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PAPER-AND-OIL INSULATION, PROPERTIES, METHODS OF DRYING AND IMPREGNATION

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1. Introduction

The electrical insulation system for the vast majority of power transformers consists almost entirely of a combination of paper and mineral insulating oil. This situation has existed for many years and will quite probably continue for a long time in the future. In general, other materials are substituted for oil or for oil-impregnated paper for part or all of the insulation in a power transformer only in special cases. For example, dry-type air cooled transformers may be used where the flammability of oil prohibits its use, or a phenolic laminate may be used as an insulating structural part or as a terminal board in an oil-filled transformer where paper does not have the required physical strength.

It would appear that, in view of the many electrical insulating materials which are the product of modern chemical technology, some of the synthetic films, coatings, plastics or other materials should by now seriously threaten the position of oil and paper. However, there are a number of reasons why this has not occurred, the most important of them relating to (1) the excellent properties of oil and paper as an insulation system or (2) improvements in both the oil and the paper which are products of this same modern technology.

The union of oil and paper is a most happy one, resulting in electrical properties superior to that of either one separately. Both materials are low in cost and are readily available from a number of sources. The forms in which paper is available are almost unlimited, so that the solid part of the insulation system can be tailored to meet whatever electrical and physical requirements are needed in almost any part of the system. Improvements are continually being made to both oil and paper. In the past few years the resistance of both paper and oil to thermal aging has been increased by large factors, permitting the operation of transformers at higher temperatures while, at the same time increasing the life of the transformers. Studies conducted during the past several years and which are still continuing have given us more accurate knowledge of the behavior of paper and oil combination at high voltages, and have also resulted in development of papers with improved electrical properties. Application of this new knowledge and use of newly developed materials has resulted in appreciable reduction in insulation clearness, lowered product cost and improved reliability. Developments now in progress are expected to continue this trend into the future.

2. Oil

2.1 General

The oil used in transformers is a mineral oil of rigidly defined characteristics. The physical, chemical and electrical properties are held within the ranges which will result in a material which can function as an impregnant, an insulant and a coolant, performing all of these jobs effectively.

While oil is an excellent insulating material, it is very sensitive to contamination. Some contaminants will seriously damage the properties of oil, and of the oil-paper system of which it is a part, when the contaminant is present in concentrations of only a few parts per million parts of oil. These contaminants include water, air or other gasses, and many organic compounds such as metallic soaps. Particulate contamination can also be a problem, even though the particles may themselves be good electrical insulators.

For this reason, oil used in the manufacture of transformers and for filling of transformers in service is continually tested to detect contamination. Factory oil supplies are filtered in various types of filters to remove both dissolved and particulate contaminants and the use of degassing and dehydrating equipment keeps the gas and water content of the oil down. Similar purification operations are used by many utilities to maintain the oil in their operating transformers at a high quality level.

2.2 Properties

The suitability of an oil for use in an insulation system is determined by evaluating a number of characteristics. Standard tests have been established to measure these characteristics and new tests are being developed which will in the future permit more accurate evaluation of an oil. The properties that are of importance include:

1. Physical Properties - These include viscosity, specific gravity, pour point, thermal coefficient of expansion, vapor pressure and flash point. These properties determine how well the oil will serve as an impregnant and as a coolant. It is desirable for an oil to have low viscosity, a low pour point and a low specific gravity in order that it will easily impregnate thick paper or pressboard insulation, and so that it can be easily pumped to provide maximum heat transfer efficiency. A high thermal coefficient of expansion is also desirable for transformers that are self-cooled and depend upon convection currents in the oil for cooling. A low specific gravity will permit any droplets of water in the oil to more rapidly settle out. However, all of these desirable characteristics tend to go along with increased vapor pressure and lowered flash point. Low vapor pressure is necessary in order to prevent evaporation of the oil during impregnation processes and in equipment used for degassing and dehydration of the oil. Also, the

vapor pressure at or slightly above normal operating temperatures has some effect on corona levels and electrical strength, a low vapor pressure being desirable. A high flash point is desirable from a safety standpoint, both for handling the oil in the factory and in operation of the transformer in service.

2. Chemical Properties - These properties include:
   a) Acidity
   b) Interfacial surface tension
   c) Resistance to emulsification
   d) Color
   e) Water content
   f) Dissolved gasses
   g) Resistance to aging
   h) Solvent characteristics

   The first six properties listed are measures of contamination. A number of aging tests are in existance for estimating the deterioration that will occur in service. The first four properties above are affected by aging as well as by external contamination, so that they may be used as part of the aging tests. The solvent characteristics of the oil determine to what extent the oil will attack other materials in the insulation system. This in turn will have an effect on the amount of dissolved contaminants picked-up by the oil from these other materials. The acidity of the oil may affect the aging characteristics of the paper and other solid materials in the system, so that it is important that the acidity be low.

3. Electrical Properties - The properties most frequently measured in this group are 60 cycle breakdown strength, power factor and resistivity, in that order. The dielectric constant is also of importance from a design standpoint, but is essentially the same for all oils and is not ordinarily measured. The 60 cycle breakdown strength is mainly a quick method of detecting free water or some other heavy contamination. Power factor is quite sensitive to certain contaminants, but is more complicated to measure than breakdown strength.

2.3 Other ~~Insulating~~ Liquids

A number ~~of~~ liquids other than mineral insulating oil are available for use in special cases. The only one of any importance in power transformers is askarel, used by Westinghouse under the trade name "Inerteen." The transformer ~~grade~~ is a mixture of chlorinated aromatic compounds, having about the same viscosity as mineral insulating oil. Askarel is used because it is nonflammable, thus making it safe for subway network transformers which are mounted underground in congested urban areas. Another advantage of askarel is its high dielectric constant, resulting in a more uniform electrical field where discontinuities between solid and liquid materials occur in the insulation structure.

A major disadvantage of askarel is its high cost relative to oil. In addition, its high specific gravity--almost twice that of oil--adds considerably to the weight and shipping costs of transformers. Askarel is rather irritating to the skin, and cannot be contacted at all by some people. Also, the solvent properties of askarel are sucn that many materials that are suitable for use in oil are attacked by askarel. Thus, more care must be used in selecting such things as adhesives, varnishes and gaskets for use in askarel-filled transformers.

Other insulating liquids are available, including the silicone oils and various fluorinated hydrocarbons. These liquids offer certain advantages over both mineral oil and askarel, but they are generally much higher in price than askarel, so that their commercial use to date has been restricted to small special purpose units.

3. Paper

3.1 The Paper Making Process

The term "paper" as used herein is intended to include all thicknesses from thin conductor insulation only one or two mils thick to heavy pressboard that may be laminated to several inches in thickness. The general trend during the past 15 to 20 years has been to replace all other cellulosic papers with those made from wood pulp. At one time the majority of electrical papers and boards were made primarily from cotton rag pulp. The principal exception to this was paper made from manila rope pulp, used as conductor insulation. With the advent of synthetic fibers for textiles and marine cordage, the sources of clean pure cotton rags and of used manila ropes began to diminish so that problems arose with availability, cost and quality of rag and rope papers. At the same time improvements in the properties of kraft pulps and of papers made therefrom were improved so that adequate physical and electrical properties could be obtained at lower cost, using kraft papers. In some cases, in order to obtain certain physical properties blends of kraft pulp with rag pulp on rope pulp are used. The use of the kraft pulps in the blend results in reduced material cost.

All paper, regardless of grade or thickness, is manufactured in basically the same manner. The two materials used to make paper are pulp and water, the water being largely removed during the final operations. Kraft pulp is produced from wood by a series of chemical processes which remove nearly all of the non-cellulosic material originally present in the wood, separate the individual wood fibers from each other, and change the physical structure of the fibers as may be required to produce the desired characteristics in the finished paper. The wood used to make the pulp is important to the properties of the finished paper. For electrical papers, softwood pulps from trees grown in the northern latitudes are most commonly used. As compared with southern pine pulps, northern pulps are made up of finer and stronger fibers which produce a more uniform paper, particularly when thin papers are being made. Most electrical paper manufacturers buy pulp, then refine and modify the pulp to obtain the desired characteristics. The refined pulp, which may be a blend of two or more kraft pulps or of kraft pulp with rag or rope pulp, is mixed with enough water so that there is less than one percent of pulp in the mixture. This mixture is used to form on a wire screen belt (Fourdrinier process) or on a screen covered cylinder (cylinder process) a continuous thin web which, when dried and calendered, is no more than a few mils thick. Enough water is drained or sucked out through the Fourdrinier screen or the cylinder so that the paper web can be carried on a felt belt onto heated drying rolls which remove the rest of the excess moisture, then in between calender rolls which give the paper a smooth finish and establish its final thickness and density.

Fourdrinier machines produce papers from about .15 mils to about 15 mils thick from a single web of paper. A number of machines are in operation which produce paper in excess of 250 inches wide at a speed of over 2,000 feet per minute. However, electrical papers are generally made on machines of 100 to 120 inch widths at somewhat lower speeds.

Cylinder paper machines generally are furnished with more than one cylinder, the wet webs from each cylinder being combined into a thicker sheet before drying and calendering. Thus, the finished paper, having a maximum thickness of about 30 mils, may be made-up of as many as six individual layers. Cylinder machines in operation today range from 40 to 100 inches in width.

When paper in excess of about 30 mils thickness is needed, it must be produced one sheet at a time rather than in a continuous roll. A pressboard mill begins as a cylinder machine with one or two cylinders. The wet one or two layer web is wrapped around a large "making roll" until the required number of plies ~~has~~ been built-up. Then the thick mat is cut off of the making roll to form a rectangular sheet equal in length to the circumference of the making roll and in width to the width of the original web. Present sheet size limitations in the United States are 60" x 180" and 112" x 160". One European manufacturer can produce sheets up to about 125" x 250". The wet sheet is then carried through a horizontal tunnel oven to remove excess moisture.

The final operation is to calender the sheet to thickness. A sheet up to about ¼" thick can be produced in this manner. For greater thicknesses, sheets must be laminated to obtain the required thickness.

It is also possible to produce pressboard by gluing together thinner sheets of paper to obtain the desired thickness. This has the obvious economic advantage of the paper being handled in continuous roll from through almost the entire manufacturing operation. At present board of this type is available only up to 54" x 120" sheet size, but it is hoped that much larger sheets, at least 82" x 240" will become available in the future. The best present estimate is that these large sheets will not be available before 1968.

The foregoing description of the papermaking process is intended to show that, while all papers bear a family resemblance to each other, it is possible to start with a given kraft pulp and by varying the refinement and further purification and by the choice of the papermaking machine and its operating conditions produce an almost unlimited variety of finished papers. A few examples:

1. Capacitor tissue manufacturers use a very pure pulp which is further washed and mechanically worked for a relatively long time. Generally the water is deionized to limit the inorganic impurities as much as possible. This pulp is fed into a special Fourdrinier machine to produce a dense nonporous sheet, in thicknesses from .15 to 2 mils. The specific gravity is normally about 1.0 grams per cubic centimeter, but for particular grades may be from 0.8 to 1.3.

2. Layer insulation in thicknesses from 5 to 20 mils may be produced either on a Fourdrinier machine or a cylinder machine, from about the same pulp as is used for capacitor tissue. However, the amount of beating (working) is reduced and less care is taken to remove impurities.

3. This same pulp can be used for making pressboard, as described above. By proper choice of the amount of beating and washing, boards of a variety of characteristics may be obtained. Boards may be produced of low to medium density, which can be punched or formed readily, or a high density board with low compressibility may be produced. Other properties may be emphasized as may be desired.

In all cases, care is taken in the manufacture of electrical papers to keep all non cellulosic matter to as low a value as possible. The amount of care used varies from product to product.

but is always present. When the paper is received from the paper maker, it is in effect free from all contaminants except water.

3.2 Moisture

Water is present in all paper to some extent. When the paper is received from the paper mill it contains from 5% to 10% by weight of water (based on dry weight.) Water acts to plasticize the paper, so that some moisture must be present in the paper during most fabricating operations. The water is absorbed by the individual fibers in the paper, softening and swelling the fibers. The swelling action increases the diameter of the fibers more than their length, so that the amount of change in each dimension of the paper is a function of the average orientation of the fibers in the paper. The greatest dimensional change is in the thickness of the paper, and the least change is in the length or "machine direction." The change in width or "cross machine direction" is generally greater than in length, the difference depending upon the degree of orientation.

For the purpose of estimating its effect upon physical properties and dimensional changes, we are concerned with moisture contents of from a few percent on up. This amount of moisture can be determined with sufficient accuracy by simply determining weight loss on oven drying at temperatures of 105°C to about 140°C. Differences of a few tenths of a percent might be obtained, depending upon the oven temperature and the amount of moisture in the air, but these differences are small and of little significance compared with the total amount of moisture being measured.

In addition to its effect upon physical properties, water affects the electrical properties of paper, so that it must be regarded as a contaminant when paper is used as an electrical insulating material. For this reason, it is necessary to remove as much water as possible from the paper insulation before the paper is oil impregnated. The methods used for drying and impregnation are discussed below.

3.3 Properties of Paper

Physical Properties - Until recently nearly all papers used for transformer insulation were selected entirely on the basis of their physical properties, or more accurately, on the basis of fabricating characteristics which were, in turn, a function of various physical properties. Beyond making certain that the papers were reasonably pure and uniform, little attention was paid to the electrical properties of an individual grade of paper. This situation is changing, not by reducing the emphasis on physical properties, but by increasing the attention paid to electrical properties in particular cases. It is still essential that the paper be suitable for use in the various manufacturing operations necessary to produce a transformer. Depending upon the grade and thickness of the paper and the application in which it will be used, any of a number of physical properties may be of importance. Some of these properties can be measured quantitatively, while others can only be evaluated by indirect methods such as by shop trials of the paper in the actual operation.

Each of the following characteristics are of importance to one or more of the applications in which paper is used to insulate transformers:

1. Thickness
2. Specific Gravity
3. Basic Weight
4. Tensile Strength
5. Elongation
6. Tear Strength
7. Bursting Strength
8. Compressibility
9. Air Porosity
10. Surface Smoothness
11. Surface Friction
12. Ply Adhesion
13. Puncture Strength
14. Shear Strength
15. Compressibility
16. Abrasion Resistance
17. Flatness
18. Dimensional Stability
19. Stiffness
20. Rate of Water Absorption
21. Formability
22. Suitability for Shearing, Slitting, Punching or Scarfing
23. Fold Endurance

No more than half of the above characteristics are specified quantitatively in any Westinghouse specification for insulating papers, although all except about three or four of the properties can be evaluated by standard tests. In most cases the final physical evaluation of the paper is done in the manufacturing operation.

Electrical Properties - The most commonly used electrical tests on all thicknesses of paper and pressboard up to about 1/8" thickness are the 60 cycle and full-wave impulse puncture tests, almost always made on dried, oil-impregnated specimens at room temperature. In some cases tests are made of the surface creep strength or of the internal rupture strength parallel to the surface.

Some of our specifications call for 60 cycle puncture tests of paper in air, after conditioning at 50% Relative Humidity. There is little correlation between this test and the properties of oil-impregnated paper although a low dielectric strength in air might indicate certain undesirable characteristics such as lower than normal density, non-uniform formation of the paper, or the presence of gross contaminants such as metallic particles.

On very thin papers a conducting particle test is sometimes specified. This is of value mostly for papers less than 1 mil thick, such as capacitor tissue, but it is specified for our 2 and 3 mil turn insulation. In this test a 60 cycle voltage of 100 v/mil is applied to a single layer of paper in air. An area of paper totalling a number of square feet is subjected to this voltage and the test results expressed in terms of conducting particles per square foot.

The 60 cycle dissipation factor of dried, oil impregnated paper is of value in detecting impurities in the paper. A recently developed test procedure has been added to some of our material specifications and is being used to evaluate all new papers. This procedure permits measurement of dissipation factor at various temperatures. For specification purposes, 125°C is the standard temperature.

Recently more interest has been directed toward the dielectric constant (S.I.C.) of oil-impregnated paper, particularly for conductor insulation. This property is a function of the specific gravity of the paper, so it is not specified for any present grade of paper.

A considerable amount of effort has been expended recently on the subject of corona detection, measurement and prevention. The extent to which the characteristics of insulating papers affect corona is as yet undefined. Allied with this subject is the effect of corona upon the insulating materials. No standard test exists as yet for measuring these properties, although it is to be expected that such tests will be developed as a result of the work being done to learn more about corona.

<u>Chemical Properties</u> - The following chemical tests are used in evaluating electrical papers:

1. Total Ash
2. Conductivity of Water Extract
3. pH of Water Extract
4. Soluble Chlorides
5. Solvent (Alcohol, Toluol, Water) Extractibles
6. Nitrogen Content
7. Oil Contamination
8. Askarel Contamination

All except the last two of these tests are only indirectly related to the suitability of a paper for use as electrical insulation. However, these tests can be used as indicators to predict undesirable changes in other properties of the paper.

Thermal Aging Properties - The resistance of paper to thermal aging is measured by an accelerated test in which paper is heated in oil in a sealed container at some specified temperature. Changes in one or more of the characteristics of the paper are measured periodically and curves showing the change in properties as a function of time and temperature can be plotted. In most cases, the bursting strength of thin papers is used as a criterion. Tensile strength is used for pressboard and by some investigators on the thinner papers also. If resinous laminates (Micarta) or similar materials are being tested, flexural strength may be the best criterion. For paper, the electrical properties change very little until the physical properties of the paper are such that it cannot be tested electrically. Therefore, some physical property is used as a criterion for measurement of thermal aging.

3.4 Types of Insulating Papers

All of the many papers available and the many places in which these papers are used can generally be classified into one of three main categories for transformer applications. These categories, and the important properties of the papers, are as follows:

3.4.1 Conductor Insulation - In the past "conductor insulation" or "turn insulation" has meant just one material for liquid-filled transformers--manila rope paper. This paper was selected because it could be readily slit into narrow widths and then applied to wire on high-speed taping machines. This paper is made on a cylinder paper machine using pulp made from the hemp fibers from old manila ropes. The cylinder machine produces a paper with most of the fibers oriented in the machine direction (lengthwise). The manila rope pulp has long tough fibers so that the paper is quite strong and elastic with greater tear strength and elongation than that of other papers. These properties are concentrated in the machine direction which makes the paper easy to slit, yet tough enough so it will not tear when it is being taped or during the later coil winding operations.

Manila rope paper is over twice the cost of a good quality kraft paper, so efforts have been made to substitute kraft pulp for rope pulp in this application. At present a paper is being used which has 40% of kraft pulp with 60% of rope pulp Efforts to use a 70% kraft paper furnished by the same supplier have been unsuccessful. Therefore, the present paper is apparently the most economical paper to use in this application if only physical characteristics are considered.

In the design of interleaved core-form coils, and to some extent in shell-form coils, the turn-to-turn capacitance of the winding is of importance. This is directly a function of the dielectric constant of the turn insulation. Also, the thickness of the turn insulation is determined by the impulse distribution in the coil and by the impulse strength of the turn insulation material. All of these factors are related to each other, as the impulse distribution is determined to a large extent by the series capacitance.

Therefore, an effort has been made to obtain for use as turn insulation a material of higher impulse strength and of higher dielectric constant than standard rope-kraft paper. For paper the dielectric constant can be increased by increasing the specific gravity which will usually increase the impulse strength also. However, this approach, using our standard paper as a starting point, has definite limitations because increasing the density of rope paper tends to make it more brittle and the physical properties become less desirable.

Another approach to this problem has been taken, by starting with a paper of the grade presently used for paper capacitors. This paper is a very pure high density paper which has an impulse strength in oil almost 50% higher than that of rope-kraft paper. However, it is so brittle that it cannot be applied to wire at a practical speed. One supplier has been able to modify this paper physically, at the same time retaining the high density and high impulse strength, in such a way that it can be applied to wire at high speed. Present indications are that this paper, now being applied experimentally to a commercial order, can be used on large interleaved core-form windings and possibly on most shell-form windings.

Enamelled wire has been improved over the years to such an extent that it has virtually eliminated paper from use as turn insulation on smaller transformers. Distribution transformers and some small power transformers now use no paper for turn insulation. This trend has for some time been stopped at this point. It would be foolish to state that enamel will never replace paper as turn insulation for larger transformers, but several problems will have to be solved before this can be accomplished. There are at present limits to the thickness of the enamel coating, so that for the higher voltage ratings, paper will probably maintain its position for the forseeable future. On lower voltage applications, particularly on low-voltage coils such as cylindrical or helitran windings, the problem with use of enamelled wire is more that of the mechanical one of getting the wire off of the reel and into the coil without injuring the enamel coating. With presently available handling and winding equipment, and in the absence of "clean room" conditions in the winding and assembly areas, our experience to date is that paper insulated wire is more suitable for use.

Other materials have been suggested as turn insulation materials and all of the likely candidates are examined as they come along. These materials are almost all either films or papers made using synthetic fibers. Another class of material would be that of cellulosic papers which have been modified by resin treatment or by addition of some filler material. None of the presently available materials appear to offer any net improvement over paper when all of the properties of the materials are compared.

3.4.2 Layer Insulation - Paper used as layer insulation varies in thickness from 5 to about 15 mils and is, in most cases, a medium density kraft paper. The function of the layer insulation in coils where it is used is to mechanically separate and electrically insulate adjacent layers of wire in layer wound coils. This type of coil is almost universally used for distribution transformers and small power transformers but is less common on larger transformers, about the only exception being cylindrically wound core-form coils. If foil or wide sheet conductors are used, the layer insulation is effectively the turn insulation also, since there is only one turn per layer. Frequently, particularly on distribution transformers, the same paper that is used for layer insulation, or perhaps the same grade of paper in greater thickness, may be used also as a barrier between coils or from a coil to ground, simply by applying additional layers to build up the required thickness.

In order to permit the coils to withstand the mechanical stresses resulting from short circuit conditions, adhesives are used to bond the conductors to the insulation and to bond adjacent layers of insulation together. If enamelled wire is used, this adhesive is applied to the wire over the enamel. Oven heating of the wound coil will soften the adhesive on the wire to bond adjacent wires together and to the paper layer insulation. Where bare conductors are used or where multiple layers of paper are needed, the adhesive is applied to one or both sides of the paper. The coil is thus wound in such a manner that all of the layers are bonded together and the coil will not telescope in service.

Since the layer insulation must provide physical support and separation for the conductors, the physical properties of the paper are at least as important as the electrical properties.

In some winding configurations severe shearing stresses may be applied to the paper. Therefore, a tough, incompressible paper is generally selected for this application. Most frequently only one or two layers of paper are used per layer, even though higher electrical strength could be obtained by using more layers of thinner insulation to build up the same total thickness. The reason for this practice is again that of providing physical separation of the layers, which one thick layer of paper will accomplish better than will several thinner layers.

3.4.3 Pressboard - The high voltage insulation structure of power transformers is composed almost exclusively of kraft pressboard. Multiple layers of pressboard alternately with oil ducts are used to provide the necessary clearances and to permit oil to circulate for cooling purposes. In addition to being necessary for cooling purposes, the oil ducts also facilitate removal of moisture from the pressboard when the insulation is being dried.

A substantial majority of the pressboard used for power transformer insulation is 1/8" thick. For use as dielectric barriers, generally 1/8" sheets are used, singly or in multiple, with thinner sheets used where they will do the job. Heavier thicknesses of pressboard are used, up to about 3 inches thick, where such thicknesses are needed for mechanical support.

Simple forming operations can be done on pressboard up to 1/8" thick to produce angles and channels of various configurations. If severe forming operations are performed, it may be necessary to use pressboard having some rag content. Water is generally used as a forming aid, either by moistening the surface of the board prior to forming, or by soaking the board to make it completely pliable prior to hot pressing.

Electrically, pressboard has its greatest resistance to breakdown in the thickness direction. This applies to both short-time and long-time effects, ranging from microseconds on up. The electric field in which pressboard is used should have the voltage gradient normal to the plane of the pressboard for maximum effectiveness of the insulation. Recent problems, particularly on EHV shell-form transformers, indicate that the effect of creep stresses on pressboard are not fully understood as yet. Since the creep stresses are applied along the pressboard-oil interface, such things as particulate contamination and moisture in the oil and surface smoothness of the pressboard enter into the problem.

Most applications for pressboard are filled using "standard density" board having a specific gravity of about 1.0. Where a stiffer, less compressible material is needed, a higher density (1.3 specific gravity) pressboard is used. The principal application where high density pressboard is needed is for radial spacers on core-form sectional wound coils. These spacers may be subjected to compressive loads of several thousand pounds per square inch under short-circuit conditions.

Where the mechanical requirements do not dictate the use of high density pressboard, there is generally no particular advantage to using this board from the standpoint of electrical strength. While the impulse strength increases with increasing density, the long-time 60-cycle strength is essentially unaffected by density.

Another "pressboard" application is that of dielectric barrier tubes for core-form transformers. Actually, these tubes, generally with walls 1/4" to 3/8" thick are rolled from kraft paper, bonded together with dextrine glue. In the sense that they are a thick solid piece of material, they fall into the category of pressboard. These tubes help to physically support the coils during and after winding as well as serving as an electrical barrier, so that the wall thickness is in many cases greater than it would be if only electrical requirements were considered.

3.5 Insuldur

During the past few years much of the paper used for transformers has been thermally upgraded, using the Insuldur system. In essence, an Insuldur paper is one to which has been added about 3% by weight of a specified mixture of water soluble organic compounds. This mixture is in most cases added by the paper manufacturer, a notable exception being crepe paper, to which the treatment is applied as part of the creping operation.

The Insuldur treatment has little effect on the physical or electrical properties of the paper to which it is applied. About the only changes are a slight increase in stiffness of the paper and a noticeable increase in the power factor.

Insuldur is one of a number of systems for thermally upgrading cellulosic materials which have become available. Insuldur is a patented Westinghouse system, which has been licensed for use by several of our competitors. The other leading system of thermal upgrading is Permalex, the General Electric process. Permalex is basically different from Insuldur, in that Permalex papers are made from pulp which has been chemically modified by treatment with acrylonitrile. This is a more expensive process than the simple chemical treatment required for Insuldur and is more inflexible in that it must be performed on the pulp prior to manufacture of the paper. A number of other systems are used by other electrical manufacturers, most of them being similar to Insuldur.

Based on measurement of physical properties of oil impregnated paper aged in oil, Insuldur treatment increases the life of paper at a given temperature by a factor of at least 8, or it will permit operation at at least 30°C higher temperature for the same life. We have no indication that Permalex treatment is in any way superior to Insuldur. Tests on the other systems indicate that Insuldur is decidedly more effective.

Our present practice is to use Insuldur paper functionally. This means that it is used for all paper in distribution transformers and small power transformers. It is used only for taping connections on larger units. Pressboard is, in general, not Insuldur treated. The only exception to this is the pressboard fill strips used between turns on shell-form windings.

All Insuldur materials, other than turn insulation paper, is color coded with a green dye for identification.

4. Drying and Impregnation

4.1 Processes - The process of removing moisture and air from paper and replacing them with oil is basically a very simple one. For each condition of temperature and water vapor pressure, a given amount of water is held by the paper. So it should be very simple to establish the degree of dryness desired, set the temperature and pressure conditions, and go ahead and process the insulation. However, the problem of drying and impregnating the insulation structure of a transformer is somewhat more complicated than that of applying a similar treatment to a single piece of insulation. The processing of the insulation must fit in with all of the other manufacturing operations performed on the transformers. The drying and impregnating conditions are determined by the amount and dimensions of the insulation being dried, the structure of the coil in which it is assembled, and the required final electrical characteristics of the coil and other insulation in the transformers. The manufacturing cycle for a transformer includes; winding and assembly of the coils, core building, fitting of leads and auxiliary equipment, tightening and clamping of coils, tanking, and testing. Somewhere in this sequence the insulation must be dried and impregnated, protected from reentry of moisture, and finally delivered to the test floor in good condition.

Westinghouse practice is now to do two separate drying operations on medium and large power transformers. The first is a rigorous drying and impregnation of the coils, followed by a redrying operation after all assembly is completed to remove moisture picked-up during assembly.

Both shell-form and core-form coils are dried prior to assembling with the core. The Vapotherm drying process, used for this operation first heats the coils under a partial vacuum using the vapors of a petroleum solvent as the heating medium. The vapor heats the insulation very rapidly, removing moisture at the same time. Due to the absence of air, the heating temperature can be considerably higher than would be permissible if the coils were heated in an oven.

By the time the coils are thoroughly heated, most of the moisture has been removed. After the coils have come to temperature, a higher vacuum is then applied to complete the drying operation and to remove any solvent which has been absorbed by the insulation. The process is then completed by impregnating with oil under vacuum.

As presently operated, the Vapotherm system at Sharon heats the coils to about 130°C in vapor, then, still holding this temperature, reduces the pressure to below 0.5 Torr for complete drying before oil impregnation. The total time required is about 16 hours. The Muncie system, processing much larger coils, operates at about 140°C, with a pressure at the end of the vacuum drying below 0.35 Torr. The total required time is five to seven days.

After Vapotherm processing, the coils go into the assembly operations ending with the completed transformer in its own tank. At this point, moisture absorbed during the assembly operations must be removed. This is accomplished by first heating the transformer by circulating hot oil from an external heater into the top of the transformer tank, then out the bottom of the tank back through the heater. After the transformer is thoroughly heated, it is then drained of oil and evacuated to remove moisture before vacuum filling.

The oil temperature during the heating operation is about 105°C, and the final pressure less than 2 Torr. The process at Sharon takes about 24 to 30 hours and at Muncie either two or four days.

4.2 <u>Objectives and Criteria</u> - As stated above, the drying operation is intended to remove moisture and air from the insulation and to replace them with oil. As moisture is removed from paper there is a gradual improvement in electrical properties. Improvements in 60 cycle and impulse strength, in power factor and in insulation resistance all occur as a result of moisture removal. These properties all begin to level out soon after the moisture content is reduced below about 1%. After the moisture is removed, then the voids in the dry insulation must be filled with oil. Unless this is done under vacuum, air bubbles will be left in the insulation which will ionize under electrical stress, reducing the electrical strength and increasing the corona voltage.

Another important objective of the drying operation is that of dimensional stabilization. Considerable shrinkage of paper occurs when the moisture is removed and it is desirable to have this shrinkage occur as soon as possible during the manufacturing cycle in order that the coils can be more closely fitted to the core and tank structures.

No really good means exists for determining when a coil is adequately dried. It is possible to dry models in which are inserted electrodes for power factor measurement, or which can be taken apart for direct moisture determination. Some coils are of such design that measurements can be made on the coil itself to monitor the power factor of the heaviest insulation. This is normal practice for shell-form coils but is not suitable for use on core-form coils. The processes used for core-form coils and for the assembled transformers are simply time-temperature-pressure cycles, with no provisions for monitoring the condition of the insulation as the process progresses.

The presence of oil in dried paper does not change the equilibrium between paper and moist air. The only difference is that if the paper is oil-soaked, or immersed in oil, the moisture must get to the paper from the air through the oil, rather than directly, which slows down absorption of water greatly, but does not eliminate it. Also, any water that is absorbed by oil-soaked paper is more difficult to remove because of the presence of the oil. Therefore, in planning a manufacturing sequence, the elapsed time of exposure of insulation to the air must be definitely specified and limited.

5. Bibliography

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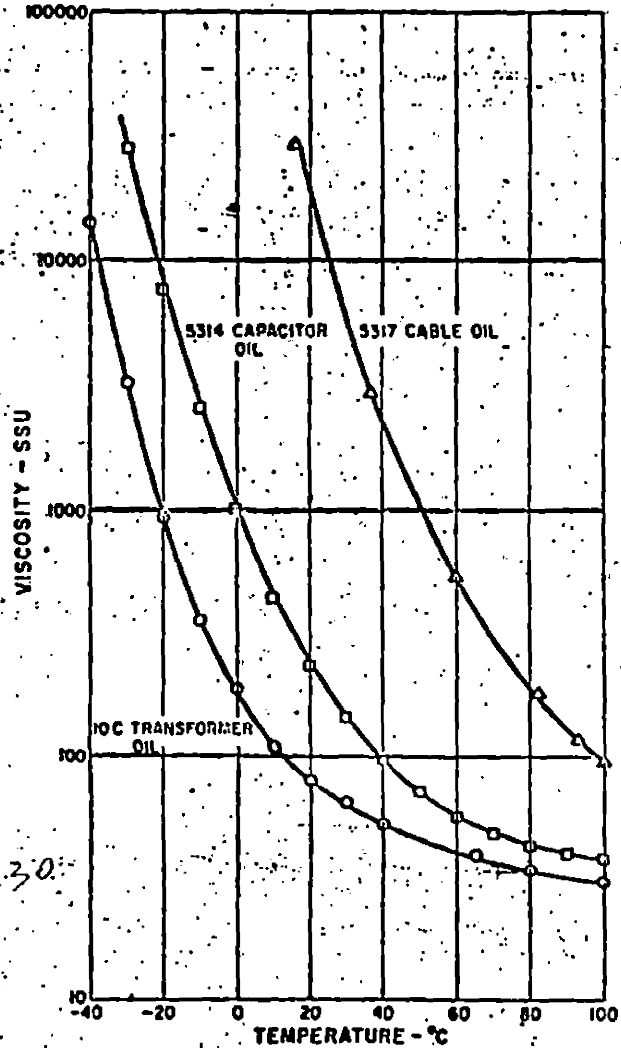

Figure 1
The viscosity-temperature relation for commonly used insulating oils.

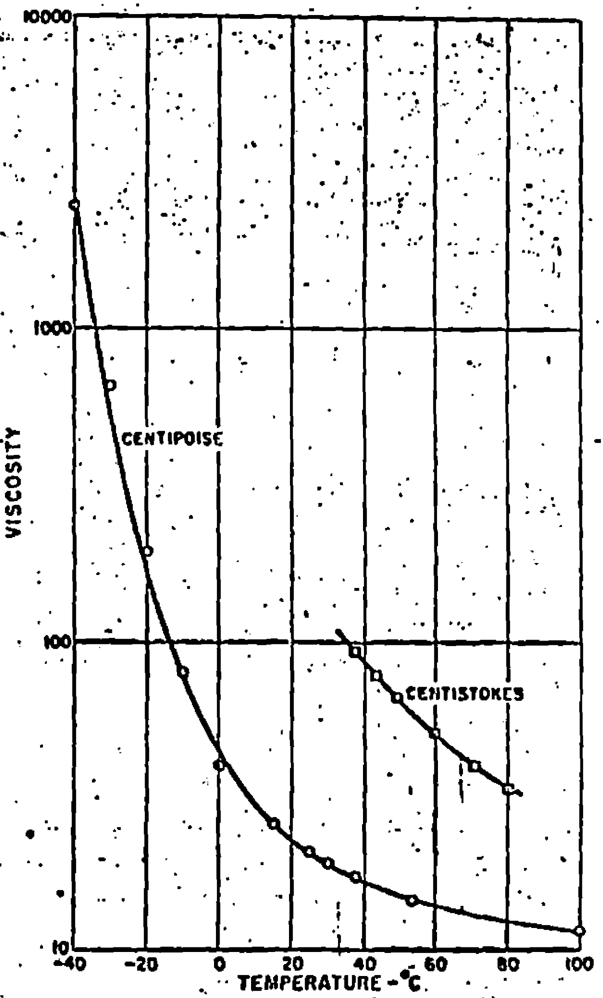

Figure 2
The viscosity-temperature relation for 10C transformer oil.

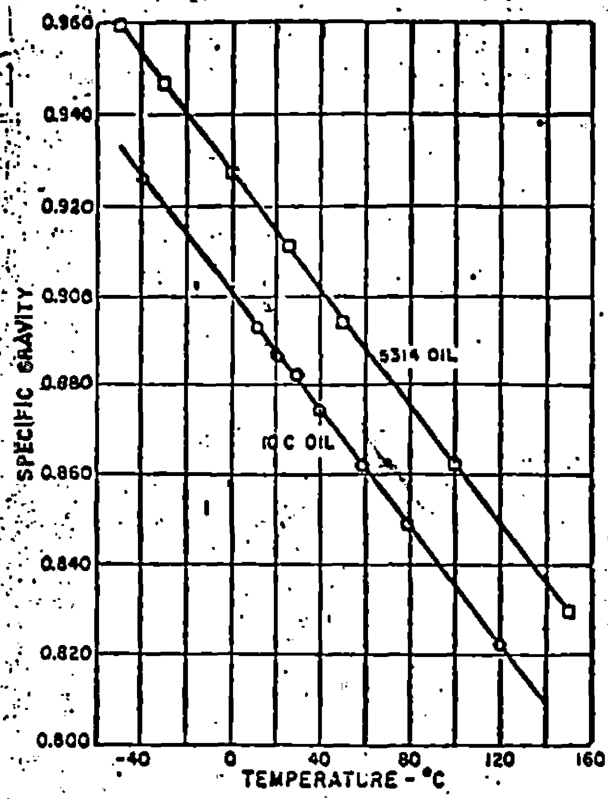

Figure 3
The specific gravity-temperature relation for mineral insulating oils.

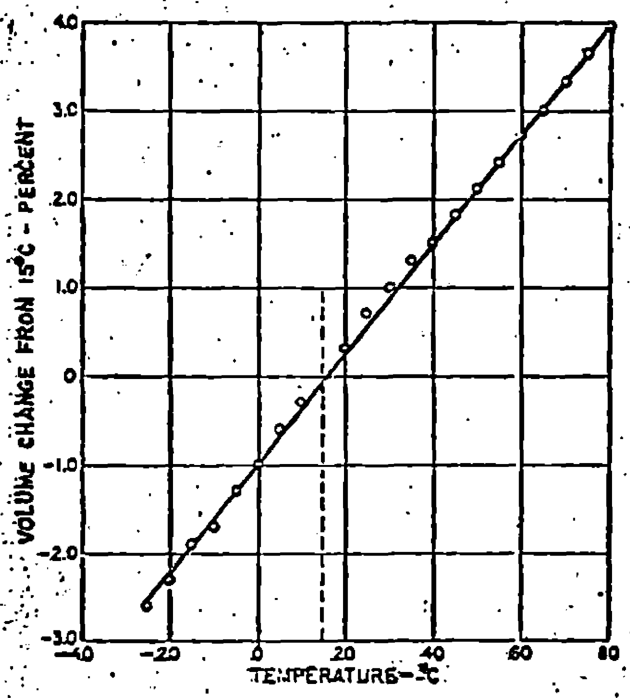

Figure 4
Volume changes in transformer oil produced by a change in temperature from a base of 15° centigrade.

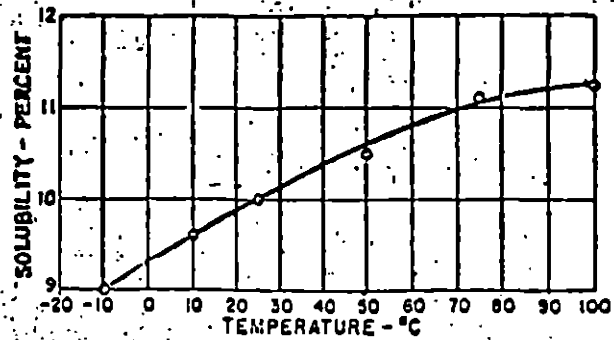

Figure 57 5

The solubility of air in mineral transformer oil of Texas origin.

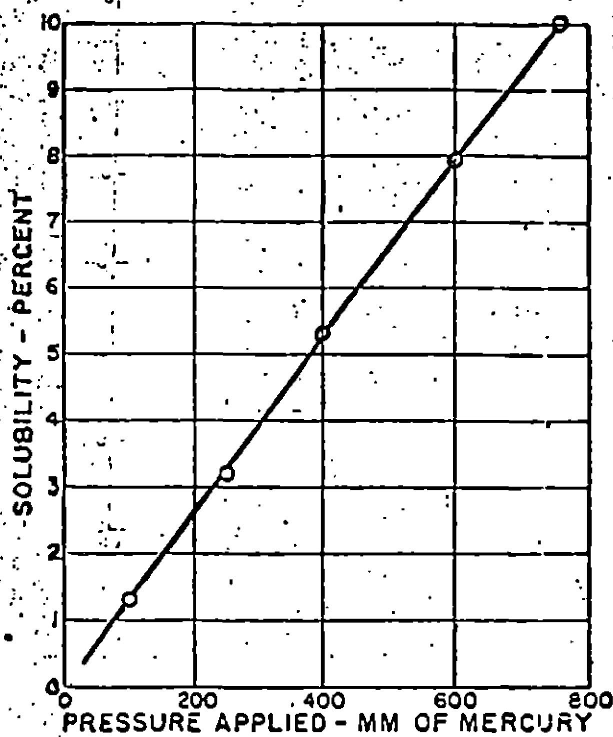

Figure 6

The air solubility-pressure relation in transformer oil of Texas origin.

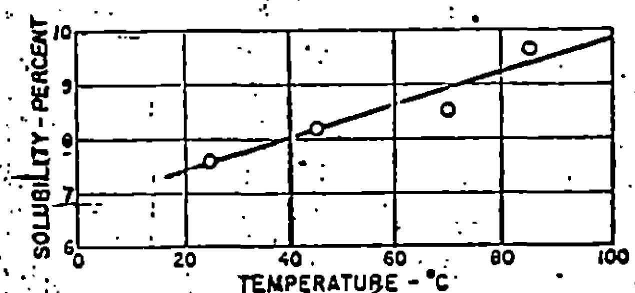

Figure 7

The solubility of air in light cable and capacitor oil of Texas origin.

Viscosity - 100 SSU at 37.8°C

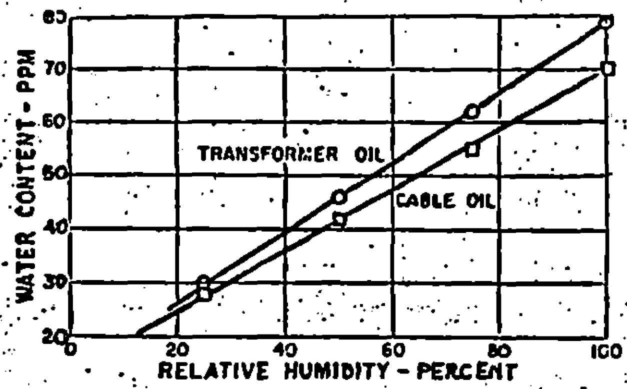

Figure 8
The total moisture pick-up by two different insulating oils of Texas origin when exposed to humid air at 25°C until equilibrium has been established under the static conditions described.

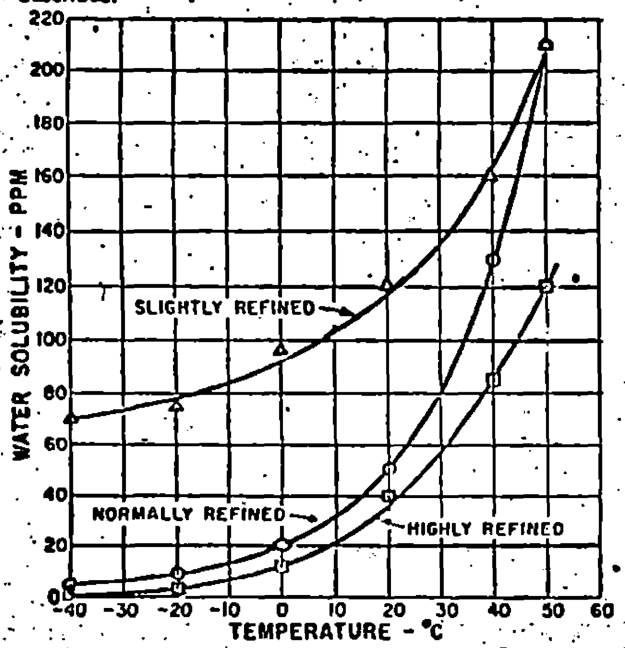

Figure 9
The solubility of water in transformer oil. (Texas origin) as affected by its degree of refinement.

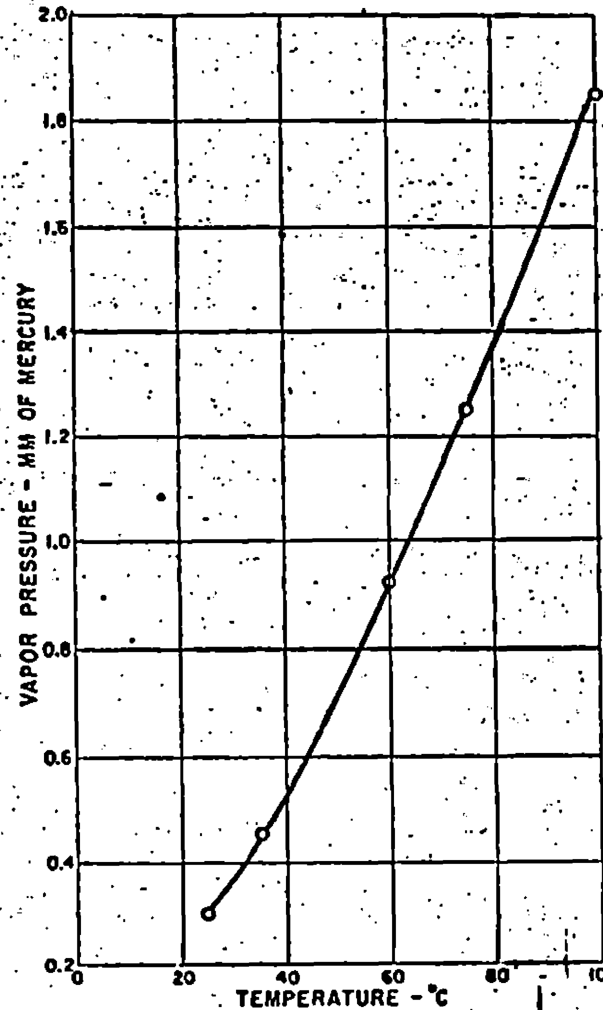

Figure 10
Showing the vapor pressure of 10C transformer oil as affected by temperature.

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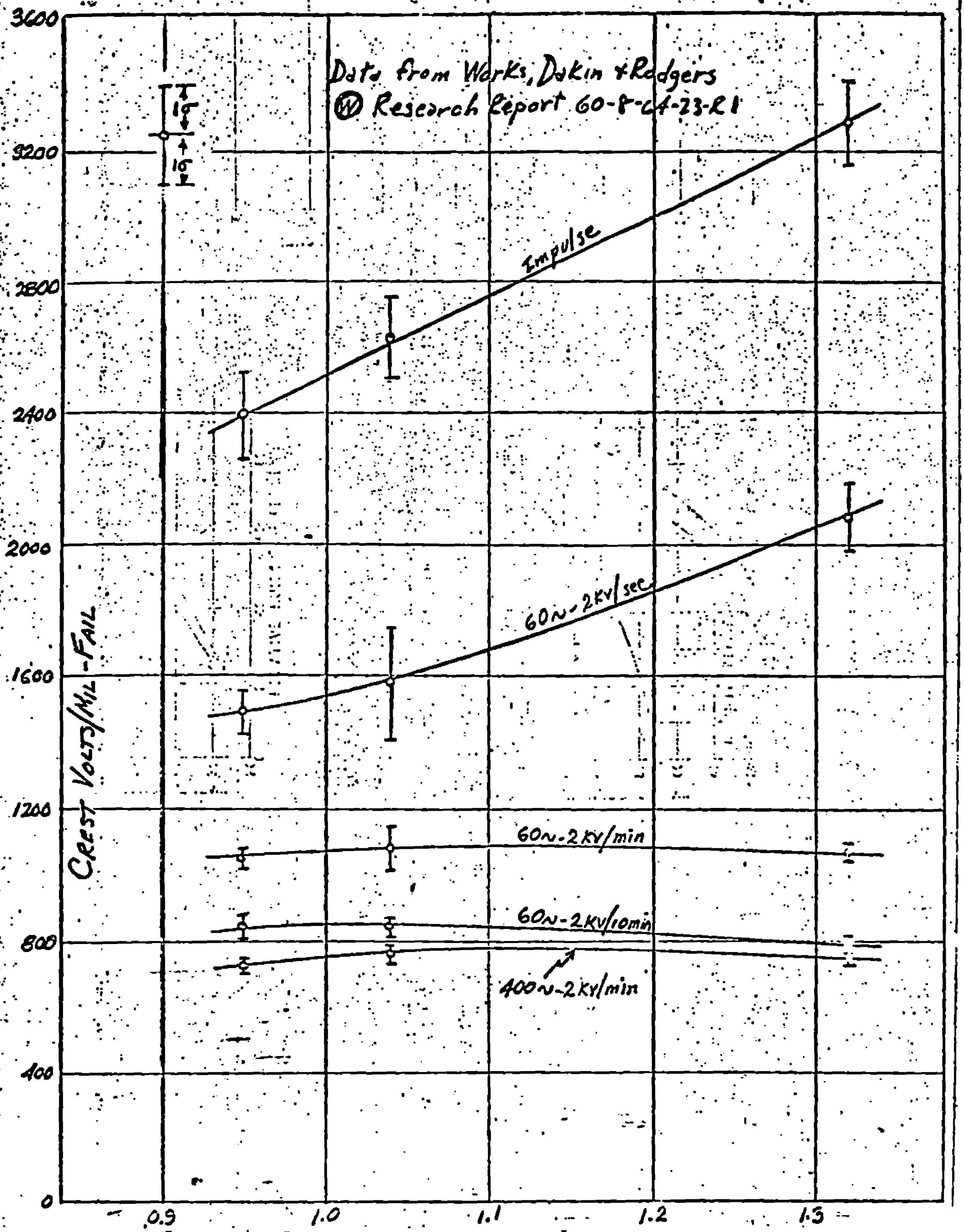

SPECIFIC GRAVITY OF DRY PRESSBOARD - .056" THICK

FIG. 11

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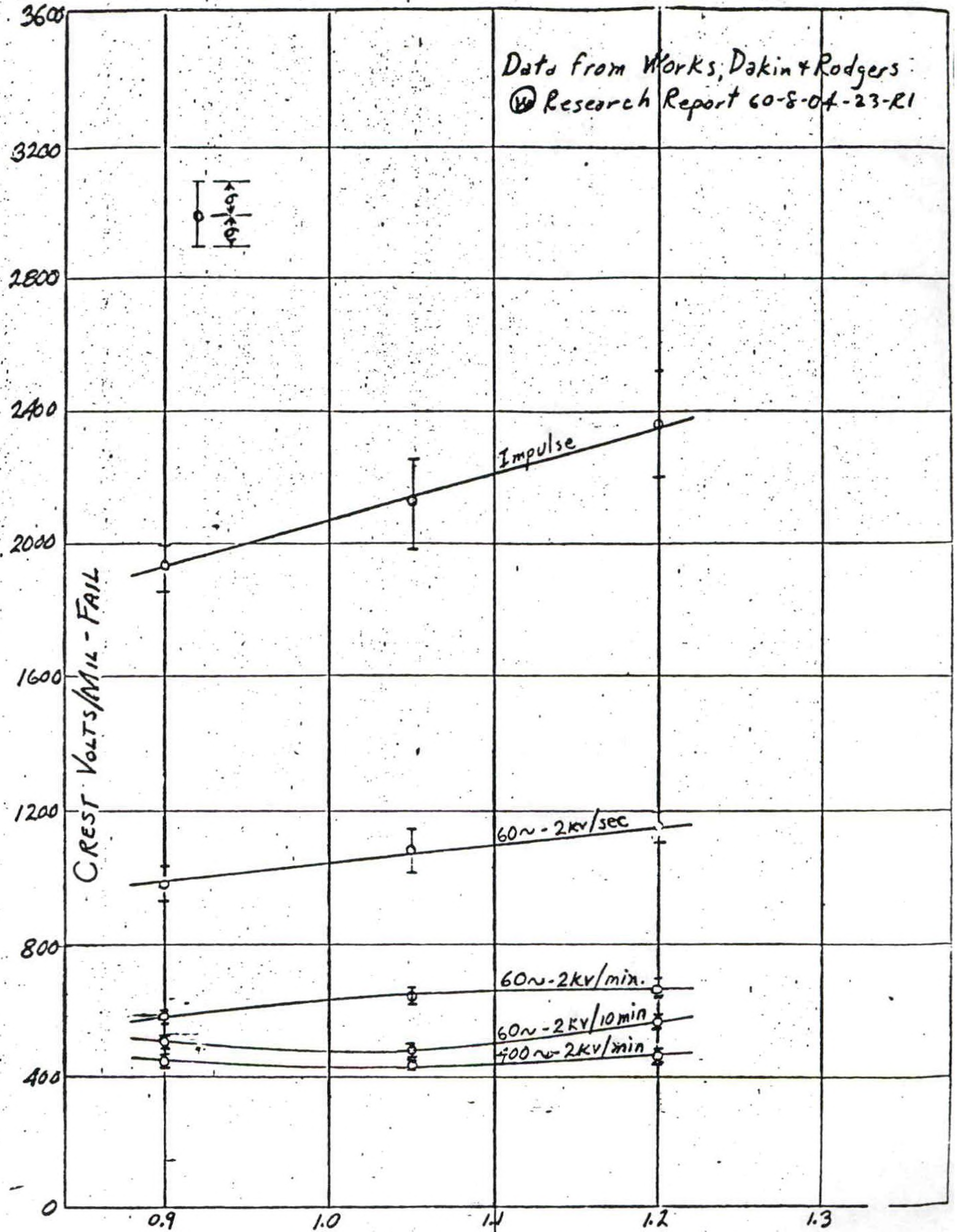

Fig 12

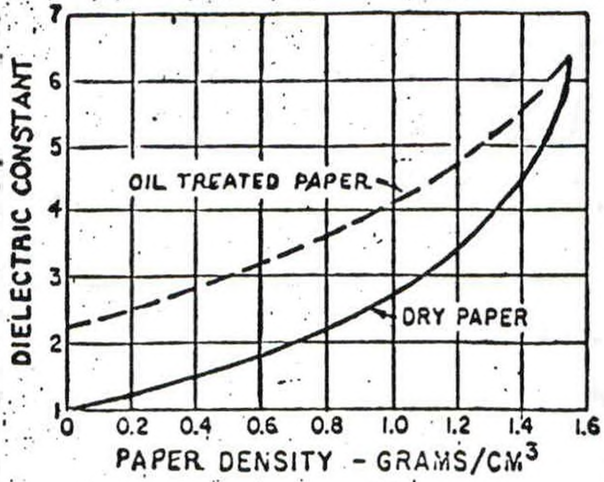

Figure 13
The effect of density on the dielectric constant of dry and oil impregnated paper.
(Based on Reference 39)

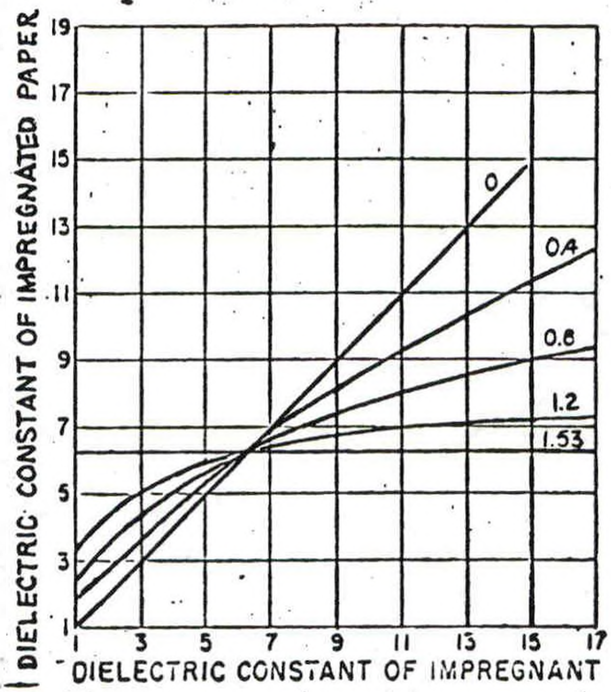

Figure 14
The dielectric constant of impregnated paper in relation to the density of the insulating paper and the dielectric constant of the impregnant.

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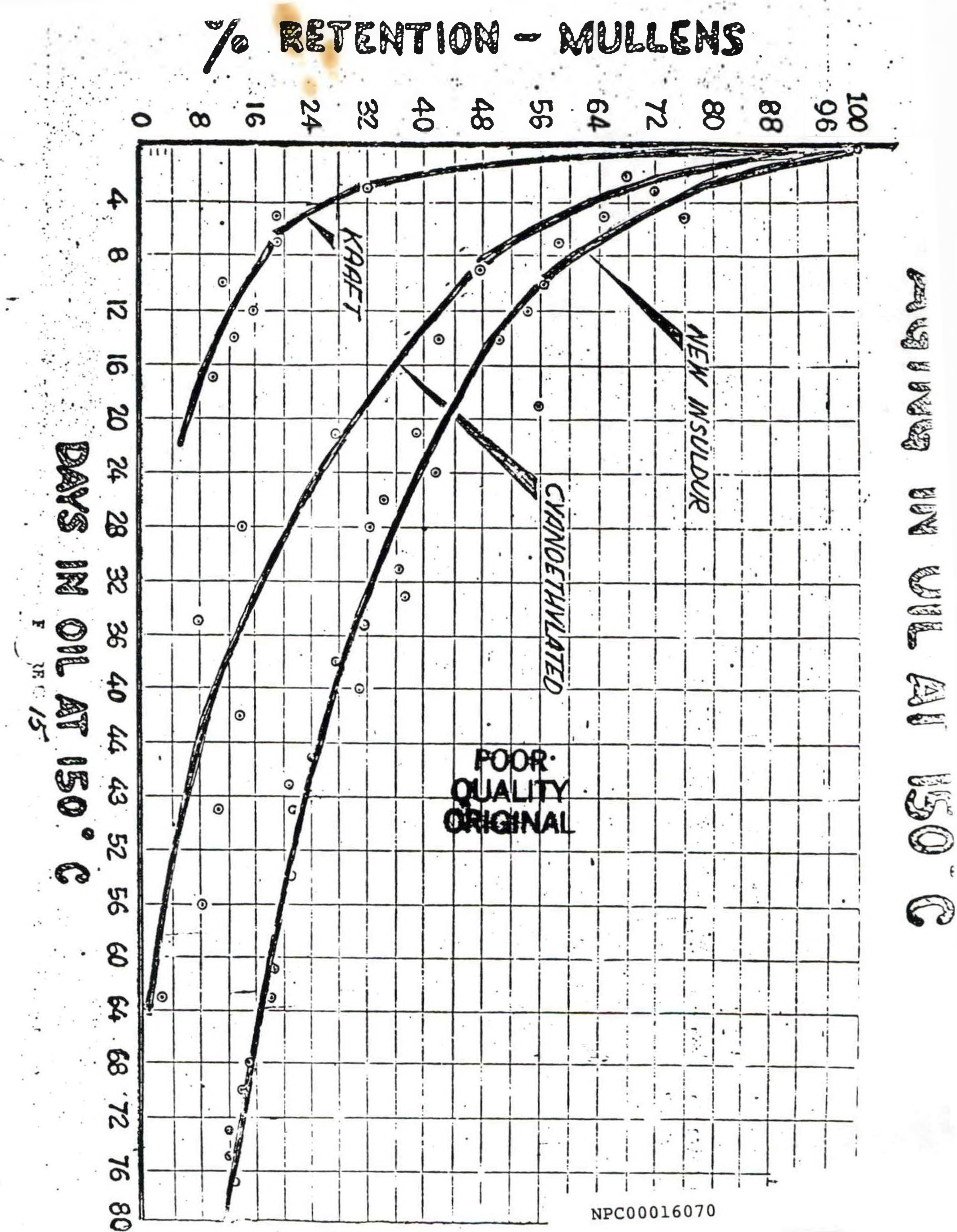

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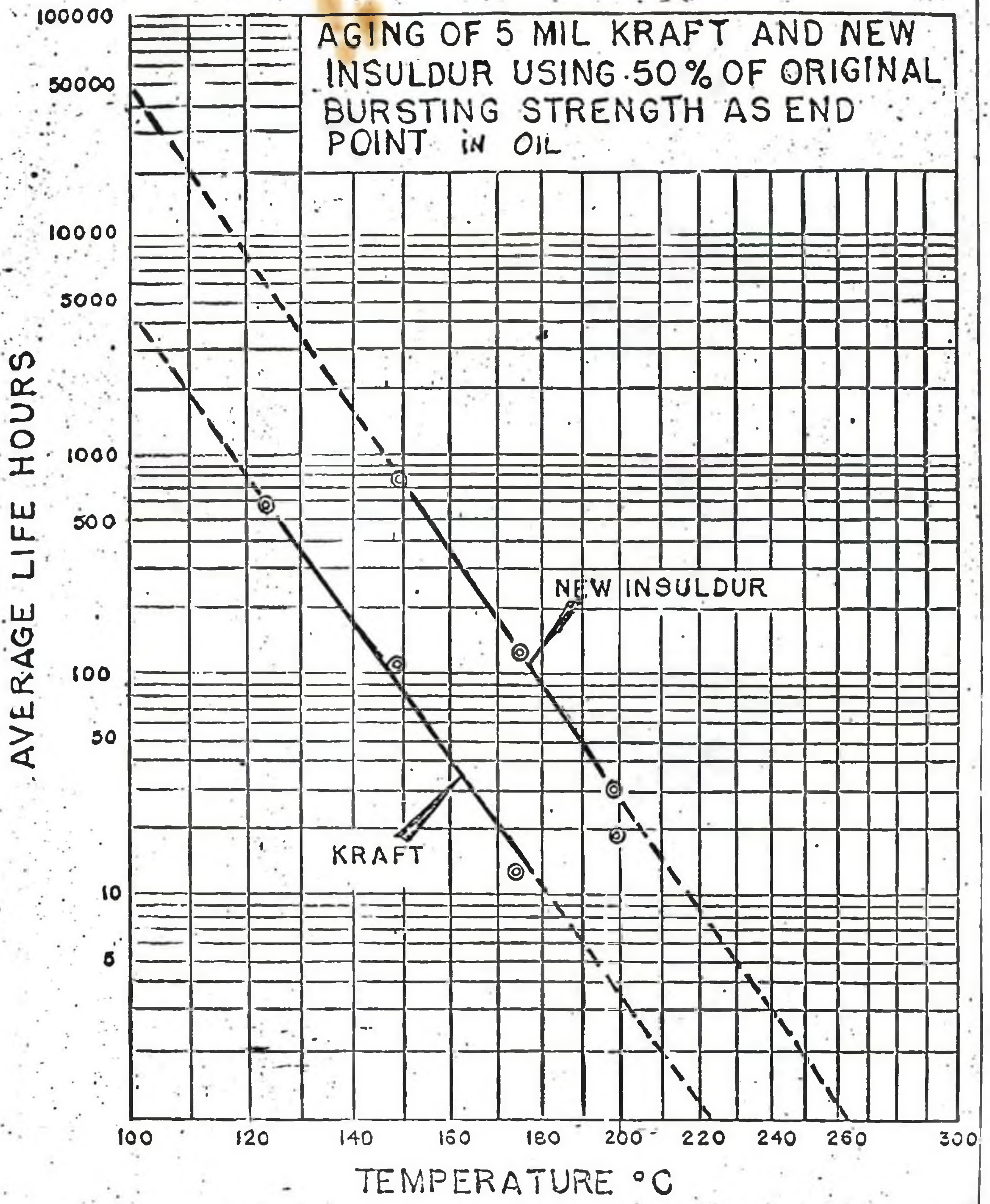
AGING OF 5 MIL KRAFT AND NEW INSULDUR USING 50% OF ORIGINAL BURSTING STRENGTH AS END POINT IN OIL
AVERAGE LIFE HOURS
100000
50000
10000
5000
1000
500
100
50
10
5
NEW INSULDUR
KRAFT
100
120
140
160
180
200
220
240
260
300
TEMPERATURE °C

Figure 16

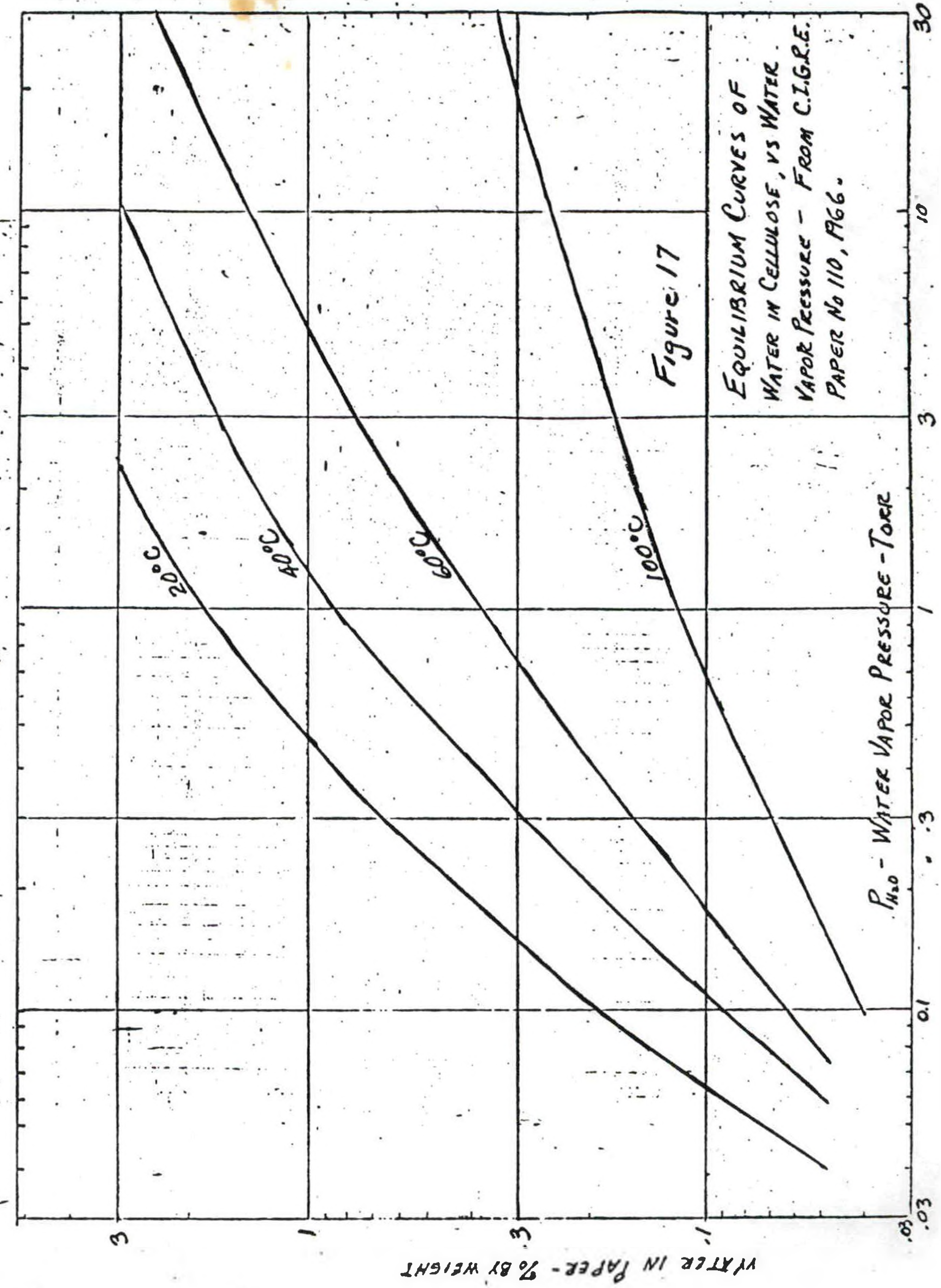

Figure 17

Equilibrium Curves of Water in Cellulose, vs Water Vapor Pressure - From C.I.G.R.E. Paper No 110, 1966.

SKETCH SHEET
FORM 28577

WESTINGHOUSE ELECTRIC CORPORATION

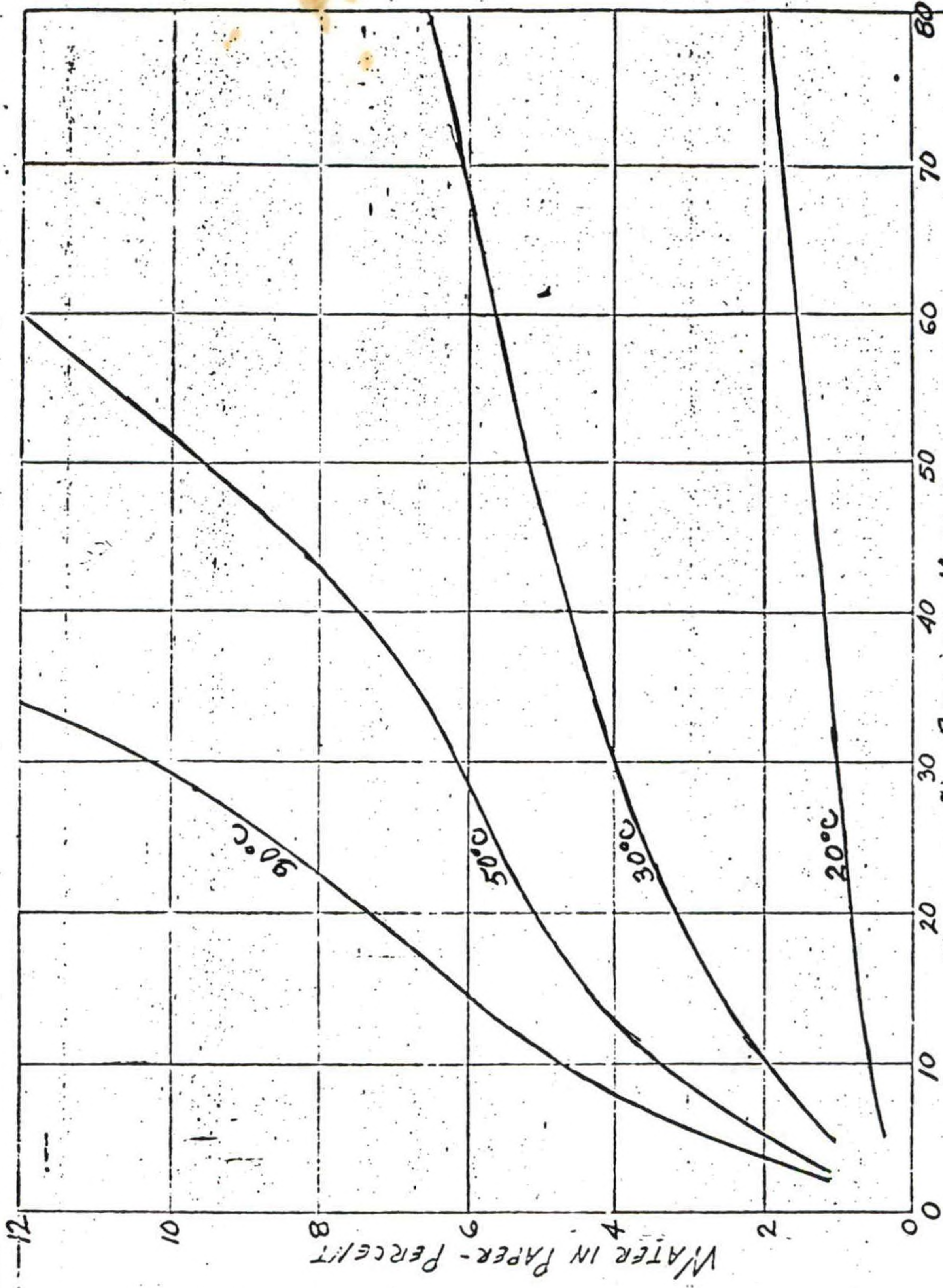

FIGURE 18
HUMIDITY EQUILIBRIUM IN AIR-OIL-PAPER SYSTEM

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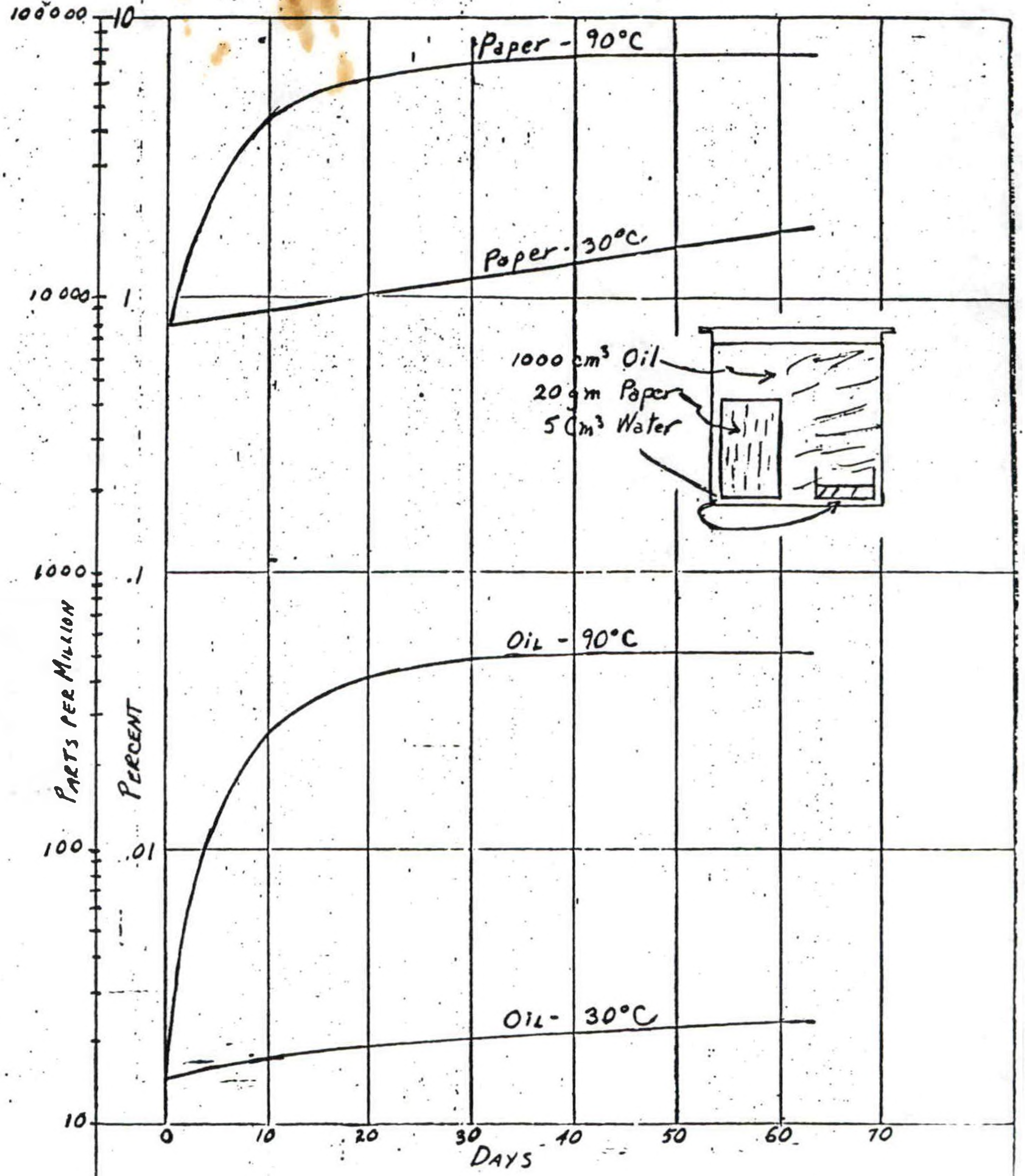
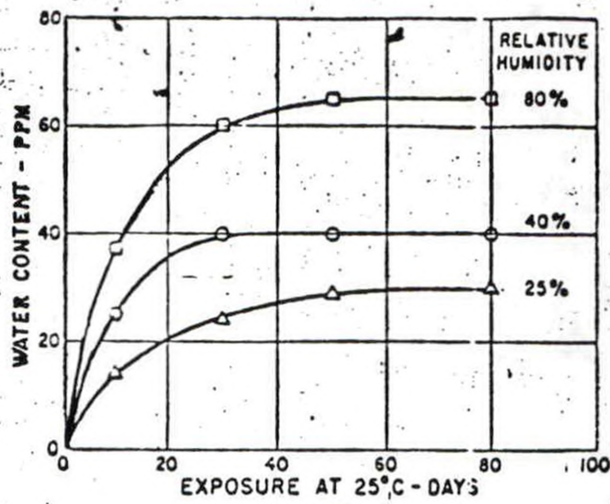


Absorption of water by dry paper and oil, with an excess of water present.

Figure 19

Source - Fabre "Chemical Criteria of the Degradation of Oil-Impregnated Paper in Electrical Apparatus"



The rate of moisture pick-up by transformer oil when exposed to humid air under controlled conditions as described.

volume of liquid	7500 cc
surface area exposed	375 sq. cm.
depth of liquid	20 cm

Figure 20

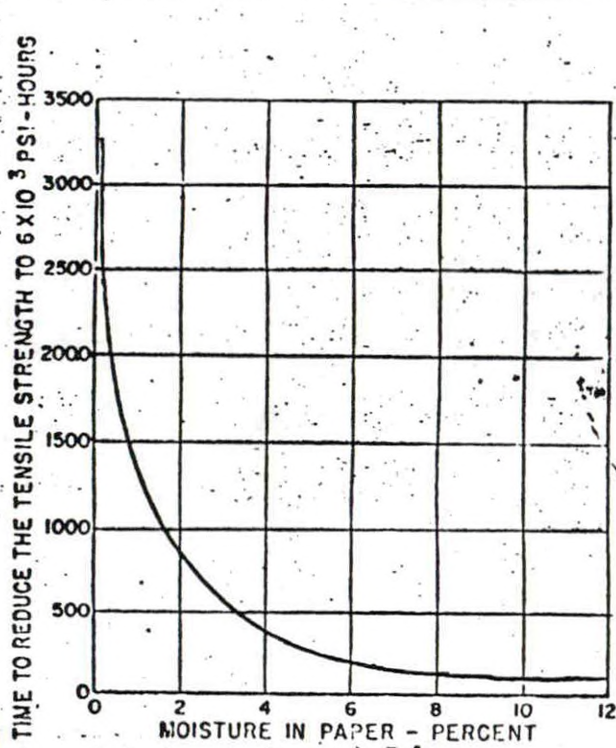


Figure 21
Showing the effect of minor additions of moisture in the range below 2% on the time necessary to reduce the tensile strength of manila paper to 6 pounds per square inch when aged in nitrogen filled, glass tubes at 120°C.

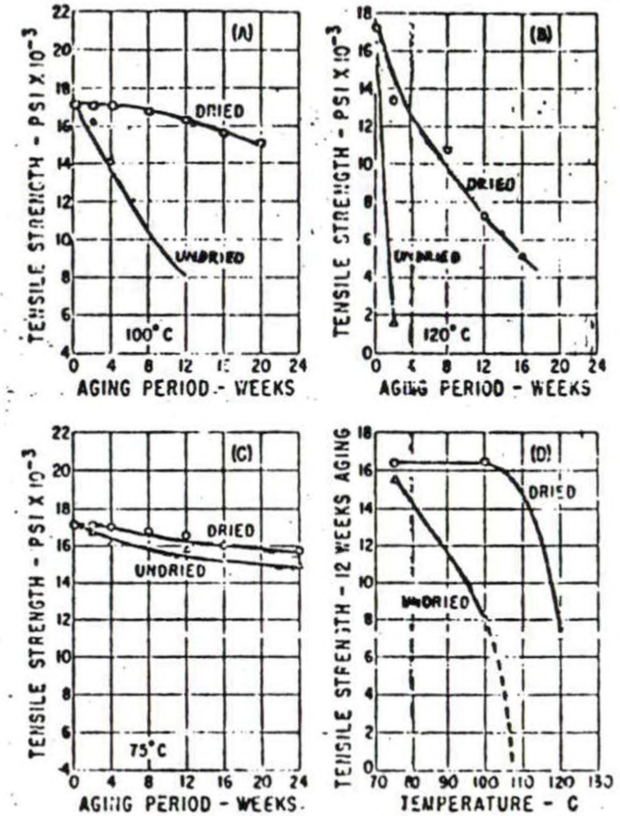


Figure 22
The aging characteristic of oil impregnated manila cable paper in sealed glass containers, as affected by the presence of moisture.

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J. Hilko

J. Hilko

TESTING OF LIQUID DIELECTRICS (OIL AND INERTEEN)

Process Specification SH-80124
11th Revision

This specification covers sampling and testing of Liquid Dielectrics.

Section 7.6 removed.
Section 8.2.1 modified as per meeting 3/26/71.

Effective date: 4-2-71

/klt

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