 per cent humidity be compared with a similar average on the Bakelite-Dilecto, the hard rubber will show a much higher value, in the ratio of about 10^{15} to 10^{12} . At 84 per cent humidity the ratio of surface resistivity of hard rubber to the X grade, Bakelite-Dilecto sample, is about 3×10^{10} to 1×10^8 .

Some of the second-grade samples (Bakelite-Dilecto, X, and Bakelite Micarta, 323 and 213) show a higher surface resistivity at the lower humidities than the first grades. This may be owing

to the smaller percentage of varnish in the second-grade materials or to the slightly rougher surfaces on such grades.

A table of average values of surface resistivity of the various kinds, grades, and thicknesses of laminated phenolic insulating material is given on page 587. It is evident from these data that the surface resistivity of a particular grade of material varies within wide limits. The following table shows the observed range of variation:

TABLE 36.—Range of Variation in per cent from the Lowest to the Highest Value of Surface Resistivity at 25 per cent Relative Humidity for Phenolic Electrical Insulating Material Irrespective of Thickness

Material	Grade	Variation
		Per cent
Bakelite-Dilecto.....	XX.....	680
	X.....	11 000
Bakelite Micarta.....	32-X and 21-X.....	700
	323 and 213.....	210
Condensite Celoron.....	10 and 15.....	130
Formica.....	M.....	380
	M-2.....	690
	P.....	550

6. MOISTURE ABSORPTION.

The effect of moisture contained in or absorbed by an insulating material is now considered very carefully. The effect on permanence of shape and mechanical properties may be temporarily disregarded for the more serious effect on insulation resistance and power loss.

By referring to the itemized data on pages 524 to 533 or to the summary tables on page 593, one can see the different amounts of water absorbed by the materials of different grade. As an example, the average per cent of water absorbed by a sample of Bakelite-Dilecto, grade XX, 5 by 10 by 0.64 cm, is 0.30. The amount absorbed by a sample of the same dimensions but of grade X is 2.35 per cent. The grade XX material is advertised to be made from paper saturated with Bakelite varnish and grade X from paper coated with the varnish. The data show less moisture to have been absorbed by the saturated paper material. This same comparison can be made between Bakelite Micarta, grades 32-X (21-X) and 323 (213), or between Formica, grades M and P. The other grades and kinds are not so readily compared because either the binder or filler (base), or both, may be different. Consult pages 508 and 509 for this difference.

The percentages of moisture absorbed by the different kinds and grades of material can not be compared directly unless samples of the same size and thickness are used. Where samples of the same grade are considered, it is evident, from most of the data given on page 593, that the percentage of moisture absorbed apparently decreases as the thickness increases. This is because the percentage values are based on weight and the weight of the samples does not increase in proportion to the absorbing area of samples of different thicknesses. Future measurements of moisture absorption expressed in grams per square centimeter of cut and uncut surface will be independent of sample size and thickness.

The impression that any of the laminated phenolic insulating materials are strictly nonhygroscopic is erroneous. One has only to oven dry a small piece of this material (5 by 5 by 0.64 cm) and try to weigh it in the open atmosphere by using a very sensitive chemical balance to determine this point. The dried sample immediately absorbs moisture (in minute quantities) from the air and renders a permanent balance difficult. If one weighs the sample before drying and compares that with some momentary dry weight, there is an evident loss in weight. If one claims that this loss in weight is due to passing off of vapors from continued chemical reaction, then the impression that such materials are unaffected by heat is erroneous. This is discussed more fully under "Thermal properties" below.

7. TENSILE STRENGTH

EFFECT OF GRAIN.—The apparent effect of the grain of the paper used in these insulating materials has been mentioned on page 511. The data given on pages 524 to 533 in the columns headed ultimate strength in most cases are followed by x or y. When the samples were cut from the large sheets, those cut in one direction were labeled x and those cut at a right angle to x were labeled y. It is practically impossible to know the direction of the grain of some of the materials before testing, so the labels x and y refer only to different directions of cutting. This explains why some of the x values are greater than the y values.

The data mentioned above shows a greater apparent effect of grain for those grades that are recommended for mechanical work. Such grades are designated in this report as second grade (see p. 617). There is a difference of from 30 to 100 per cent in the x and y data for these grades of material.

It is interesting to notice that the canvas base materials (see p. 590) do not have as great tensile strength as the paper or fiber base materials. This is contrary to the first beliefs of many. There is a quite apparent explanation of this lower strength in the fact that, although there is greater strength in a single canvas sheet than in a single paper sheet, a single sheet of canvas is so much thicker that in a built-up piece of canvas base insulating material there are fewer binding cellulose fibers in a given space than in the paper base material. The canvas base material does have greater resistance to impact. This is discussed in section V-10, page 604.

DUCTILITY.—The difficulty met in determining the elongation of the tensile test specimen under stress has been stated in the paper mentioned on page 506. Values of elongation are, therefore, not determined at more stresses than are sufficient to locate the proportional limit. The last points plotted in the curves on page 562, do not represent ultimate strength. By referring to these curves (Fig. 40) on page 562 one will notice that the greatest total elongation or deformation of any of the specimens is about 0.019 of an inch in 2 inches, while the average of the specimens plotted is about 0.013 of an inch in 2 inches.

8. TRANSVERSE STRENGTH

The method of making transverse or cross-bend strength tests on laminated insulating materials is described and illustrated in another Bureau publication mentioned on page 506.

The curves (Figs. 42 to 51, inclusive) on pages 564 to 573 were plotted from data obtained by the screw-press method of applying the load. The curves (Fig. 41) on page 563 differ from the curves shown in Figs. 42 to 51, in that in Fig. 41 fiber stress has been plotted against deflection instead of load in pounds against deflection. By plotting the data in this way the transverse proportional limit is obtained and is marked by the point at which the curve deviates from a straight line.

Not enough curves are shown here to give a complete comparison of the modulus of rupture or maximum fiber stress of all the materials. Curves on B. S. samples Nos. 18 and 24, 19 and 25, 20 and 26 show quite well the effect of grade on the modulus of rupture. One of each of the three pairs of samples is Bakelite Micarta, grade 32-X, the other being grade 323. As outlined on page 617, grade 323 is classed as second-grade material but

possesses better mechanical properties. It is interesting to notice also that the moduli of rupture of one-fourth inch Bakelite Micarta, grades 32-X and 323 (B. S. samples Nos. 19 and 25) are higher than the values for the corresponding grades in three-eighths inch thick material.

As stated above, the curves in Figs. 42 to 51 were plotted from data found by using the screw-press method of applying the load. From these particular curves it is not feasible to make an intercomparison of kinds and grades of insulating material except for shape of curve, because the samples were not all cut the same width. The actual load in pounds is plotted against deflection, so the area of cross section does not enter. If the actual moduli of rupture or moduli of elasticity values are desired on these samples, reference may be made to the tables on pages 524 to 533.

It is quite apparent that, by using the screw-press method of applying the load and a platform scale for determining the magnitude of the load, the measured load is entirely dependent on whether the sample sustains or yields under the applied load. This explains why some of the load-deflection curves for the canvas base materials run part of their course about parallel with or even approach the ordinate with an apparent increase in load. The curves for the paper and fiber base phenolic insulating materials have a much steeper curve throughout, being less flexible than the canvas base materials.

The first curve on Fig. 45 shows the effect of failure of the outer layers of canvas under tension. The sample finally broke under a load lower than the maximum load previous to the failure of the lower strata.

The curves on pages 570 to 573 (Figs. 48 to 51) were plotted from data obtained by suspending a known mass from the test sample midway between the supports and measuring the deflection at the center in inches. This method is called the dead-weight method here. In many ways it is superior to the screw-press method. The load is independent of the yielding of the sample under stress. This is shown by the fact that all curves by this method have a continuous and more or less gradual upward trend. It is impossible by this method to get a curve similar to the first curve in Fig. 45.

It is worthy of note that all of these curves for samples of like thickness are directly comparable, in that all samples were

machined quite accurately to the same width. It does not seem necessary to analyze particular curves in this group. The effect of grade on the magnitude of applied load at rupture and the effect of grade on the ultimate yield or deflection is quite clearly pictured. Reference is again made to the differentiation of grades on page 508. Attention is called to the first and third curves in Fig. 49, page 571. These samples were both more or less poorly laminated. The magnitude of the possible suspended load and computed modulus of rupture is correspondingly lowered.

9. HARDNESS

The hardness of the laminated phenolic insulating materials is mainly dependent on the amount of varnish (phenol condensation product) in the material and upon the press pressure and length of time the material is cured in the press. In the event one is considering sheet-asbestos-filled phenolic insulating materials, then it would be necessary to include filler as one of the factors influencing hardness. The effect of the various papers used may be neglected, however, in their bearing on hardness.

Hardness and brittleness are associated in some respects. Brittleness affects the impact strength or shock-absorbing property of a material. With this in mind, the impact strength data on Bakelite-Dilecto, grades XX and X, and Bakelite Micarta, grades 32-X and 323 (p. 592), seem to bear out the conclusion that the amount of phenol varnish affects hardness, other factors being equal. Grades XX and 32-X, which contain more varnish than grades X and 323, have lower impact strength values and higher hardness values than grades X and 323.

It is quite apparent that the press-pressure temperature and length of curing will affect the hardness of these materials, the effect of pressure being more apparent than temperature and duration of curing. A more complete chemical reaction caused by higher temperature and longer curing renders the phenolic varnish more hard and brittle.

The data on pages 524 to 533 and page 591 show that the Brinell hardness numerals of all the materials have been lowered somewhat by heating the material to 50° C. The values of hardness (B. h. n.) of the materials at 50° C are from 2 to about 16 per cent lower than at 20-30° C. This is in accord with the conclusions drawn in section V-13, page 607.

10. IMPACT STRENGTH

The determination of impact strength of insulating materials with our present equipment we have found rather difficult. The impact testing machines in our strength-of-materials laboratory are all designed for testing of metals. They are, therefore, of larger capacity than is advisable for the more brittle insulating materials. When the pendulum hammer was drawn to some workable angular distance from the position of rest, so much potential energy was stored in the pendulum hammer that when released the hammer would break the sample and swing too far beyond its position of equilibrium. More accurate results are obtained when the total kinetic energy of the pendulum hammer exceeds but little the energy absorbed by the sample during fracture.

The data shown on page 574 divides the phenolic insulating materials reported into three classes with respect to impact strength. The following classes are in the descending order of strength, and the grade names are alphabetical.

Class 1 contains Bakelite Micarta, grade 21-D; Condensite Celoron, grade 20; Continental-Bakelite; and Formica, grade R.

Class 2 contains Bakelite-Dilecto, grade X; Bakelite Micarta, grade 213; and Formica, grade P.

Class 3 contains Bakelite-Dilecto, grade XX; Bakelite Micarta, grades 21-X and 32-X; Condensite Celoron, grades 10 and 15; and Formica, grades M and M-2.

The above classification does not imply that the materials in a certain class have an equal impact strength, but that the several grades manufactured by each of the four companies when inter-compared fall into these classes.

It is interesting to notice that even by using testing machines having large capacity the grades of material having no dissimilarity, except that of color or kind of varnish, the values of impact strength are almost identical. Condensite Celoron, grades 10 and 15, and Formica, grades M and M-2, show this.

It has been mentioned in section V-7 above that the canvas-base materials have lower tensile strength than the paper or fiber base materials. The data on page 574 show, however, that the impact strength of the canvas-base material of a certain make is from 2.5 to 10 times as great as the grade having the best electrical properties in that same make. As an example, Bakelite Micarta, grade 21-D, has over 10 times greater impact strength

FIG. 55.—Test samples for determination of thermal expansion, tensile strength, transverse strength, permanent distortion, phase difference, high-voltage high-frequency endurance, surface resistivity, and moisture absorption

than grade 32-X. Likewise, Formica, grade R, has an impact strength almost 10 times higher than grade M. Because of this shock-absorbing property of the canvas-base materials and other good mechanical properties they find a ready use in the manufacture of pinions, racks, and other such parts.

11. PERMANENT DISTORTION

The data given on pages 575 and 576 on permanent distortion or warp under stress is not as complete or conclusive as we had hoped it would be. By referring to the method of determining permanent distortion as described in the Bureau publication mentioned on page 506 it will be seen that a complete test on the 52 samples would have required several months.

The various increments of added load were not small and numerous enough to plot curves that would show the relation of stress applied for a specified time to permanent distortion or deflection. However, the data do give a general idea of how strips of these phenolic insulating materials yield under the stress of a dead weight. No attempt will be made to show which manufacturer's material is the better in this respect. The data are not sufficient.

The data given on the sag of panels under stress are practical (see p. 577). They show that a three-eighths inch thick sample 18 by 24 inches when loaded between V blocks 22 inches apart is apparently perfectly elastic to about 400 pounds applied for 24 hours. A half-inch sample seemed perfectly elastic to about 600 pounds applied for 24 hours. The latter sample took a permanent set of 0.156 inch when a load of about 800 pounds was applied for 24 hours.

NATURAL WARP.—The manufacturer of instrument panels or other parts requiring sheets of insulating material of fair dimensions often has greater concern over the natural warp of the sheets than over later warp or distortion under stress. As reported on page 578 some of the samples as received from the manufacturers had a natural warp of 2 cm in a distance of 1 m. For many uses the sheet of material must be free from this natural warp.

12. MACHINING QUALITIES

The summary tables on pages 579 to 580 is the result of sifting about 500 single page reports covering the opinions of the two mechanics after machining as many samples of insulating material.

The detailed reports are interesting and satisfactory. It is quite evident that but few of the details can be given here.

In so far as possible black materials only were used. This made it practically impossible to identify the several materials. These black samples were numbered in such a way as to give no indication of the kind of material or grade. Two or more samples of each grade were given to machinist L and one of each to machinist R.

It is interesting to see how generally consistent L's reports were. If a given grade of material was represented by two samples arbitrarily numbered 9DX and AB, as a rule he decided either that both worked equally well in a certain test or that they worked very similarly. There were, however, some inconsistencies in the machinists' reports.

The mechanics' reports on test No. 6 showed that the majority of the samples drilled undersize. In some cases the hole diameter was 0.005 inch less than the drill size. This made some of the samples more difficult to tap for the one-fourth inch 20 thread.

Tests Nos. 4, 8, and 9 are particularly severe. Test No. 4, die threading, determines how well the laminations adhere. Since the samples were cut from laminated sheet material and lathe turned, the die cut threads in two ways of the laminations. In many cases the thread would not hold in the cross-lamination direction.

Test No. 8 would have been less severe if the samples had been clamped in a vise before tapping. This would have supported the laminations but would not have tested the relative strengths of adhesion.

The samples in test No. 9 would have had more perfect corners and edges if the samples had been backed where the shaper tool left the cut. This was intentionally omitted. All the samples stood this test surprisingly well.

A summary of the results of this series of tests may be given as follows:

For general machine work there hardly seems to be a preference among the grades of material tested.

Where the machining work requires strongly adhered laminations, the first-grade materials are better. These grades usually have a higher percentage of varnish.

The materials with the lower per cent of varnish affect the machine tool the least.

Paper and canvas-base materials differ in machining qualities.

The experience which the particular machinist has had with this type of material has more to do with the finished product than has the kind or grade of material.

13. THERMAL PROPERTIES

The results of measurements on thermal expansion are quite completely given on pages 581 to 583. It may be concluded from the changes in dimensions caused by high temperatures that when a phenolic insulating material is to be used at temperatures above 60° C it should be carefully ascertained that the changes of dimensions will not injuriously affect the operation of the device in which it is used. For such temperatures these materials would not be suitable in delicate instrument parts but would be suitable for such devices as a magneto distributor cap and similar parts.

MISCELLANEOUS TEMPERATURE EFFECTS.—When samples of the laminated material were heated in a closed electric muffle furnace, three stages of destruction were noticed, and in the following order: (1) Blistering of the surface; (2) cracking within and along the body; (3) smoking, with the odor of phenol and of charring organic matter.

The sample of Bakelite-Dilecto, grade XX, Bakelite Micarta, grade 32-X, and Formica, grade M (the only grades which were given this test), all blistered at about the same time at about 235° C. The second grade materials (Bakelite-Dilecto, grade X, and Bakelite Micarta, grade 323) started to blister at about 185° C.

The second stage of destruction has no definite limits of temperature but comes approximately between 200 and 400° C. The second-grade materials precede the first-grade in the tendency to curl and split. At about 500° C all the materials began to glow and burn to ash. This is equivalent to the third stage prolonged.

14. EFFECTS OF ACID AND ALKALI

The reasons for making this test have been given on page 515 of this paper, and the method can be found in the Bureau of Standards publication mentioned on page 506.

ACID.—It is evident that either sulphuric acid or caustic soda (NaOH) would attack cellulose in the form of rag or wood pulp base paper. This is a test of how well the phenolic condensation product (varnish) protects the cellulose from the acid and caustic solution and how the varnish itself resists the action of the acid

and caustic. It appears from the data given on page 584 that in all cases the samples have increased in weight when immersed in a 22 per cent solution of sulphuric acid for 48 hours. This shows that these materials are somewhat permeable. It is interesting to notice, however, that the first-grade materials of each make show less change in weight and little or no change in hardness after being immersed in the acid. The other grades contain a lower per cent of varnish and show a resulting greater increase in weight and decrease in hardness. The hardness tests point to the probability that in the first-grade materials the fluid of lower specific gravity (water) has been absorbed, while water and acid have been absorbed by the second-grade materials, since the acid surrounding the cellulose fiber or filler tends to carbonize that fiber and render it soft.

Continental-Bakelite and Bakelite Micarta, 21-D, canvas-base materials, seem to be exceptions, for they are about one point (B. h. n.) harder after immersion in acid than before. This difference is slight and may be due to errors in measuring the diameter of indentation.

Some irregular tests were made on different kinds and grades of laminated phenolic materials using 20 per cent solution of sulphuric acid at 80° C. The samples were immersed in this solution for 48 hours. None of the samples withstood the test. All crumbled in the hardness testing machine.

Pieces of Formica, grade M, have been used in a commercial way in a 10 per cent sulphuric-acid bath at room temperature for about a month. This use is not for the purpose of a test. The pieces were used for about six months and were found to have sufficient insulating and mechanical properties.

ALKALI.—The acid solution mentioned above showed practically no discoloration after the samples had stood in it for 48 hours, while the caustic solution was very much discolored, with a noticeable amount of sediment. It is recognized by the manufacturers of phenolic varnish and resin that such compounds are affected by even weak caustics if time is sufficiently prolonged and are disintegrated by stronger caustics. In comparing the Brinell hardness as shown in the table on page 585 one should bear in mind that only 250 kg pressure was used on the Brinell machine when testing the samples after being subjected to the caustic. The samples were too soft to bear 500 kg. Although pressure (*P*) enters into

the formula for B. h. n. (formula 9, p. 521), the values of hardness are not directly comparable when different pressures are used.

15. EFFECTS OF SEASON OF YEAR

ON PHASE DIFFERENCE.—The results tabulated on pages 524 to 533 show some variations of phase difference of the same sample when tested at different seasons of the year. These changes may be attributed to the ordinary changes of atmospheric conditions. The building in which the insulating materials are kept and tested is heated by hot, dry air. This heat is probably effective from November to March. During the warmer months the windows are open and temperature and relative humidity are more nearly the same as the outdoor air. The autumn months are very humid in this locality. It is evident, then, that since there is a gradual change of moisture conditions from winter to summer there will be changes in the insulating materials. The changes are not visible. These may be only temporary physical changes. Our data do not cover sufficient cycles of seasons to merit an opinion as to permanent changes of any properties.

The effects of season are particularly noticeable in the phase difference of B. S. samples Nos. 5, 8, 14, 18, 146, and 212. As an example, in the tabulated data (p. 526) the phase difference (ψ°) of B. S. sample No. 146 is as given in Table 37.

TABLE 37.—Phase Difference Measurements Made Six Months Apart on the Same Sample of Phenolic Electrical Insulating Material

Wave length (λ_m) (in Meters)	Phase difference (ψ)	
	Oct. 21, 1918	Mar. 4, 1919
	Degrees	Degrees
696.....	4.28	3.71
1376.....	5.31	3.90
3482.....		
3420.....		

This shows the probable effect of moisture on the sample as tested in October and March. High humidity accompanies large phase difference. These changes are presumably owing to the varying amount of moisture absorbed from the air by the materials.

ON DIELECTRIC CONSTANT.—The effect of the season of the year on dielectric constant at radio frequencies is strictly parallel to the effects on phase difference. The measurements of dielectric constant of the insulating material are made simultaneously with

measurements of phase difference. The preceding examples of the change of phase difference of a given sample from season to season are directly applicable to the discussion on the change of dielectric constant.

One additional example will serve as an illustration. Many such examples can be found in the tabulated results on pages 524 to 533.

TABLE 33.—Dielectric Constant Measurements Made on Same Sample on Different Dates, Using Radio-Frequency Current

Date	Wave length (λ_m)	Dielectric constant (K)
	Meters	
Mar. 29, 1919.....	1919	5.9
Apr. 19, 1919.....	1963	6.1
Feb. 20, 1920.....	2027	6.7

ON SURFACE RESISTIVITY.—While no measurements of surface resistivity have been made on samples exposed to an open atmosphere of varying humidity, the same effect has been attained and measurements made on samples using a cabinet in which the humidity could be carefully controlled. The data are given on pages 524 to 533 and summarized on page 587. The effects are very large. It would naturally be expected that a surface property would be more affected by atmospheric conditions than properties of the inner volume of the material such as phase difference and dielectric constant.

16. EFFECTS OF BAKING OR DRYING

ON PHASE DIFFERENCE.—The foregoing explanation of the change in phase difference of this type of insulating material with atmospheric humidity is substantiated by the fact that the phase difference of most samples can be lowered by subjecting it to a moderate heat for several hours. The sample is tested again after it has returned to room temperature. The above sample (B. S. No. 146) shows this effect also.

TABLE 39.—Phase Difference Lowered by Baking or Drying Sample

Baking or drying	Date of test	Wave length (λ_m)	Phase difference (ψ)
		Meters	Degrees
After drying 120 hours at about 70° C.....	Mar. 11, 1919	1264	2.20
After standing 5 months.....	Aug. 2, 1919	677	2.79

Also B. S. sample No. 5, Table 40.

TABLE 40.—Phase Difference Lowered by Baking or Drying Sample

Baking or drying	Date of test	Wave length (λ m.)	Phase difference (ψ)
		Meters	Degrees
Before baking.....	Mar. 4, 1918	1025	3. 17
	Sept. 20, 1918	672	5. 40
	Oct. 17, 1918	707	5. 71
After drying 150 hours at about 70° C.....	Oct. 25, 1918	664	3. 79
	Mar. 25, 1919	1002	3. 67
	Sept. 20, 1919	1064	5. 97

B. S. samples Nos. 7, 60, 61, and 117 show similar results.

ON DIELECTRIC CONSTANT.—In accordance with the explanation that the greater part of the change of phase difference with time is owing to surface moisture, it would be expected that when the moisture content is high the effective capacity of the insulating material condenser would be proportionally higher. The dielectric constant should thus tend to decrease as the sample is dried. A part of the change of phase difference and dielectric constant may also be owing to some varying property of the organic constituents of the insulating material. The phenolic insulating materials are rather complex chemically.

One example of the change of dielectric constant of a sample of laminated phenolic material with a greater and lesser amount of surface moisture on the sample is given below. Others are given in the data tables on pages 524 to 533.

TABLE 41.—Dielectric Constant Lowered by Baking or Drying Sample

Baking	Date of test	Wave length (λ m.)	Dielectric constant (K)
		Meters	
Before baking.....	June 7, 1918	1355	5. 6
After baking for 90 hours at about 70° C.....	Dec. 17, 1918	1597	5. 0

17. EFFECTS OF FREQUENCY

ON PHASE DIFFERENCE AND DIELECTRIC CONSTANT.—The detailed results on pages 524 to 533 give numerous examples of the effect of frequency on phase difference and dielectric constant of laminated insulating materials over a range of radio frequencies. As stated in the heading above the data on pages 524 to 533, the values of phase difference and dielectric constant given there include those at the extreme frequencies only. If five determinations were made, using 500 to 3500 m wave lengths (frequencies, 600 000 to 85 700 cycles per second), the values of phase differ-

ence and dielectric constant would be recorded in these tables for only 500 to 3500 m.

The curves on pages 534 to 548 show the change of phase difference, capacity, and equivalent resistance with frequency, of a few representative samples. These curves have been plotted, using all the frequencies at which the above properties were determined. Values of wave length in meters have been used on the abscissas, but this can be converted to frequency (f) in cycles per second, by the relation,

$$f = \frac{3 \times 10^8}{\lambda_m} \quad (10)$$

The curves of phase difference are derivable from those of capacity and resistance, since phase difference is a function of resistance, capacity, and frequency (see formula 1a).

The curves of capacity in micromicrofarads may be converted to curves of dielectric constant (K) by using formula 2 in the form

$$K = \frac{C T}{55.047}.$$

The capacity (C) and the thickness (T) may be taken from the curves (T is given more accurately in the tables on pp. 524 to 533).

By glancing at these curves one will notice that the effect of frequency change on different samples of the same grade is not the same. Using the curves shown on pages 534 to 538 it appears that the phase difference of Bakelite-Dilecto increases with frequency. The phase difference of some grades of Bakelite Micarta increases with frequency and of others decreases. Different grades of Formica also have phase difference curves increasing as well as decreasing with frequency, while in Condensite Celoron it increases with frequency. The tests have covered a wave length range of about 500 to 3000 m. It is rather difficult to give the magnitude of the variation of phase difference with frequency or wave length when considering so many samples. Over this range, however, the apparent changes in phase difference are from 2 to 30 per cent. About 75 per cent of the curves show an upward trend with increasing frequency (or decreasing wave length).

In addition to the above-mentioned determinations of phase difference and dielectric constant at radio frequencies, a few measurements of these properties have been made at 100, 500,

and 3000 cycles per second. Average representative values at these frequencies are:

TABLE 42.—Phase Difference and Dielectric Constant at 100, 500, 3000, and 300 000 Cycles per Second

Radio frequency	Phase difference (ψ)	Dielectric constant (K)
Cycles per second:	Degrees	
100.....	9.0	6.9
500.....	5.0	6.0
3000.....	4.0	6.0
300 000.....	2.8	5.3

The phase difference measuring apparatus used in the laboratory is being improved so as to make possible measurements at any frequency from 3000 to 3 000 000 cycles per second. It is expected that tests can be made at this Bureau on insulating material condensers over the range of 100 to 3 000 000 cycles per second of alternating voltage. More extensive data on the effect of a wide range of frequency on phase difference and dielectric constant can then be given.

18. EFFECTS OF THICKNESS

ON PHASE DIFFERENCE.—Some results of our early work on laminated insulating materials of the phenol-methylene type showed a tendency of phase difference or power factor to increase with the thickness of the sample. It is an established fact that the 60-cycle puncture voltage of this type of material does not increase in proportion to thickness, so one might reason that the phase difference might be greater in thicker dielectrics, but our data do not show it sufficiently to merit a conclusion. The change in properties from sample to sample may be sufficient, however, to cover up any change owing to thickness.

Some early measurements of phase difference made on a 2.52 cm (1 inch) thick sample were compared with measurements made on a 0.64 cm (one-fourth inch) thick sample of the same make, grade, and color. The values were lower for the 0.64 cm thick sample. A possible explanation of this difference was thought to be incomplete curing of the phenolic varnish in the center of the thicker sample. To test this belief, a 25 by 31 by 2.52 cm sample was sawed into three samples 25 by 31 by about 0.6 cm, one of which came from the middle of the original slab. As shown in the tabulated results, the thinner samples did have a lower phase

difference, but the sample taken from the center of the original sample shows lower phase difference than the two outside samples. This did not substantiate our beliefs in regard to incomplete chemical reaction and high volatile content in the middle of thicker sheets of insulating material.

TABLE 43.—Phase Difference of Four Samples, the First Being 1 Inch Thick, the Other Three Obtained by Cutting the Original Sample into Three One-Fourth Inch Samples

B. S. sample number	Thickness		Wave length (λ_m)	Phase difference (ψ)	Date of test	Source
	cm	Inch	Meters	Degrees		
3-0.....	2.52	1	459	4.0	Feb. 20, 1919	The original sample 25 by 31 by 2.52 cm No cut surfaces
			713	3.3	Feb. 24, 1919	
			1078	3.3	Feb. 20, 1919	
			1375	3.3		
			2756	3.3	Feb. 21, 1919	
3-0-A.....	.64	$\frac{1}{4}$	1027	3.1	Mar. 29, 1919	Outside sheet 25 by 31 by 0.64 cm One cut surface
			1919	3.3		
			3430	3.4		
			1038	3.2	Apr. 19, 1919	
			1963	3.5		
			3443	3.7		
			1133	4.7	Feb. 20, 1920	
			2027	5.3		
3-0-B.....	.64	$\frac{1}{4}$	3670	5.6		Inside sheet 25 by 31 by 0.64 cm Two cut surfaces
			2035	5.3	Feb. 24, 1920	
			960	2.7	Mar. 27, 1919	
			1822	2.8		
			3245	2.8		
			976	2.6	Apr. 18, 1919	
			1848	2.8		
			3207	2.9		
3-0-C.....	.57	$\frac{1}{4}$	1059	4.0	Feb. 20, 1920	Outside sheet 25 by 31 by 0.57 cm One cut surface
			1886	4.4		
			3383	4.5		
			983	3.8	Apr. 12, 1919	
			1865	4.0		
			3228	4.3		
			1855	3.9	Apr. 14, 1919	
			3222	4.1		
			1051	5.1	Feb. 20, 1920	
			1910	5.7		
			3423	6.2		

ON MECHANICAL PROPERTIES.—From the data thus far collected thickness of sheet has little or no effect on the mechanical properties of the laminated phenolic insulating materials. By referring to the data on pages 524 to 533 one will notice that in some cases the thicker samples of the same grade show a higher tensile strength, but if the variation of values for different samples of the same thickness and grade are considered also, the probable variation owing to thickness alone is small.

ON MOISTURE ABSORPTION.—As pointed out in the Bureau publication mentioned on page 506, experimental data on percentage by weight of moisture absorbed can not be compared unless samples of the same size and thickness are considered. It is quite

readily apparent, however, that the percentage, by weight, of moisture absorbed increases as the area of the cut surface (and hence thickness of sample) increases. To obtain experimental data on this would necessitate a determination of moisture absorption based on a unit area of cut and uncut surface. Such work would be a separate research in itself and should be undertaken.

19. EFFECTS OF COLOR OR DYE

ON PHASE DIFFERENCE.—By consulting the summary of data on pages 524 to 533, one will notice that for some of the materials there is apparently a greater phase difference for the samples containing black pigment. Theoretically, this should be the usual result. The pigment is occasionally lampblack (amorphous carbon), which means that a conducting material is added to the insulating material. There should be little or no change in electrical properties when aniline dyes are used.

A careful determination of the effect of dye on phase difference at radio frequencies requires that color be the only characteristic that is changed—a difficult limitation in a factory without an experimental laboratory. The data above mentioned often show quite different values of phase difference of insulating materials of the same make, grade, color, and thickness. Since the materials do differ in this respect, it is difficult to determine how much difference in phase difference is owing to color and how much is owing to process variation.

ON FLASH-OVER VOLTAGE AND SURFACE RESISTIVITY.—What has been written above about the variation of phase difference with color is equally true when applied to flash-over voltage at radio frequencies and surface resistivity. The data on pages 524 to 533 show very wide variations of resistivity from sample to sample of the same grade and color, so it is again difficult to separate the differences owing to color and process variation.

20. EFFECTS OF SURFACE FINISH

ON FLASH-OVER VOLTAGE AND SURFACE RESISTIVITY.—A determination of the effect of surface finish on flash-over voltage at radio frequencies and surface resistivity is difficult. As pointed out elsewhere in this paper, it is not conclusive to determine these properties on two different samples—one with a highly burnished surface and the other with a dull surface. Such results would be a combination of effects owing to surface and process changes. Such an error could be brought to a minimum provided the manufacturer would fabricate the two samples at the same time, using

the same varnish bath and press the samples together in the hydraulic press. We have not received such samples.

If two test samples are cut from the same burnished sheet, the one having the natural burnished surface and the other a sand-papered or sand-blasted surface, the results would be only an approximation of the effect of surface on these properties. If a dull sample is used, one part could be tested as it is and the other buffed to a polish, but then the heat of friction and buffing paste have added their share of changes.

Theoretically, the flash-over voltage and the surface resistivity should be increased when the sample surface is irregular, because the actual surface distance between metallic contacts is greater. If an etched or like surface is considered, there is also a tendency for congealed moisture to form in globules at the apex of the minute mounds instead of coating the whole surface. It is to be understood that when the electrical properties of an irregular or etched surface (similar to the surface of a copper halftone plate) are compared with plane surfaces all surfaces shall have about the same degree of polishing or burnishing.

21. EFFECTS OF ULTRA-VIOLET LIGHT

ON SURFACE RESISTIVITY.—We have made but few tests using the ultra-violet light as a rapid aging medium. The data given need no further comment. We do not know the number of hours' exposure to sunlight which is equivalent in its effect to 30 hours' exposure to ultra-violet light.

TABLE 44.—Effect of Ultra-violet Light on Surface Resistivity of Phenolic Electrical Insulating Material. Tests Made at 42 Per Cent Relative Humidity (See Also B. S. Sci. Paper No. 234)

Material	Grade	B. S. sample number	Approximate thickness		Surface resistivity	
					Before exposure to ultra-violet light at 42 per cent humidity	After exposure to ultra-violet light for 30 hours at 42 per cent humidity
			cm	Inch	Ohms $\times 10^8$	Ohms $\times 10^8$
Bakelite-Dilecto.....	XX.....	14	0.95	$\frac{3}{8}$	9000	3700
	XX.....	14	.95	$\frac{3}{8}$	7500	2700
	XX.....	11	.64	$\frac{1}{4}$	4000	1900
Bakelite Micarta.....	32-X.....	21	1.27	$\frac{1}{2}$	400	220
	323.....	27	1.27	$\frac{1}{2}$	3000	650
Formica.....	M.....	2	1.27	$\frac{1}{2}$	90	37
	M.....	2	1.27	$\frac{1}{2}$	100	45
	M.....	7-0	.95	$\frac{3}{8}$	180	5.6

22. EFFECTS OF RATIO OF VARNISH TO PAPER

ON PHASE DIFFERENCE.—There was an attempt made to analyze the effect of the per cent of absorbed phenol varnish on the phase difference of the sample. Such a test has many difficulties. The ratios of varnish to paper of the samples here considered were determined by the manufacturer making the insulating material and were only approximate. There was no attempt made to calculate the ratio of solid resin to paper, which necessitates a correction for the volatile matter escaping in the drying and pressing.

There is no simple analytic method of making a percentage composition test after the insulating material is made, for then the varnish has passed to practically an infusible, insoluble state.

Our density determinations on the various samples point to a probable error in the percentage composition data supplied to us. If one assumes the percentage values correct, then our data give little light on the electrical effect of the varnish. Each sample has been tested at various frequencies, but only those frequencies that are about equal will be shown here for comparison.

TABLE 45.—Possible Effect of Relative Per Cent of Varnish to Paper on Phase Difference

Per cent of varnish	Wave length (λ_m)	Fre- quency, cycles per second	Phase difference (ψ)
	Meters		Degrees
30.....	1335	224 700	2.83
40.....	1415	212 000	4.07
50.....	1340	223 900	2.56
55.....	1325	226 400	3.00
60.....	1305	229 900	2.05

A more complete understanding of the effect of composition on the electrical properties of such materials may be obtained when the testing is done under controlled atmospheric conditions.

By referring to the tabulated data (p. 588), one may see that, in general, most second-grade materials have lower phase difference than first-grade material. Materials of this grade average about 30 per cent varnish. In some cases there may also be a different base paper used in the second-grade material.

By second grade we mean here the following materials and grades:

Material	Grade
Bakelite-Dilecto.....	X
Bakelite Micarta.....	323 and 213
Formica.....	P

Formica, M-2, may be considered as second grade also, but is a different type of material and does not show the peculiarity cited above.

The above grades are not recommended by the manufacturers for use on radio apparatus. These grades have a distinct use as commercial insulators possessing better mechanical and, in some respects, better machining properties than the first-grade materials.

ON MOISTURE ABSORPTION.—What has been said above concerning the samples prepared for a study on phase difference may be said of the samples considered in the table below. It will be noticed that the percentage by weight of water absorbed by the various samples does not decrease as the percentage of varnish increases, neither does the density decrease as the percentage of varnish increases. The varnish should protect the cellulose fiber of the paper from the water in proportion to the degree of saturation of the cellulose fiber by the varnish. This assumes that the surfaces of the several samples are uniform, and that the size, thickness, and weight of the samples are about the same.

If the density of the paper is taken as 1.44 and of the varnish as 1.30, then the experimental value of density ($D = 1.40$) for the 30 per cent resin sample is about correct, but the percentage of moisture absorbed is low.

TABLE 46.—Effect of Percentage of Varnish Upon Percentage by Weight of Moisture Absorbed in 24 Hours

Percentage of varnish	Density	Percent- age by weight of water absorbed in 24 hours	Size of sample
	g/cm ³		cm
30.....	1.40	0.17	5 by 10 by 0.64
40.....	1.35	.34	.....
50.....	1.39	1.13	.....
55.....	1.35	.18	.....
60.....	1.38	.34	.....

It will be noticed in the data on page 593 that the second-grade materials have a higher percentage of moisture absorption. In some cases the second-grade materials absorb 10 times as much water in 24 hours as the first grades. That is why only the first grades are recommended for the majority of radio work.

It is not to be understood that this type of material absorbs water, swells and becomes flexible as does vulcanized fiber. We have not made any moisture-absorption tests extending more than 24 hours.

ON MECHANICAL PROPERTIES.—Theoretically if one considers only well-cured samples of laminated phenolic insulating materials, the sample with the higher percentage of varnish will have lower tensile and transverse strength, be harder, be more brittle, and be difficult to manipulate in some machining operations.

For reasons stated on page 617 we can not illustrate the theory by data on samples of different percentage of varnish, nor are we sufficiently sure that the samples we have hold closely enough to the percentage composition stated.

23. COMPARISON OF PROPERTIES OF HARD RUBBER, VULCANIZED FIBER, LAMINATED AND MOLDED PHENOLIC INSULATING MATERIALS

A comparative summary of the properties of these materials is tabulated below. This is based upon the results of many investigations and the experience of many users and manufacturers. Hard rubber and vulcanized fiber have been used by engineers for many years. Some still find in these materials the particular property needed for their work, others have felt a need for some other material but have not had sufficient information to choose that better material. Some engineers have failed to study these two materials—hard rubber and vulcanized fiber—sufficiently to use them wisely and economically. Often too little or too much has been expected of an insulating material.

The problem of the proper use of the proper insulating material has been at once facilitated and complicated by the advent of the laminated and molded phenolic materials. These materials lend themselves to many uses not satisfactorily filled by either hard-rubber or vulcanized fiber, but they are likewise used where hard rubber or fiber might better be used. The phenolic insulating materials are for many purposes not hard-rubber substitutes. They are distinctly different. It is evident that the idea of phenolic insulating materials as a hard-rubber substitute has been overworked. This tendency may well be explained on the ground that the phenolic insulating materials are really quite new and yet in a state of development. Engineers have turned to this new material but have found little data at hand to direct them in its use.

Hard rubber is composed of crude rubber, sulphur, and usually some mineral filling compound. As previously stated, the great demand for raw rubber in other industries in 1917 to 1919 induced some makers of hard rubber to use reclaimed rubber or else load the new rubber with a high percentage of mineral filler. The lack of a proper understanding of this fact between the maker and the user has often resulted in unjust censure of hard rubber as an insulator. The better grades of hard rubber are made of new rubber containing no mineral filler and are free from excess sulphur. With these points in mind it is evident that the values assigned to a particular property or the effect of a certain test must necessarily be broad. Neither the best nor the poorest grade of hard rubber is considered in the data and opinions given in the following table.

Vulcanized fiber is made of parchmented paper. For the better grades of fiber rag base paper is used. The paper is run slowly through a warm concentrated solution of sulphuric acid or zinc chloride, the one solution being used in making fiber sheets one-eighth inch thick or less, the other solution being used for thicknesses greater than one-eighth inch. The purpose of the acid or zinc chloride is to soften the walls of the cellulose (cotton) fibers, so that when several sheets of treated paper are pressed together the fibers tend to mat and cohere. The treated paper is wound on a drum until the cylindrical tube of the desired thickness is obtained, the cylindrical tube being then cut so as to form a sheet whose width is equal to the width of the paper and whose length is equal to the circumference of the drum. The composite sheet of treated paper is then soaked in water to remove the acid or zinc chloride, dried, and pressed. The term "vulcanized" is somewhat misleading. Fiber does not depend upon heat and pressure to cure it as does hard rubber.

Vulcanized fiber varies much in both mechanical and electrical properties. The properties depend somewhat on the quality of rags used, the amount of residual sulphuric acid or zinc chloride, and upon the density of the finished product. Since the various processes of fiber making are difficult to control, the following statements relative to fiber must be taken as general and the recorded numerical data as average data.

The several makes and many grades of laminated phenolic insulating material have been discussed quite fully in this paper. It will be evident to the reader that any numerical value or statement given in the following summary table is an approximation.

The molded phenolic insulating materials are subject to as many variations as hard rubber. There is probably not as much variation in the phenolic resin binder in the molded phenolic materials as there is in the crude or reclaimed rubber binder of hard rubber. There are many other chances for variation in the press pressure and temperature, length of curing in the presses, and kind and quality of filler. Some of the fillers used are wood flour, pulverized mica, and asbestos. The kind and amount of filler will affect both the mechanical and electrical properties. All these possible variations make the data only approximate and require rather general statements in the summary table.

Most of the numerical data given in the table below are from tests made at the Bureau of Standards. Actual results on hard-rubber samples are given on page 622. The statements concerning the effects of various things on the different insulating materials are based on the experience of various members of the Bureau of Standards staff and upon the experience of the manufacturers of these materials. The manufacturers' experience on hard rubber and vulcanized fiber extends over many years, while the experience on the phenolic insulating materials is much more limited.

While it is possible to make up insulating materials which would give results different from those recorded for any particular property, yet it is believed that this table gives information in a condensed form which will serve to show some of the limitations as well as some of the possibilities of these various materials as now obtainable commercially.

TABLE 47.—Comparison of Properties of Hard Rubber, Vulcanized Fiber, Laminated and Molded Phenolic Insulating Materials

Properties	Hard rubber	Vulcanized fiber	Phenolic insulating materials		
			Laminated	Molded	
Surface resistivity at 50 per cent relative humidity, ohms.....	10^{12} to $>10^{15}$.....	.....	10 ¹¹	10 ¹¹	
Phase differences (ψ) at radio frequencies, degrees.....	0.5 <i>a</i>	3.0 to <i>b</i>	1.5 to 4.0.....	1.5 to 4.0.....	
Dielectric constant (K) at radio frequencies.....	3.0 <i>a</i>	5.0 <i>b</i>	4.5 to 6.0.....	5.0 to 7.5.....	
Dielectric strength..... volts/mm.	10 000 to 38 000 <i>c, d</i>	9 000 to 16 000 <i>c, d</i>	27 000 to 45 000 <i>c, d</i>	9 000 to 40 000 <i>c, d</i>	
Tensile strength..... lbs./in. ²	3 500 to 6 500.....	9 000 to 20 000.....	10 000 to 25 000.....	10 000 to 7 000.....	
Water absorbed in 24 hours, percentage by weight.....	0.02.....	26 to 45 <i>e</i>	0.2 to 1.0 <i>f</i>	0.05 to 0.2 <i>g</i>	
Density..... g/cm ³	1.12 to 1.40 <i>h</i>	1.3 to 1.5.....	1.3 to 1.4.....	1.3 to 1.4.....	
Thermal expansivity (at 20 to 60° C).....	60 to 80×10 ⁻⁶	27×10 ⁻⁶	20 to 30×10 ⁻⁶	25 to 45×10 ⁻⁶	
Effect of age.....	Deteriorates slowly, but if properly vulcanized and protected from light it is not affected.....	Improves in quality by seasoning <i>i</i>	Improves <i>i</i>	No depreciation in physical or chemical properties; slight increase in hardness <i>j</i>	See statement for laminated materials <i>l</i>
Heat.....	At 65.5° C (150° F) pure hard rubber softens perceptibly; at 100° C (212° F) it is so soft it may be bent easily. At 115.5° C (240° F) it becomes leathery and may readily be cut with a knife; melts at 200° C (392° F) <i>c</i>	Will not melt under any circumstances; not readily inflammable; at very high temperature chars, and becomes brittle; active combustion begins at about 343° C (650° F).....	Not readily inflammable; will withstand continuously a temperature of 149° C (300° F); heat tends to complete the reaction and volatile substances are driven off. Hence, when cooled it shrinks considerably and may split; shrinks and loses in weight above 60° C <i>k</i>	No visible effect <i>n</i>	
Sunlight.....	Surface discolors and deteriorates after a few months; the sulphur of the hard rubber is oxidized, forming the equivalent of sulphuric acid; this may take up ammonia from the air or may attack the filling materials forming the various sulphates upon the surface; the surface resistivity is greatly reduced <i>m</i>	No effect <i>c</i>	Appreciable lowering of surface resistivity.....	Appreciable lowering of surface resistivity <i>m</i>	After two and one-half years some materials show a slight change, such as discoloration or very fine cracks; other materials show no such change <i>c, n</i>
Effect of ultra-violet light for 20 hours.....	Surface discolors and deteriorates; the action is as pronounced for a few hours' exposure to ultra-violet light as for many months' exposure to sunlight; the surface resistivity is greatly reduced <i>m</i>	No data.....	Appreciable lowering of surface resistivity.....	Appreciable lowering of surface resistivity <i>m</i>	

Moist air.....	Hard-rubber compounds excepting those containing organic substances other than rubber are practically moisture proof	Absorbs water freely, but without permanent injury; while saturated it becomes soft and flexible and swells; warps and twists upon drying	Absorbs slight amount of water, reducing dielectric properties ^o	Absorbs slight amount of water, reducing dielectric properties
Steam.....	The only effect is that due to the high temperature	Same as above, except absorption is more rapid	Best grades not affected beyond slight absorption of moisture; after a few days in steam the cheaper grades will swell appreciably and split; superheated steam tends to warp and blister all grades of the material	Absorbs a slight amount of moisture; if steam is superheated, the high temperature will cause decomposition
Solvents:				
Acetone.....	Attacks, dissolving oils and free sulphur ^c	No permanent effect ^c	No effect ^{c, p}	No effect ^{c, p}
Alcohol.....	Attacks to a slight degree ^c	do. ^c	do. ^{c, p}	Do. ^{c, p}
Ammonia.....	No effect ^c	do. ^c	Strong solutions may cause material to swell ^c	No effect other than slight absorption of moisture ^c
Aniline.....	Softens it at ordinary temperature ^c	Not known	Probably no effect ^c	Probably no effect ^c
Benzol.....	do. ^c	No permanent effect ^c	do. ^{c, p}	Do. ^{c, p}
Carbon bisulphide.....	Dissolves small amount of hard rubber and any free sulphur ^c	do. ^c	do. ^{c, p}	Do. ^{c, p}
Ether.....	do. ^c	do. ^c	No effect ^c	Do. ^{c, p}

^a These values were obtained at frequencies between 750 000 and 75 000 cycles per second (400 to 4000 meters wave length), there being very little change throughout this range. The grade of the sample tested is unknown, so values differing somewhat from these might be expected on other samples using different quantities and kinds of filler.

^b Values of ψ and K may be somewhat lower or much higher, depending on amount of moisture present in the fiber.

^c Information obtained from sources other than the Bureau of Standards.

^d Values vary with the thickness of sample, kind of filler, shape of electrodes used, rate of increase of voltage, as well as atmospheric conditions under which tests are made.

^e The Railway Signal Association specifications require an absorption when immersed in water at 70° F for 24 hours, not to exceed 45 per cent by weight for one-eighth inch fiber, 30 per cent for three-sixteenth inch fiber, and 26 per cent for one-fourth inch fiber.

^f Dependent upon nature of surface, surface area, and kind and amount of filler.

^g Varies with polish of mold, press pressure, and temperature, length of curing, ratio of resin to filler, kind of filler, and size of sample.

^h The density depends on the amount of sulphur present and increases with the increase in amount of filler. Pure hard rubber ranges from 1.12 to 1.25. A fair commercial quality ranges from 1.25 to 1.40.

ⁱ This means seasoning or aging in a protected place, such as a storage house.

^j These materials are of comparatively recent development, and hence no information has been gained covering very long periods. Theoretically, under certain conditions the chemical reactions would tend to continue, which would age and improve the material. One manufacturer claims a slight improvement in dielectric properties and a marked improvement in machining qualities when the aging takes place under ordinary atmospheric and temperature conditions. If the aging takes place in a moist atmosphere, the dielectric properties are subject to deterioration.

^k See pages 580 to 583 and 187 of this paper.

^l When subjected to temperatures above 60° C (140° F) some of the volatile matter is driven off, resulting in the shrinking and loss in weight of the material. This can be carried out many times with the same result, the material becoming more brittle. Tests made on these materials show that they are very erratic in behavior and do not expand or contract in a uniform way. It seems altogether probable that a point would be reached after all volatile matters had been driven off, when further subjection to a moderate temperature and subsequent cooling would not result in further shrinkage. This has not been proved experimentally. High temperature will produce decomposition. Further information regarding these tests will be found in Scientific Paper of the Bureau of Standards No. 352. (See also pages 580 to 583 and 187 of this paper.)

^m A further discussion of the tests at the Bureau of Standards may be found in Scientific Paper of the Bureau of Standards, No. 234.

ⁿ See effect of ultra-violet light.

^o See discussion on pages 599 and 600 of this paper.

^p Strong solvents affect the phenolic binder of the material to a limited extent unless the chemical reaction has been carried to the point where it is in the insoluble state. This condition would render the sheet material too brittle for general use. When water is present, the material will absorb it in various amounts.

TABLE 47.—Comparison of Properties of Hard Rubber, Vulcanized Fiber, Laminated and Molded Phenolic Insulating Materials—Continued

Properties	Hard rubber	Vulcanized fiber	Phenolic insulating materials	
			Laminated	Molded
Solvents—Continued.				
Naphtha.....	Softens and swells to slight extent <i>c</i>	No permanent effect <i>c</i>	Probably no effect <i>c</i>	Probably no effect <i>c, p</i> <i>Do, c, p</i>
Oil of turpentine.....	Dissolves in boiling oil <i>c</i>	<i>do. c</i>	<i>do. c</i>	
Oil:				
Mineral.....	Slight softening <i>c</i>	Slight absorption <i>c</i>	Practically impervious <i>c</i>	Practically impervious <i>c</i> <i>Do, c</i>
Organic.....	Unaffected <i>c</i>	<i>do. c</i>	<i>do. c</i>	Practically unaffected <i>r</i>
Effect of weak acids.....	<i>do</i>	Swells due to absorbed water; may be attacked after some time <i>c</i> <i>do. c</i>	absorption of water <i>q</i> <i>Do</i> not successfully resist the action of alkali unless very dilute	
Weak caustic alkalis.....	<i>do</i>	<i>do. c</i>		Does not successfully resist the action of alkali unless very dilute
Stronger acids (HNO_3 , HCl , H_2SO_4).....	Not attacked by concentrated hydrochloric, hydrofluoric, acetic acids; not attacked by sulphuric acid of less than 1.50 specific gravity or nitric acid of less than 1.12 specific gravity <i>c</i> No effect.....	Cellulose fiber attacked soon decomposes <i>do</i>	Decomposes; rapidly depends on specific gravity and temperature of acid	Decomposes; rapidly depends on specific gravity and temperature of acid <i>t</i>
Stronger caustic alkalis.....			Blinder and filler decompose <i>r</i>	Completely destroy; speed of the reaction depends on the strength of the solution
Ozone.....	Oxidizes and soon ruins it for electrical purposes	No effect <i>c</i>	Not known.....	Not known
Metallic inserts.....	Cases have been observed in which there is corrosion of copper and brass inserts at the exposed junction of metal and hard rubber; no such corrosion of bronze or tinned inserts has been reported	<i>do</i>	No effect.....	No effect
Machining qualities.....	Admits of a high polish; machines less accurately than would be supposed, due to great resiliency; the better the grade the more readily it is machined; quality may be judged roughly by color and texture, toughness, color, and grain of a shaving; has tendency to warp; can be molded to size within plus or minus 0.002 inch	Admits of a fine finish; may be sawed, punched, drilled, stamped, embossed, turned, planed, bent, tapped; tough, resists shock; can not be molded <i>t</i>	Admits of a good polish; can be sawed, punched, drilled, knurled, embossed, milled, tapped either with or against the grain, though not as easily as hard rubber and vulcanized fiber; tough, resists shock; can not be molded <i>t</i>	Admits of a fine lasting polish; can be machined, cut, filed, sawed with difficulty; can be molded to size within plus or minus 0.001 inch; quite brittle

Cost.....	About \$0.50 to \$1.10 per pound in sheet form	50-80 cents per pound up to 1 inch in thickness; about \$5 per pound for 2 inches in thickness	About \$1 per pound.....	Cost varies with complexity of steel molds
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^c Information obtained from sources other than the Bureau of Standards.
^p Strong solvents affect the phenolic binder of the material to a limited extent unless the chemical reaction has been carried to the point where it is in the insoluble state. This condition would render the sheet material too brittle for general use. When water is present, the material will absorb it in various amounts.
^q The effects vary with the materials, different molding mixtures, and acids. Nitric acid is harmful. In general weak acids will mar the surface and attack the edge of a sample soon after it comes in contact with the sample, but there is little or no further change.
^r See page 608 of this paper.
^s The action differs for various materials and grades. Some materials resist the action of a 30 per cent solution of H₂SO₄ for several months and will withstand hydrochloric acid without any visible sign of attack. On other materials of this class sulphuric and nitric acids attack the surface of the sample and form a protective coating. This ruins the sample as far as further electrical use is concerned, but on removing the sample from the acid and cutting it open it is found that the acid has not penetrated more than one-sixteenth inch after several months' exposure to the acid.
^t Thin sheets can be pressed to simple shapes when warm.

VI. SUMMARY

A comprehensive experimental research has been made upon the principal electrical and mechanical and a few other properties of the laminated phenolic materials. The measurements were made upon the sheets of materials as furnished commercially. Specimens for measurement of all the various properties were cut from the same large sheet, so the results are comparable. The influences of a large number of factors upon the properties were studied and have been discussed herein. The scope of the work may be judged from the table of contents. The properties varied greatly with the thickness of sheet as well as grade of material. While there were, furthermore, considerable variations from sample to sample, characteristic values of the properties are given by the summary table below. This table gives the averages of all data on samples received at the Bureau of Standards between December 20, 1917, and August 24, 1919.

TABLE 48.—General Summary of Properties

Property	Bakelite-Dilecto, grade—			Bakelite Micarta, grade—		
	XX	X	Continental Bakelite	32-X and 21-X	323 and 213	21-D
Phase difference .....degrees..	2.1	1.9	3.8	2.9	2.4	5.6
Power factor.....per cent..	3.6	3.3	6.6	5.1	4.2	9.9
Dielectric constant.....	5.2	5.5	5.3	5.8	5.9	6.4
Flash-over voltage, radio frequency.....	19 800	19 800	21 100	20 000	19 700	22 000
Volume resistivity.....ohm-cm×10 ⁸ ..	18 800	520 000	200	9 400	29 900	100
Surface resistivity at 24% humidity.....ohms×10 ⁸ ..	38 900	445 000	100	3 300	10 400	580
Surface resistivity at 50% humidity.....ohms×10 ⁸ ..	3 900	4 000	9	900	2 700	130
Surface resistivity at 84% humidity.....ohms×10 ⁸ ..	48	6	1	22	30	3
Density.....	1.34	1.34	1.30	1.35	1.37	1.36
Water absorbed in 24 hours.....per cent..	.21	1.76	.49	.33	.88	.91
Ultimate tensile strength.....lbs./in. ² ..	12 800	17 800	8 700	10 900	16 600	8 900
Modulus of (tensile) elasticity.....1000 lbs./in. ² ..	1 500	2 100				
Modulus of (transverse) rupture.....lbs./in. ² ..	18 000	22 700	13 600	16 200	21 400	13 900
Modulus of (transverse) elasticity.....1000 lbs./in. ² ..	1 310	1 900		1 260	1 600	
Brinell hardness at 20-30° C.....	41	28	32	39	34	37
Brinell hardness at 50° C.....	40	26	30	34	32	32
Scleroscope hardness at 20-30° C.....	88	68	58	83	81	75
Scleroscope hardness at 50° C.....	83	64	58	80	76	70
Impact strength.....ft.-lb..	0.7	0.9	1.2	0.2	0.8	2.1

TABLE 48.—General Summary of Properties—Continued.

Property	Condensite Celoron, grade—		Formica, grade—			
	10 and 15	20	M	M-2	P	R
Phase difference.....degrees..	2.9	6.3	3.0	3.7	2.9	4.5
Power factor.....per cent..	5.1	11.0	5.3	7.7	5.1	7.9
Dielectric constant.....	6.6	6.8	5.6	5.8	5.8	6.5
Flash-over voltage, radio frequency.....	21 000	27 800	19 700	20 600	18 300	21 000
Volume resistivity.....ohm-cm×10 ⁸ ..	15 100	63	2 200	250	900	60
Surface resistivity at 24 per cent humidity.....	12 500	1 800	600	340	670	340
Surface resistivity at 50 per cent humidity.....	2 300	275	160	120	300	220
Surface resistivity at 84 per cent humidity.....	77	13	10	5	34	80
Density.....	1.41	1.34	1.36	1.34	1.38	1.38
Water absorbed in 24 hours.....per cent..	.26	.39	.26	.49	.60	1.22
Ultimate tensile strength.....lbs./in. ² ..	12 300	7 800	12 600	13 200	18 200	9 900
Modulus of (tensile) elasticity.....1000 lbs./in. ² ..				1 950	2 260	.....
Modulus of (transverse) rupture.....lbs./in. ² ..	15 800	11 100	17 700	17 300	21 400	15 100
Modulus of (transverse) elasticity.....1000 lbs./in. ² ..			1 270	1 430	1 410	.....
Brinell hardness at 20-30° C.....	38	38	35	44	38	39
Brinell hardness at 50° C.....	35	32	34	41	34	34
Scleroscope hardness at 20-30° C.....	86	87	84	90	86	70
Scleroscope hardness at 50° C.....	82	82	80	89	82	64
Impact strength.....ft.-lb..	0.4	1.0	0.3	0.3	1.5	2.9

WASHINGTON, November 30, 1921

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