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The role of electrical noise in screening transformers prone to failure

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THE ROLE OF ELECTRICAL NOISE IN SCREENING TRANSFORMERS PRONE TO FAILURE

by
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APPROVAL SHEET

Title of Thesis: The Role of Electrical Noise in Screening Transformers Prone to Failure

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ABSTRACT

Title of Thesis: The Role of Electrical Noise in Screening
Transformers Prone to Failure

Rajeev D. Shirodkar, Master of Science, 1983

Thesis directed by: Dr. R.P. Misra, Professor of
Electrical Engineering

Insulation used as a barrier between the high voltage and low voltage windings of a transformer has sites of inhomogeneities like pinholes, cracks or voids, developed during the manufacturing process. Thus, these minute air pockets are stressed much more than the solid dielectric, on the application of a voltage stress, because the dielectric constant of the solid insulation is many times that of the air dielectric. As a result, excitation or ionization takes place in the air (gases). The amount of excited or ionized molecules is proportional to the volume of the inhomogeneities within the insulation.

Therefore, experiments were conducted to monitor the electrical noise generated due to partial ionization of the tiny air gaps in the insulation. This was done by placing the transformer in a plexiglas tubing, around which an antenna was wound. The antenna was connected to a highly sensitive Hammerlund receiver, whose carrier level meter was calibrated in S-units. For 5S units of noise to be generated, the voltage stress required to be applied to the insulation was measured for a sample of three hundred transformers.

The voltage readings were analyzed statistically and were found to have a normal distribution.

Seven units which gave high voltage readings and seven units which gave low voltage readings were subjected to accelerated life tests. This data has been analyzed statistically and has been found to be significant. The coefficient of correlation has been found and a linear regression equation has been formulated. The F-test of significance has been applied to the regression equation and has been found to be statistically significant.

ACKNOWLEDGEMENTS

It has been my privilege to have Dr. R.P. Misra as my advisor. A father-figure in this foreign land, his help has been invaluable in the guidance of this work. For his kindness and patience I am indebted to him.

To S. Mantha and S. Pathak, who epitomize friendship, I am grateful for their continuous assistance in the conduction of the experiments.

Thanks are due to Hewlett Packard, New Jersey Division, for graciously providing the transformers for the experiments.

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CHAPTER I

In the commercial and industrial fields there has been a long-standing motto concerning the requirements for a component: Quality, Price, Delivery. A vendor of components is often judged by his ability to furnish a well-made product, at a low price, in a short period of time. The experienced buyer knows that the three requirements may conflict with each other. High quality, for example, implies more costly ingredients and more testing time, and an increase in testing time and in the number of rejects tends to increase the delivery time as well as the cost. The modern version of the motto requires that the component be tested to explicit standards of quality, that it be competitively priced, and that delivery be accomplished in a reasonably short period of time.

Two additional requirements dominate present day specifications: miniaturization and reliability. Miniaturization is the design or redesign of a component for minimum size and weight. Reliability is the confidence that the part will perform to specifications.

Reliability is now considered so important that it is given priority over cost, delivery and miniaturization. It is sought as a separate item, for it is recognized that reliability and quality, although closely related, are not synonymous, that high cost does not necessarily ensure reliability, and that reliability can be adversely affected by miniaturization unless the designer is very careful. Low reliability, even though inexpensive in the beginning, results in high cost due to maintenance and repair and secondary expenses incurred due to failure.

This project endeavors to study the reliability screening procedures with respect to electronic transformers, the purpose being to select from a set of devices those devices having higher reliability or alternatively to reject those devices having inferior reliability. It should be noted that reliability screening differs from quality control in several respects. First, it is not the purpose of life testing to detect devices which are defective at the time of measurement. In fact, it is assumed that all devices are initially good. Second, unlike acceptance sampling, parts qualification, etc., reliability screening is a 100 percent inspection procedure. Third, classification by a screening procedure is accomplished with respect to lifetime requirements and operating conditions involved in the intended application of the device. Thus it is seen that the concept involved in reliability screening, as opposed to quality control, is not to reject a device strictly because one or more initial parameter measurements are in some unacceptable region, but to consider such measurements as precursors of early failure.

Noise analysis of electronic components has been applied in the detection of defects in components on a broad scale. Reduction in failures of components of an order of magnitude or more has been achieved by noise screening, where the major defects have been noise generators. Success using noise measurements in the improvement of quality whether by screening or manufacturing process control is dependent on an understanding of the noise generators within the component. Certain noise generators must exist, and their magnitudes are predictable by theory or empirical data. However other types of noise, or excessive noise, could be indicative of a defect within the component, and in certain physical conditions is necessarily an indication of early failure due to high electric field or localized high current density.

The scope of this study is to examine the major insulation between the transformer windings. The noise generated by the dielectric under high electric stress, but substantially below the withstanding voltage, is measured for the entire sample of three hundred transformers. The results obtained by statistical sampling theory are verified by accelerated life tests.

Chapter II discusses the properties of dielectrics, their merits and demerits which aid in their selection for the intended application, as also their behavior under the influence of different stresses. Chapter III is devoted to the study of dielectric breakdown mechanisms. The theory of corona and how it affects the performance of an insulator is studied in Chapter IV. Study of electrical noise emanating on account of corona is conducted in Chapter V. The experimental procedure involving measurements of electrical noise under high electric stress is depicted in Chapter VI. The statistical analysis of the voltage measurement on the sample is presented in Chapter VII. Inferences from the accelerated life test data are worked out in the Appendix.

CHAPTER II

FUNDAMENTALS OF DIELECTRICS

2.1 Introduction

Insulating materials, being extremely poor conductors of electricity, are used for barriers between two conductors carrying electricity. They are expected to resist physical, chemical, and electrical stresses over a range of temperatures; hence the selection of an insulating material depending upon the requirements, i.e., the kind and degree of stresses to which it is expected to be subjected. It is impossible to get a perfect insulating material as such; compromises have to be made with respect to its use under different stress conditions.

Essentially, an insulator must be selected depending on its application and it must be able to meet the following important properties:

a. Intrinsic electrical strength;

b. Reduced susceptibility to degradation due to ionization;

c. Thermal stability;

d. Radiation susceptibility.

This chapter deals with the fundamentals of dielectrics — their properties, their characteristics, their merits and demerits.

In transformers we encounter two kinds of insulations, major and minor. Major insulation is the one between HV and

LV windings, between HV and ground, and between LV and ground. The minor insulation is the one between turns of windings, between coils, at the tap leads and at the winding leads. So what we are dealing with is a whole system of different insulations.

2.2 Division of Voltage Stresses

When more than one layer of insulation material is used in series between circuit elements of a.c. potential difference, the stress in each is inversely proportional to the dielectric constant (ϵ) of each material. Thus the insulation with the lowest ϵ has the highest stress. Often this is air or gas which has the lowest dielectric strength. When the voltage is d.c. the voltage drop is simply IR. Therefore the material with the highest resistance will have the highest stress. It should be noted that the total resistance may be composed of both volume and surface resistances.

When the stress is unidirectional pulses, there is an a.c. voltage component which will be the source of a.c. stresses and may be the source of corona. Even a large ripple on d.c. voltages may produce a.c. stresses sufficient to require investigation and may be a corona source.

2.3 Dielectric Constants

The dielectric constant (more precisely, the relative dielectric constant) is a function of temperature and frequency. The change with temperature is small for many materials, but some plastics increase with temperature in a manner which should not be ignored. As an example, a filled epoxy resin, used for embedding electronic apparatus, has an ϵ of 3.22 at 25°C, 4.17 at 100°C and 5.29 at 160°C. The change of with frequency is usually not as dramatic but often significant when frequencies reach the MH_z range.

The ϵ for composite materials such as filled resins or impregnated paper varies with composition. It should be self-evident that if air ($\epsilon=1$) is replaced by a resin ($\epsilon>1$) the dielectric constant of impregnated material should increase over unimpregnated material. This emphasizes an important reason for complete impregnation (using a good vacuum): by replacing the air, the dielectric strength of impregnated material is increased, and the dielectric constant is in fact the expected value.

2.4 Dielectric Strength of Insulation

The dielectric strength of materials, available from trade literature, is the short time value which usually is considered higher than the long time withstand value. In addition, the long time withstand strength may be quite sensitive to gas excitation or corona. In many instances, the usable dielectric strength may be considerably higher if no excited or ionized gases are present.

The dielectric strength of air is given by familiar Paschen's curve which tells us several interesting things, among them that at pressures below the minimum of the curve larger gaps break down at lower electric fields than smaller gaps. The curve also tells us that the dielectric strength in volts per mil decreases with increasing spacing. For this discussion it is important to remember that when gas is in series with other insulation and is overstressed, the result is corona.

The Paschen's curve in Figure 2.1 is for uniform field, and of course many insulation configurations are not uniform field. A utilization factor of 1/3 is sometimes used for point electrodes, but as indicated in Figure 2.2 at small spacings the utilization factor approaches unity. The effect of electrode shape is most pronounced in gases although it is obvious that stress concentrations will occur at point or sharp edge electrodes in liquids and solids. In this connection it is well to remember that a small wire is a sharp edge.

The dielectric strength in terms of breakdown electric field of liquids and solids also decreases with increasing thickness. The presence of gas bubbles in liquids reduces the dielectric strength drastically and liquids saturated with gas will break down at lower stresses when subjected to lower pressures. This again points to the necessity of vacuum impregnation. The dielectric strength of liquids is also subjected to deterioration by oxidation or dissolving of substances in solid insulation in the system. It should be unnecessary to caution against the presence of water, but

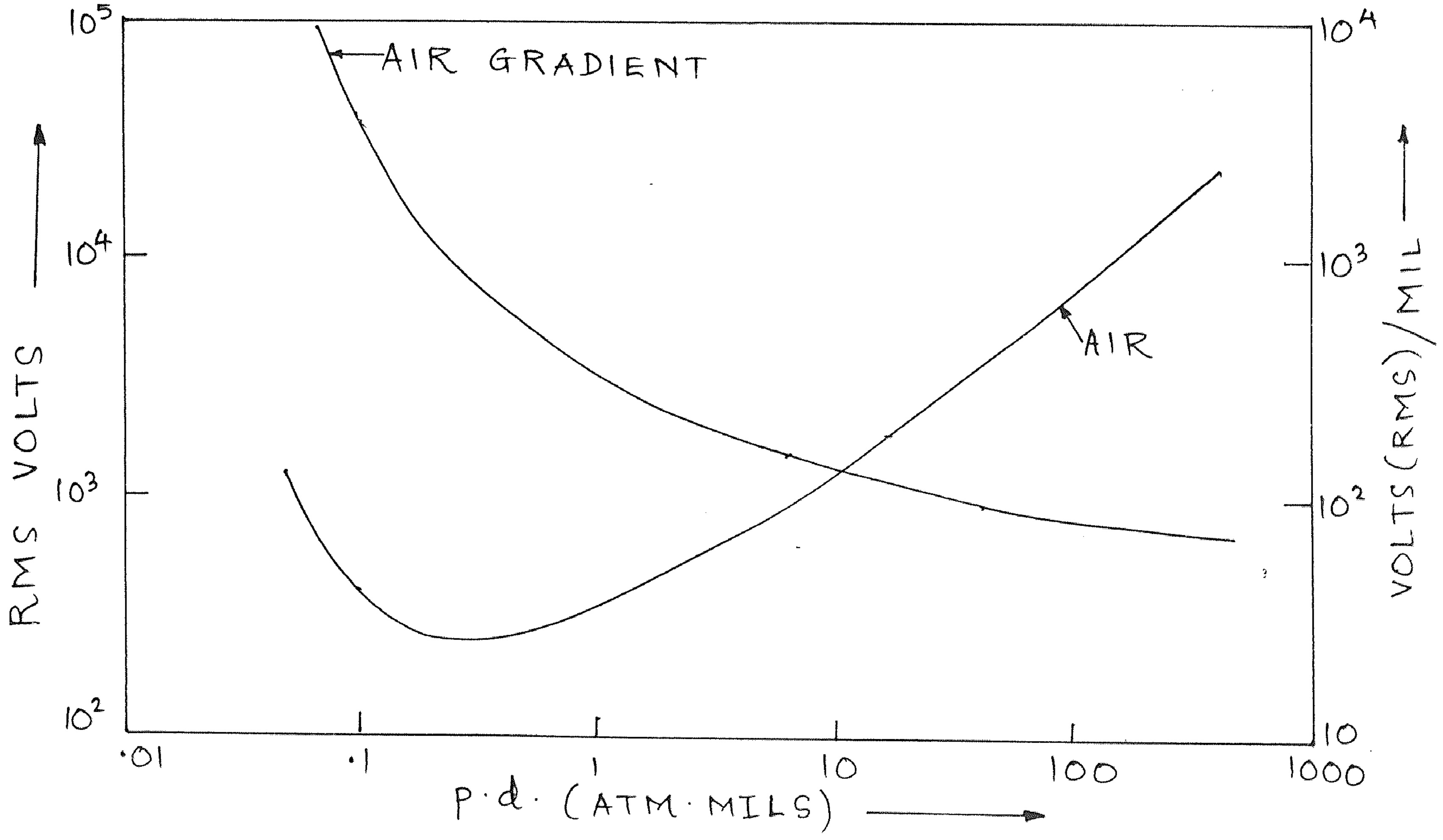


Fig. 2.1 Pressure-Spacing Dependence of the Dielectric Strength of Gasses (Paschen's Curve).

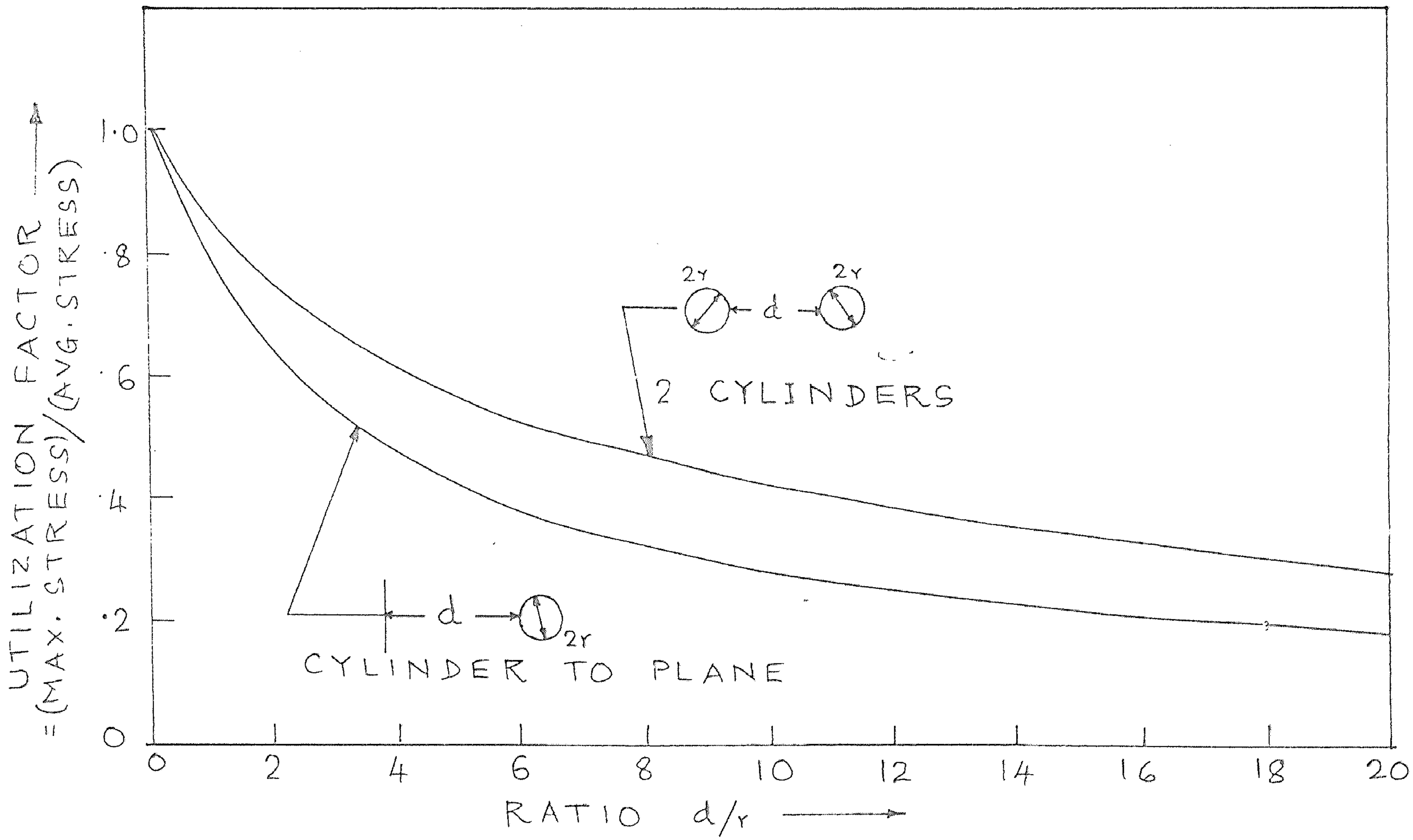


Fig. 2.2 Utilization Factor as a Function of Spacing to Radius Ratio

water acts as a catalyst to increase deterioration and is one of the products of thermal deterioration of many insulation materials, notably cellulose.

Solids typically have much higher dielectric strength than liquids or gases. The utilization of their inherent strength is often difficult due to conditions existing adjacent to the solid insulation where gas may form corona. The inherent dielectric strength of solids can only be achieved by having a uniform field and avoiding series air gaps. Series gas gaps come in many forms, among which are: internal voids due to incomplete impregnation or insufficient vacuum during potting, shrinkage cracks which may vary in size with temperature, interfaces due to poor bonding, intentional design spacing, etc. Another factor which must be considered in solids, especially in high voltage or in high frequency applications, is dielectric heating. The internal temperature rise due to dielectric heating is proportional to the square of the thickness. This then is another factor requiring a reduction of stress as the thickness increases.

2.5 Series Gas Spaces

The proper evaluation of insulations in series is important in the calculation of insulation stresses. Voids in moulded plastics may contain gas of unknown composition at an indeterminate pressure and the pressure will vary with temperature. Stabilization of the pressure within the void will come with time at temperature through diffusion if the temperature is constant. Complete elimination of this type of void is the best solution.

If the void is a shrinkage or a crack (e.g., within the transformer coil insulation), it may be assumed that the thickness varies from zero to some finite value which a designer would have to assume. Then it must be assumed either that the thickness of the solid insulation is constant and that the void results from an increase in electrode spacing or that the electrode spacing is constant and the crack is the result of shrinkage of solid insulation. In the first case as the crack widens, the stress on the gas decreases, and as the gas space increases, the dielectric field strength of the gas decreases, but not necessarily at the same rate. In the second case, as the space increases, the stress on the gas increases and the strength of gas decreases.

2.6 Calculation of Voltage Stresses on Each Element

If any a.c. voltage, a spacing and a basic insulation are known or assumed, the voltage stress in series may be obtained approximately by multiplying the stress on the basic insulations by the ratio of the dielectric constants.

When $T_1 \gg T_x$

$$G_x \simeq G_1 \cdot \frac{\epsilon_1}{\epsilon_x}$$

T = thickness in mils

G = stress in volts/mil

ϵ = dielectric constant

Subscript 1 = Designation of basic insulation

Subscript x = Designation of insulation under investigation.

The voltage stress on each insulation element in series may be calculated by:

$$G_x = \frac{E}{\epsilon_x \left(\frac{T_1}{\epsilon_1} + \frac{T_2}{\epsilon_2} + \ldots\ldots + \frac{T_n}{\epsilon_n} \right)}$$

E = total volts

G = stress in volts/mil

T = thickness in mils

ϵ = dielectric constant

So far we have considered some aspects of the electric strength properties of the insulation system of transformers. The two other aspects which we will now consider briefly regarding the properties required of insulating materials are (i) reduced susceptibility to degradation due to ionization, and (ii) thermal stability.

2.7 Ionization

The gases subjected to applied high voltages undergo ionization. It may be a small discharge or an arc. Damage so incurred is observed as carbonization, which is detrimental to insulating materials. Hence it is necessary to eliminate sources which cause ionization, like residual gases, moisture and decomposition products of hydrocarbons and cellulose. Hence it is necessary to evacuate residual gases to as low vacuum as possible and for moisture to be driven out by heat.

Potting of transformers is done to prevent moisture. However it was observed that reliability is lowered. The probable reasons for lower reliability are:

a. Potting causes air bubbles, which in turn cause carbonization, leading to failure.

b. Sufficient heat not being removed causes a rise in temperature of windings.

2.8 Thermal Degradation

Thermal degradation of insulation occurs due to impurities within its material, which creates localized spots weak in resistivity. When field is applied, low current flows through these spots but increases as temperature increases, leading to hot spots. Since current increases, therefore temperature increases further. This cumulative process leads to thermal breakdown. Hence components in insulation should have low dielectric loss to ensure good thermal stability. Dielectric loss is a function of capacitance and the dissipation factor of each component. But dielectric strength under surge conditions needs high capacitance. So we see that surge strength and loss factors oppose each other. Hence a compromise between these two must be reached.

2.9 Thermal Characteristics of Insulations

All insulations have the property of aging in mechanical strength at all temperatures, and the rate of aging increases quite rapidly with increased temperature; in fact, the rate approximately doubles for each 8°C increase in temperature.

For Class A insulation, two principal characteristics must be considered: the dielectric strength and the mechanical strength. When aged in oil the dielectric strength of insulation remains high until it reaches a certain point when it falls off suddenly. An examination at this point shows its mechanical strength is practically zero. In other words, the material is quite brittle and carbonized. Dielectric strength alone, therefore, cannot always be depended upon to judge the effect of temperature on insulators.

Several means of determining the effect of temperature on the physical condition of the insulation are available, such as folding, tear, stretch, burst, and tensile tests. When judged by folding tests, life of insulation is short; the life is longest when judged by tensile strength.

But for dry-type transformers using Class B insulation, the tensile strength cannot be used since basic insulation is of materials like glass fiber, asbestos, whose mechanical strength is not much affected by temperature. The criterion for determining condition could be dielectric strength or the insulation resistance.

For synthetic insulating materials, their hydrophobic nature could be examined as a measure of their deterioration. The longer a material can maintain its hydrophobic nature, the longer it will preserve its surface resistivity and thus inhibit the flow of excessive leakage current. The measurement of hydrophobicity of a surface can be done by measuring the contact angle.

The selection of permissible maximum safe operating temperatures would be simple, if rapid deterioration took place above a certain temperature, and below which no deterioration took place. However, since deterioration takes place at all temperatures and amount of deterioration is a function of time, temperature and electric field, etc., it is impracticable to fix the exact allowable temperatures above which transformers should not be allowed to operate. It follows, therefore, that transformer insulation can be safely subjected to relatively high temperatures provided their duration is sufficiently short. It is this fact that makes it possible to operate transformers at short intervals at temperatures not advisable for continuous operation.

2.10 Variation of Breakdown Strength with Thickness

Dielectric strength of insulation never increases in direct proportion to its thickness, when tested in a uniform field. Dielectric strength of most insulating materials can be expressed by an exponential formula in which strength increases as the thickness is raised to some power, generally less than unity.

$$KV/_{m} = AT^{n}$$

$KV/_{m}$ = dielectric strength

A = constant depending on material

T = thickness

n = constant varying from 0.5 to 1.0

For uniform fields n is higher than for non-uniform fields.

2.11 Effects of Time of Voltage Application on Dielectric Strength

Within the time limits ordinarily used in low frequency tests the breakdown strength is influenced to a large extent by the storage and dissipation of heat in the material. When an a.c. voltage is applied the material begins to generate hysteretic and dielectric losses. At first, all the loss is stored and temperature starts to rise. As soon as temperature rises, material starts to dissipate heat. Until a state of equilibrium is reached, temperature continues to rise, resistance of the material decreases and current increases. Eventually the current runs away. The runaway point of the current is the breakdown value. After the equilibrium state is reached, no further decrease in breakdown strength occurs. This phenomenon is accelerated and can become almost instantaneous due to high electric field in a hot spot, which usually is the cause of the hot spot.

From the experimental data obtained by investigators on the breakdown strength for various directions of applied voltages, and varying frequencies, the breakdown strength can be expressed empirically as follows:[1]

---

[1] See Bibliography No. 4-67

$$V = V_o \left\{ 1 + \frac{C}{t^n} \right\}$$

Where V_o = breakdown strength at any time,

C = constant, and t = time in minutes.

If V_1 = breakdown strength at time = 1 minute,

then $V_1 = V_o (1 + C)$.

Let $R_t = \frac{V}{V_1} = \frac{1 + C/t^n}{1 + C}$

Let $1 + C = 1/a$ then $R_t = a + \frac{1 - a}{t^n}$

2.12 Effect of Frequency on Dielectric Strength

The dielectric strength of an insulation depends on the intensity of "corona," a phenomenon discussed in detail in Chapter IV. The time to failure is inversely proportional to corona intensity. The corona intensity is propritional to the voltage amplitude and frequency of corona discharges.

The corona discharge pulse frequency is dependent on the applied voltage frequency. With direct voltages corona discharge stream charges the surface to a voltage which prevents further discharge streamer from occuring until the surface charge leaks off by surface or volume conductivity. Thus with the application of d.c. voltage corona discharges appear intermittently and its intensity is considerably lower than with an a.c. voltage application on the same insulation. Furthermore, if the corona discharge rate is limited by surface charges, then increasing applied voltage frequency will increase the repetition rate of discharges and eventually will increase rate of erosion.

CHAPTER III

BREAKDOWN IN SOLID DIELECTRICS

3.1 Introduction

All final total breakdown in solid dielectrics is ultimately thermal in the sense that the discharge track involves at least the melting and probably the vaporization of the dielectric. In common usage, the classification of a breakdown process as thermal means that it can be satisfactorily explained using reasonable extrapolations of the electrical and thermal conductivities from values obtained substantially below breakdown. Conversely we classify breakdown as purely electrical when it cannot be explained as due to processes that are not in evidence until very close to breakdown.

3.2 Thermal Breakdown

Most dielectrics show increasing electrical conductivity and decreasing thermal conductivity as the temperature increases. For this reason breakdown at high temperatures tends to be thermal in nature. Much of the early experimental work was at high temperatures, or under conditions in which the electrodes were poor heat sinks; as a consequence thermal breakdown was studied extensively. The basic equation[1] for thermal breakdown is:

$$C\frac{\partial T}{\partial t} - \mathrm{div}\ (K\ \mathrm{grad}\ T) = \sigma E^2 \qquad (1)$$

---

[1] See Bibliography No. 3-81

this is where:

K = thermal conductivity; t = time

σ = electrical conductivity; C = constant

T = absolute temperature; E = electric field

The equation of current continuity is:

$$\mathrm{div}\ (\sigma\bar{E}) = 0 \tag{2}$$

The conservation of energy is expressed by equation (1) and hence is necessary. Equation (2) requires that the dielectric relaxation time be much smaller than the time intervals considered in the integration of equation (1).

If the electrical conductivity, σ, is not temperature dependent, then the electric field, E, at any point is determined only by the electrode geometry and the applied voltage. However a temperature dependent σ is itself a cause of variation in the electric field strength in order to satisfy equation (2). In the following we develop transient solutions to the equations for thermal and electrical conductivity functions given by

$$K = K_o/T \tag{3}$$

$$\sigma = \sigma_o \exp\ (-A/KT) \tag{4}$$

respectively, where K_o, σ_o, and A are constant parameters of the dielectric.

3.2a Plane Parallel Electrodes

For plane parallel electrodes with the z coordinate normal to the electrode surfaces, (1) and (2) with the use of (3) and (4):

$$C\frac{\partial T}{\partial t} - \frac{\partial}{\partial z}\left(\frac{Ko}{T}\frac{\partial T}{\partial z}\right) = \sigma_o E^2 \exp\left(-A/KT\right) \quad (5)$$

$$j = \sigma_o E \exp\left(-A/KT\right) \quad (6)$$

where j is the current density. Application of a step function voltage V_o at t = o gives the condition:

$$\int_o^d E\,dz = V_o \text{ for } t > o \quad (7)$$

where d is the electrode separation. Assuming electrodes of large heat capacity gives:

$$\left.\begin{aligned} T = T_o \text{ for } z &= o \\ \text{and } z &= d \end{aligned}\right) \quad (8)$$

where T_o is the ambient temperature.

Solution of the partial differential equation under the above conditions yields the functions T(z,t) and E(z,t) which are both symmetric about the mid-plane of the dielectric slab. We can therefore replace (8) by:

$$\left.\begin{aligned} T = T_o &\quad \text{for } z = o \\ \frac{\partial T}{\partial z} = o &\quad \text{for } z = d/2 \end{aligned}\right) \quad (8a)$$

Finally, $j(t) = \sigma(z,t)\ E\ (z,t)$ is not a function of z, and can be calculated from (6).

3.2b Cylindrical Electrodes

For cylindrical geometry with inner and outer electrode radii r_1 and r_2 respectively, equation (5) is replaced by:

$$C\frac{\partial T}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{Ko}{T}\frac{\partial T}{\partial r}\right) = \sigma_o E^2 \exp\left(-A/KT\right) \quad (9)$$

Application of a step function voltage V_o at t = o gives:

$$\int_{r1}^{r2} E dr = V_o \text{ for } t > o \quad (10)$$

If the outer electrode is maintained at ambient temperature and the inner one allowed to take up the temperature of the adjacent portion of the dielectric, the boundary conditions become:

$$\left.\begin{array}{ll} T = T_o & \text{for } r = r_2 \\ \partial T/\partial r = o & \text{for } r = r_1 \end{array}\right) \qquad (11)$$

Solution of the partial differential equation shows an instability in the current density similar to that shown in figure 3.2. The temperature distribution rises monotonically from ambient near the outer electrode to a maximum near the inner electrode. However the electric field distribution shows an interesting development depending on the electrode radii. Figures 3.3 and 3.4 show the electric field as a function of a radial distance for an applied voltage of 1.25 KV and electrode separations of 5 mm. In both cases the applied voltage is in excess of critical voltage. Figure 3.3 illustrates the change in field distribution with time, when the ratio $r_2/r_1 = 2$. At zero time the field non-uniformity is determined by geometry only; after 5 seconds thermal effects plus geometry make the field nearly uniform and after 10 seconds thermal effects dominate so that the field is large near the outer electrode and small near the central one. Figure 3.4 illustrates the different situation that prevails when $r_2/r_1 = 6$. In this case thermal effects make a contribution to the field distortion, but do not overcome the strong geometric contribution.

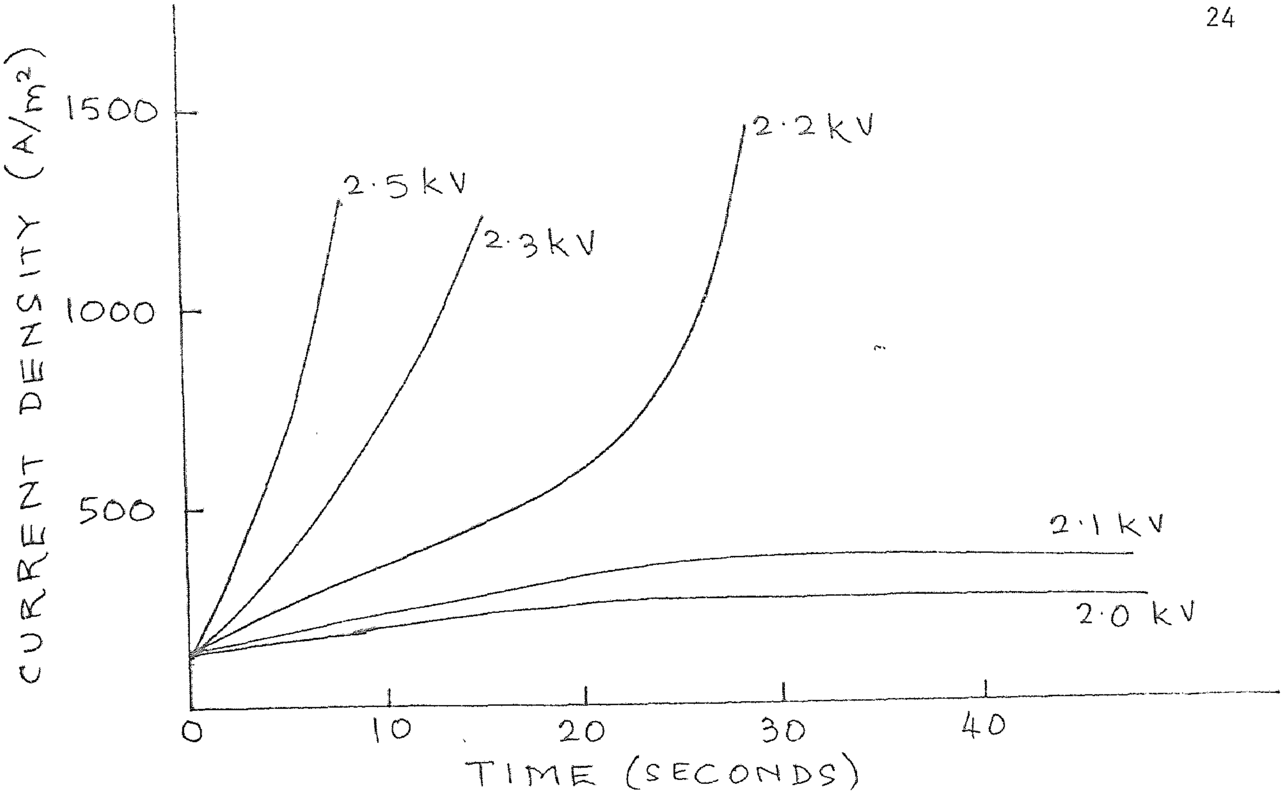
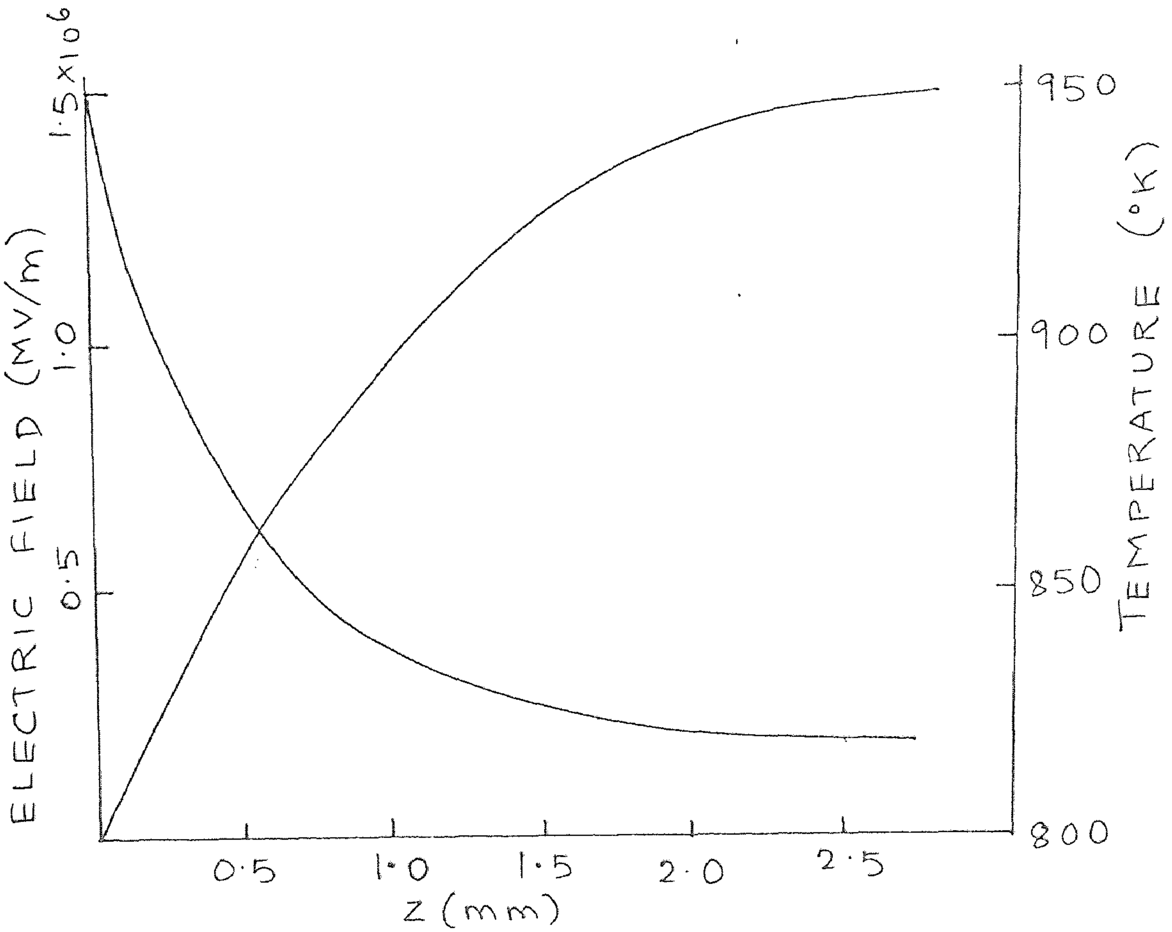


Fig. 3.1 Current Transients for Plane Parallel Electrodes



Feg. 3.2 Variation of Temperature and Electric Field Between Plane Parallel Electrodes at 5 mm Spacing and 2.1 KV Potential Difference After Attaining Steady Conditions

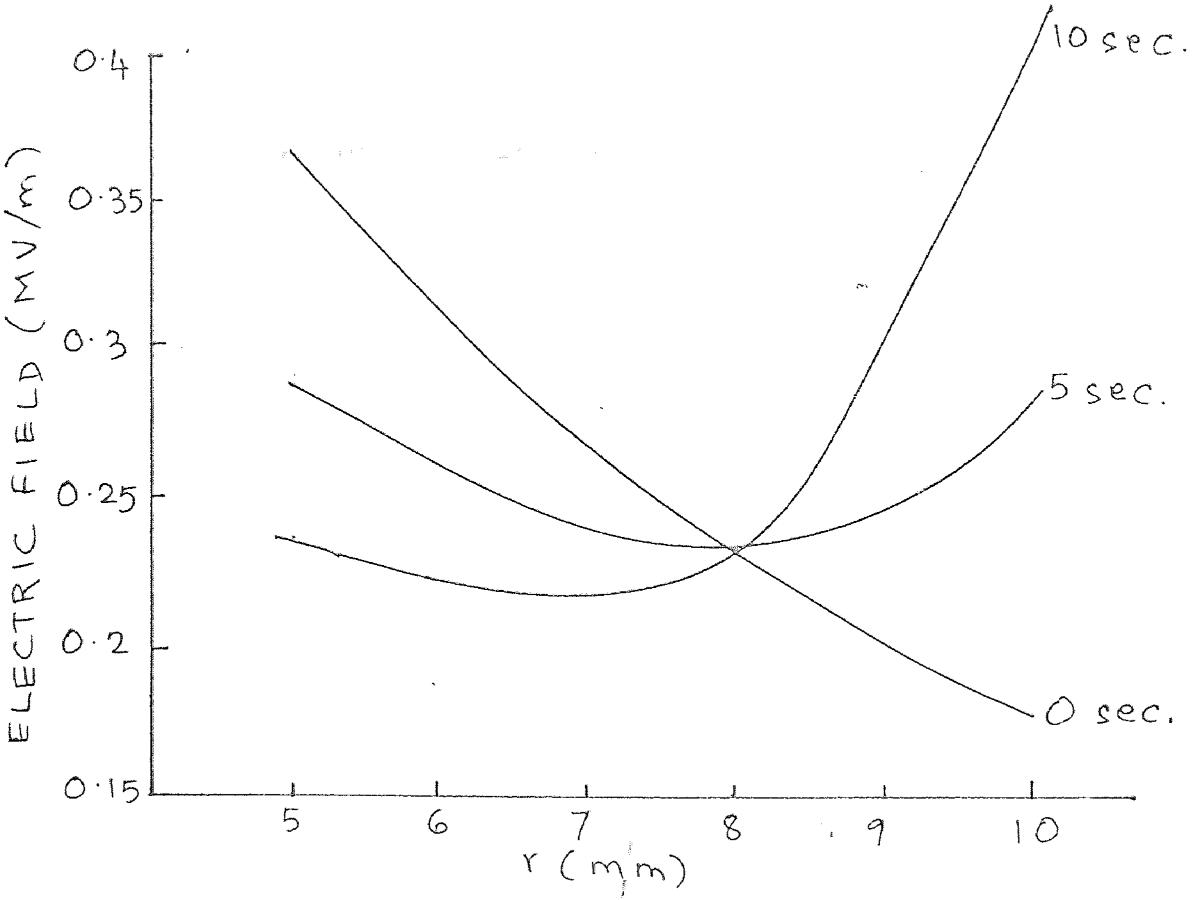


Fig. 3.3 Variation of Electric Field between Cylindrical Electrodes (5 mm and 10 mm radii), 10 secs. after Application of 1.25 KV Potential Difference

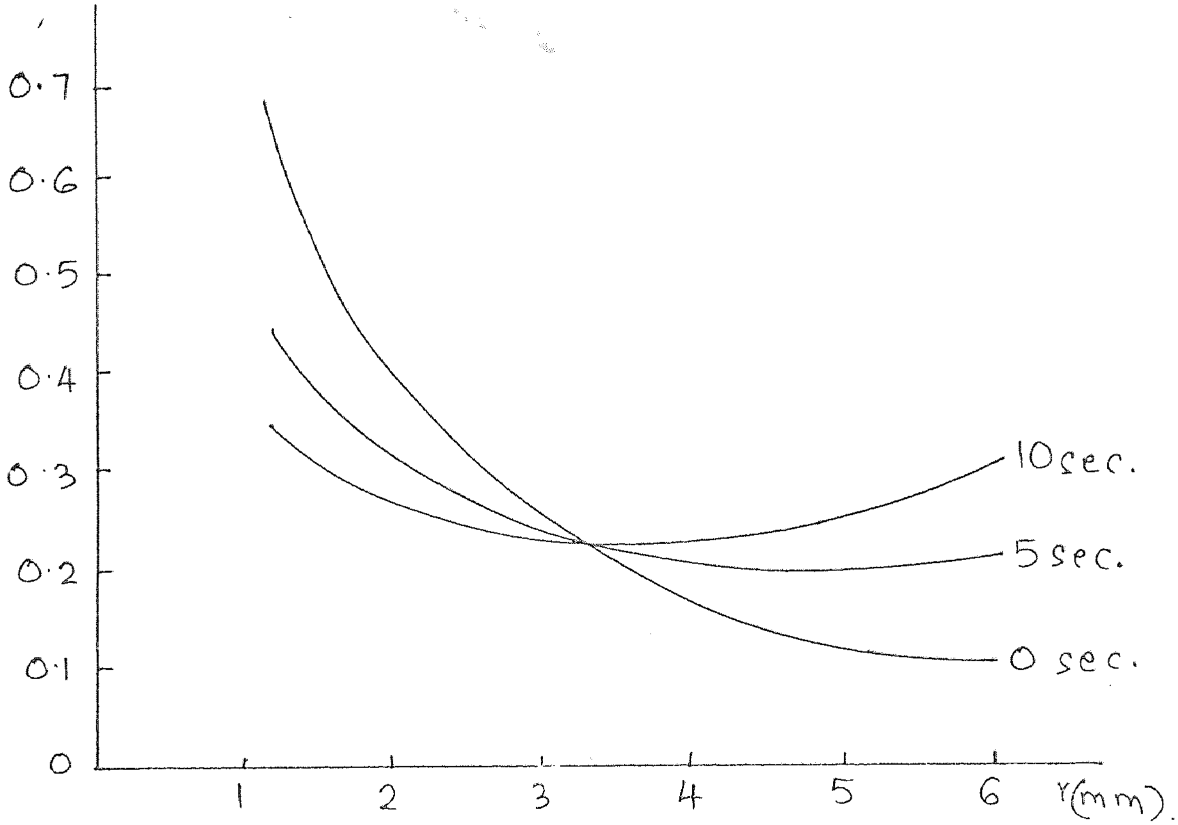


Fig. 3.4 Variation of Electric Field between Cylindrical Electrodes (1 mm and 6 mm radii), 10 secs. after Application of 1.25 KV Potential Difference

3.3 Purely Electrical Breakdown

Early scientific work on the breakdown of thin single crystal dielectrics gave rise to the impression that breakdown field strength depended only on the dielectric substances and temperature -- hence the concept of "intrinsic breakdown." Fröhlich* gave a formula for a critical field at which collision recombination no longer balances collision ionization.

$$E_c = Eo \left(1 + \frac{2}{\exp(h\omega/KT) - 2} \right)^{\frac{1}{2}}$$

In this formula Eo is a field strength determined by crystal parameters, and ω is the angular frequency of the longitudinal polarization waves. This result gave excellent order of magnitude agreement (with no disposable constants) for observed breakdown strengths of alkali halides below about 50°C. Its importance lies in giving some confirmation to the idea that collision ionization is a primary cause of breakdown in solids. It does not, of course, pretend to give a full account of the breakdown process.

3.4 Features of Electrical Breakdown

The voltage at which a dielectric breaks down, V_{bd}, depends on the electrode geometry which includes, in addition to the distance between the electrodes, "d," the physical shape of the electrodes. The latter factor determines the type of electric field developed by the application of an external voltage. It is generally recognized that for a given "d," the breakdown voltage V_{BD} will be the

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* See Bib. No. 7-82; h and k are the Plank's and Boltzman's constants.

highest for a uniform field, lower for a divergent one (needle cathode, plane or sphere anode) and losest for a convergent one (needle anode, sphere cathode). V_{BD} also depends on the waveform of the applied potential including its rise time and duration. The density of the medium ρ is of important relevance to V_{BD}. V_{BD} increases with increasing ρ. This increase is not necessarily proportional since fluctuations in ρ will also have an influence on V_{BD}. The dependence of V_{BD} on the gap "d" is a non-linear one and caution has to be exercised when one translates results obtained at a given value of "d" to those expected at a vastly different "d." The breakdown of the dielectric separating two conductors has a statistical distribution due to random nonuniformity _ the probability of its occurrence depending on factors mentioned previously as also the conditions at the metal-insulator interface. As the depth of penetration of electrons from metal into the dielectric depends on the density of the material, it will be the greatest for gases and least for solids. This emission results in the formation of thermalized electrons that will be displaced once an external potential is applied. Besides, charge injection will also occur once an external potential is applied. This cold emission involves favorable sites which have been identified by investigators as grain boundaries, asperities of molecular dimensions, and dust particles. At these sites the local work function of the metal will be 1 eV or less and the field enhancement may be 100 to 300-fold. The persistence of electron emission depends on the electron supply which comes from the conduction band of the metal.

Upon application of an electric potential to the system of 2 conductors and dielectric, electrons are injected into the dielectric. The mean free path of these electrons depends on the material density. In gases, this path is sufficiently long to cause collision ionization, and thus start a cumulative avalanche process. In solids, the emitted electrons collide at very short distances. More emissions will collide with these ionized charges, transfer momentum to them, and cause them to move away from near the emission site. In doing so, a low density region is created in the immediate vicinity of these sites. This leads to formation of tree-like regions. These <u>trees</u> are necessary but not sufficient for breakdown to occur. It is postulated that inside these trees, low density region of ions exists. Hence, electrons injected from the metal will have sufficiently long mean free paths to start avalanche ionization process. The energy released in this process causes expansion of the low density region. As the number of molecules in this region drop below the Paschen limit, local breakdown occurs which can be detected in the early stages by the associated light emission or by electrical techniques in the advanced stages. The boundary between the low density region and dielectric is believed to consist of high energy and high density electrons, hence represents a space charge. This causes a field distortion. The one between space charge and anode is enhanced and the one within the low density region is reduced. If this reduction becomes too great, electron emission may stop and no breakdown will occur.

Once a conductive path is formed between the 2 electrodes, current will start to flow, causing rapid heating and eventually plasma formation. The density of the dielectric will then determine whether the breakdown tracks are temporary or permanent.

Recent work on breakdown theory has followed various paths, each one looking at some particular aspect of the problem. One school of thought advances the viewpoint that breakdown is not to be identified with an uncontrolled avalanche of electrons. The breakdown process is divided into four stages: (1) A formative stage in which energy is deposited in preferred sites in the dielectric; there may be many mechanisms, and collision ionization could be of primary importance. (2) A tree initiation stage in which concentrations of ions in the gaseous phase are formed at places of high field concentration and deposition of energy. (3) A tree growth stage in which energy is supplied from the field to the gases which then further erode the solid. (4) A return streamer which occurs when a tree extends from one electrode to the other; current through the highly conducting streamer forms the breakdown channel.

CHAPTER IV

CORONA

4.1 Introduction

The term "corona" is used today as a generic name for any electrical discharges which take place in energized gaseous electrical insulation as the result of accelerated ionization under the influence of the electric field in the insulation, but without forming a conductive path between the energized electrical conductors or electrodes which are the boundary surfaces of the electric field in the insulation.

It is practically impossible to have insulation free from corona at high enough voltages considerably prior to breakdown, because any insulation will definitely be having some cavities or shrinkages causing air gaps and impurities. Therefore it is impossible to attain the intrinsic strength of the insulation. Thus, corona is a very appreciable factor in affecting the dielectric strength of the insulation.

It has been shown, in the operation of electrical systems and equipment, that under certain circumstances corona may shorten the service-life of electrical insulating systems and seriously interfere with electrical communications, control and measurements. Therefore, corona may become the cause of serious economical losses on account of premature repairs, and replacement of electrical equipment; reduced safety and efficiency and service interruption which may result in monetary and production losses and the good-will of clients. Economical losses like these can be prevented by testing electrical systems at the proper instance in order to prove that corona will not produce objectionable effects in operation under the service conditions which are specified for the tested systems.

Corona tests and measurements are made for several purposes. They indicate the presence or absence of corona in electrical insulating systems of electrical equipment and circuits, or in structures made of insulating materials but used for purely mechanical purposes. In this, the presence of corona is used as an indication for the presence of cracks, punctures or cavities in the material which may reduce the mechanical strength of the structure. Corona testing is being widely used in research and development, quality control at various stages in production processes, final product and acceptance testing. Also, corona tests are performed on installed electrical equipment and systems for purposes of preventive maintenance.

4.2 Definition of Corona

The corona definition as defined by ASTM [1] is given as: "A type of localized discharge resulting from transient gaseous ionization in an insulation system when the voltage stress exceeds a critical value. The ionization is localized over a position of the distance between the electrodes of the system."

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[1] ASTM D 1868 Report, 1961.

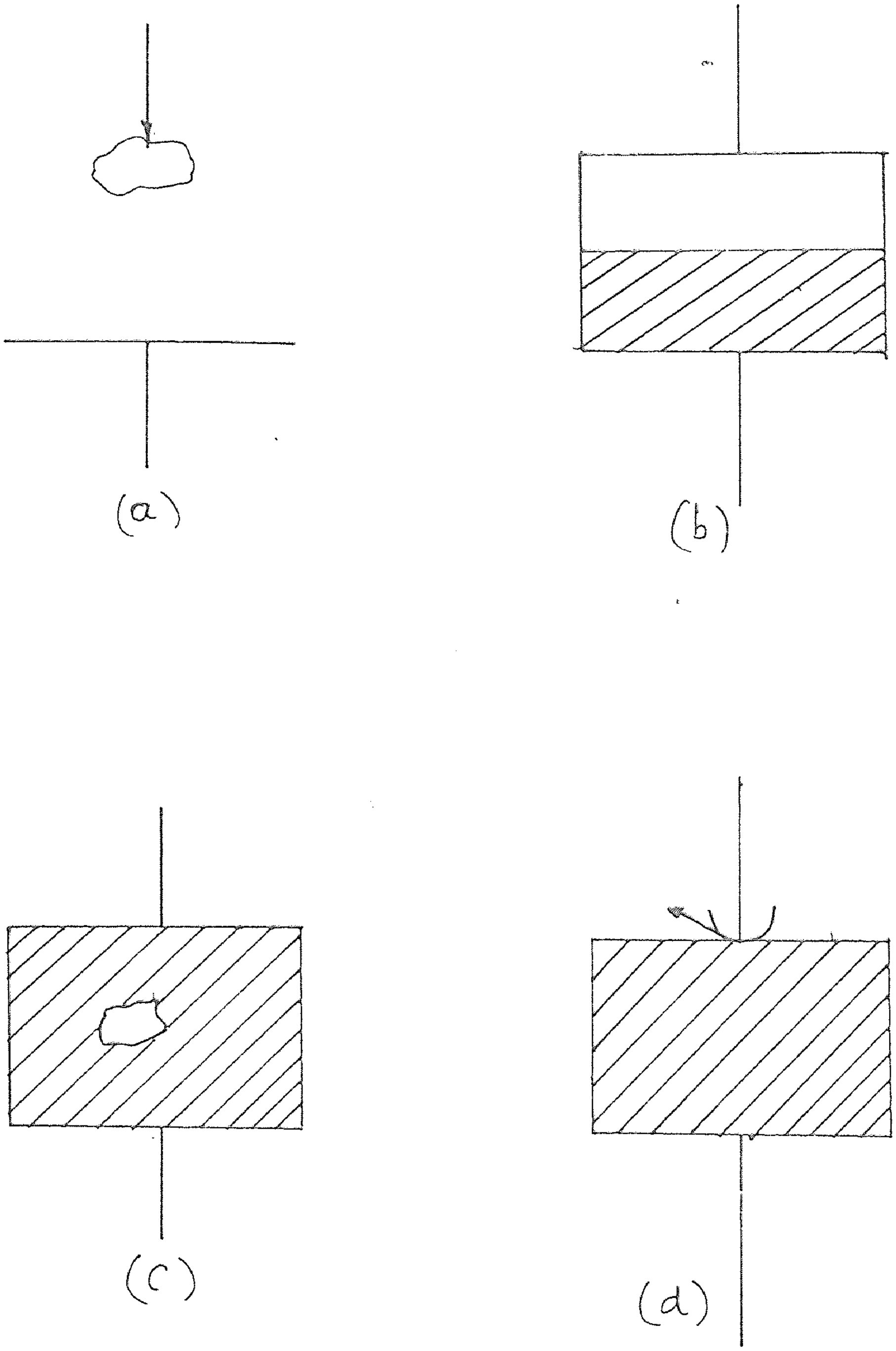

Fig. 4.1 Four Forms of Partial Discharges

The four cases shown in Figure 4.1 have been widely accepted as corona. Cases (b) and (c) are the most frequently occurring problems in practice which are the uniform field cases. Cases (a) and (d) are the non-uniform field cases. Of these four cases, case (c) is the most difficult case to control.

4.3 Behavior of Ionization Current Against Applied Voltage

To illustrate the behavior of ionization current, a simple model of point to plane gap in air is considered. This model consists of two kinds of discharges, non-self-sustaining discharge (dark discharge) and a self-sustaining discharge. The voltage-ampere characteristics would look loke as shown in Figure 4.2. It has been divided into four zones as shown in the figure.

When a voltage is first applied, current to anode increases slowly as the electrons move slowly towards the anode with an average velocity determined by the mobility for field strength existing for the particular value of applied voltage. Further increase of voltage results in saturation, i.e., all electrons are drawn to the anode. This happens for a considerable range of voltage as in region T_o. Then the current increases slowly in T_1 and rapidly in T_2 (Townsend discharges).

Increase in current as in T_1 occurs due to "collision," i.e., electrons gain enough energy to ionize by collision and rapid increase as in T_2 occurs when positive ions

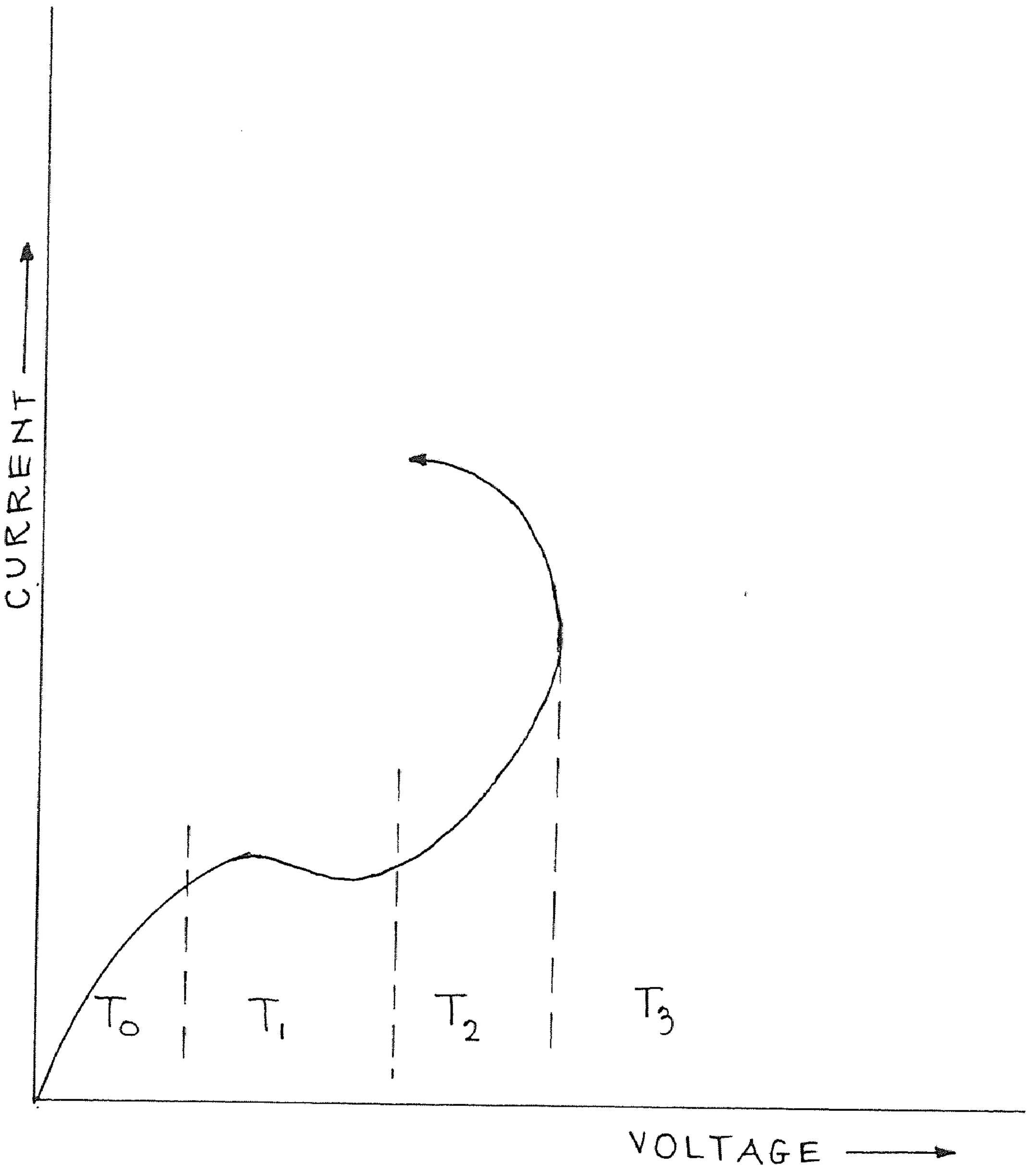

Fig. 4.2 Ionization Current Behavior

produced by collision gain enough energy to produce additional ionization. The currents in the above region cease when applied voltage is removed. When voltage reaches a critical value V_s, current increases rapidly, spark occurs and self-sustaining discharge like glow or arc occurs.

4.4 Spark Breakdown

As the electric field in a gap increases, the current increases, and at some point there is a sudden transition from Townsend or dark discharge to one of several forms of self-sustaining discharge. This discharge consists in a sudden change in the current of the gap. It depends on the shape of electrodes, the gap pressure and nature of the external circuit. For plane electrodes the result is a spark that initiates an arc discharge. For sharply curved electrodes, there may be a corona.

This definition for spark discharge is not strictly in accordance with engineering practice; e.g., such a transition occurs when a corona discharge is established in a non-uniform field. This initial corona, although it is a self-sustained discharge, represents an incomplete failure of the gap, occurring in a limited region near electrodes of small radius of curvature, while the rest of the gap carries a "dark" current. In an engineering sense, breakdown is considered to occur only when entire gap is bridged.

Breakdown may be initiated by maintaining the voltage constant and varying the gap or by changing voltage for a fixed gap. A self-sustained discharge is established only when conditions of field, pressure, gap are such that each electron leaving the cathode establishes secondary processes whereby it is replaced by a new electron leaving the cathode.

The description of the ionization process shows that electric charges are being transferred in the regions where accelerated ionization takes place. This means that current flows in these regions and power is being dissipated. As the currents flow in restricted spaces, the local current density is extremely high and intense local heating takes place. This results in gas expansions at the corona site. They produce a hissing sound and a very noticeable air motion if the corona site is surrounded by air which can circulate freely and the field strength at the site is sufficiently high. On account of this charge transfer, there occurs a corresponding charge transfer in the associated external circuit which is connected to the electrodes of the system. Hence, as the result of this momentary, short-lasting, randomly or regularly occurring transfers of charge in the insulation, transient currents or current pulses flow in the external circuit.

4.5 Effects of Corona

Corona has two effects which are economically important because they may cause serious increase of the cost of operating electrical equipment and systems. One is the possibility that corona may shorten the lifetime of electrical insulating systems. The other effect is the possibility that the transient currents, produced in circuits in the insulation of which corona is taking place, may interfere with electrical communication in its many forms, electrical control and measurements.

Corona, by electron or ion bombardment combined with the intensifying effects of heating, may erode materials, disrupt or change their atomic or molecular structure and produce as by-products materials which were not previously present. These new materials may react in turn chemically with some of the other materials which are in the vicinity of the region where corona is taking place. The result of this may be damage by corrosion.

4.6 Methods of Detecting Corona

It has been shown that corona produces light and sound at the site where it is taking place, and current pulses in the external circuit connected to the electrodes of the insulating system in which corona is taking place.

The light emission which accompanies corona is used in research work where the relation between discharge currents and time has to be displayed with as little distortion as possible. This method is obviously useful only when the corona site is visible, and in such cases it has been a useful research test.

The sound produced by corona may be detected by means of supersonic pressure transducers and special receivers.

This method is applicable only where corona takes place in freely circulating air so that the pressure waves produced by the corona can reach the transducer without great attenuation. As the pressure transducer is very direction sensitive, it is possible to locate with remarkable accuracy single corona sites which are at relatively short distances from each other.

Over the past few years accoustic techniques[1,2] have been used for partial discharge or corona tests on power capacitors. They have been valuable for detecting partial discharges caused by inadequate impregnation of the capacitor dielectric, and for sensing arcing associated with improper tab or lead wire connections.

The most widely used method today and the one used in the experiments of this thesis reveals the presence of corona by indicating the level of electrical noise, corresponding to the partial discharges in the insulating system in which corona is taking place. Monitoring the electrical signals, which correspond to the current pulses in the external circuit connected to the electrodes of the insulating system, reveals the presence and intensity of corona in the system.

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[1] See Bibliography No. 2-81

[2] See Bibliography No. 2-82

4.7 Corona Inception and Extinction Voltage

Corona inception voltage V_i is the minimum voltage which must be applied between the electrodes of an insulating system to produce the critical electric field strength at a corona site on the system to initiate continuous corona.

Corona extinction voltage V_e is the maximum voltage applied between the electrodes of an insulating system at which continuous corona, once initiated, ceases.

Thus V_i and V_e are the electrical characteristics of an insulating system which indicate whether corona is present in it or not. The initiation of corona in ionizable insulating material is determined by the electric field strength in the region where this material is present, the frequency with which the field may change its direction, the direction of the field and the freedom for motion of electrons and ions in this region. An example for field distribution in layered insulation is shown in Figure 4.3. The solid curve represents the voltage V_n across each layer of insulating material and the broken line represents the electric field strength E_n.

$$V_n = \frac{dn.V}{K_n \sum_1^n \frac{d}{K}} \quad \text{KV}^{1}$$

$$E_n = \frac{V}{K_n \sum_1^n \frac{d}{K}} \quad \text{KV/mil}$$

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[1] See Bibliography No. 5-72

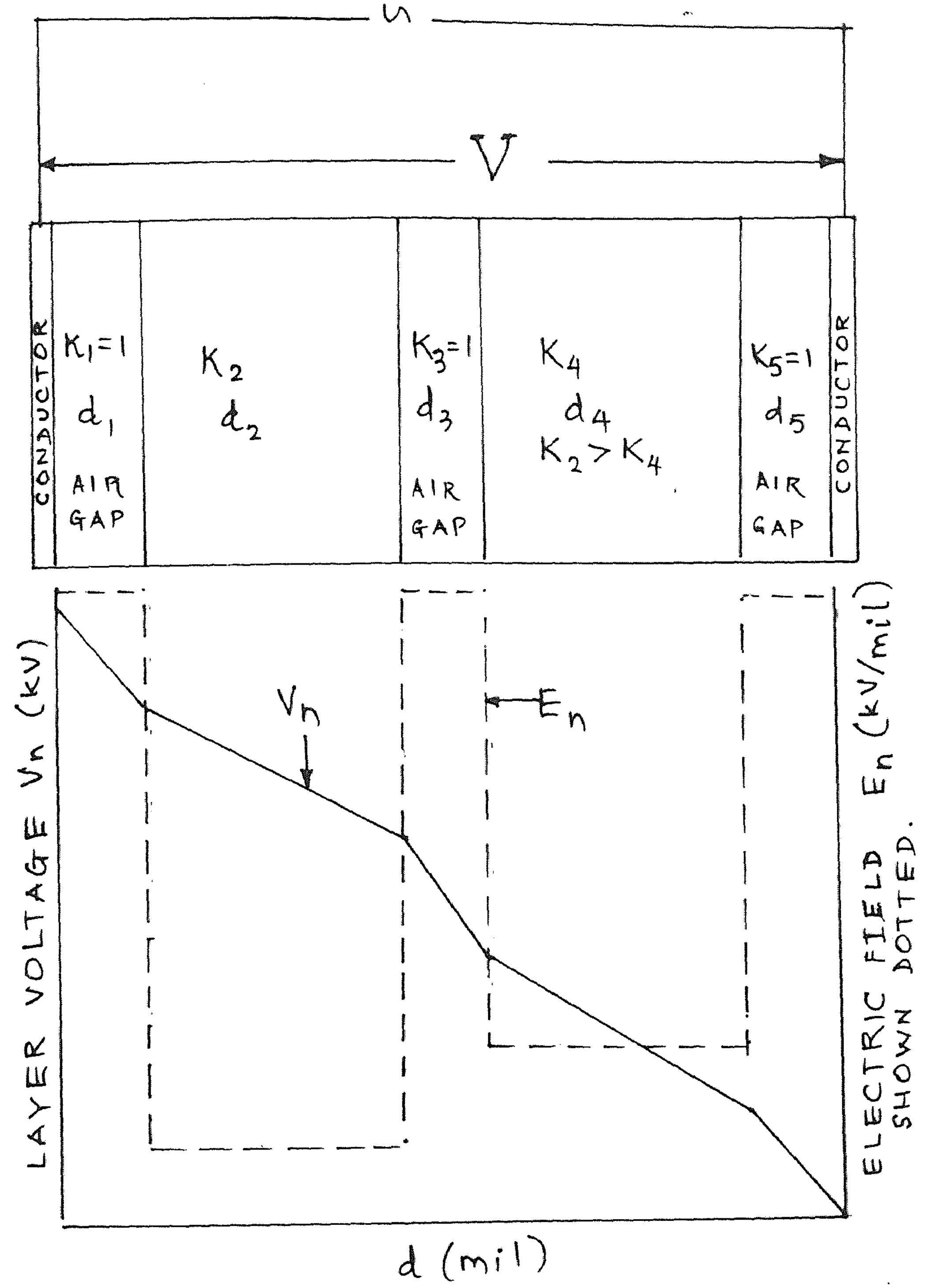

Fig. 4.3 Electrical Stresses in a Layered Insulating System.

$$V_i = f\left(\frac{p.d}{T} \right)$$

V_i = Peak voltage at which sparking occurs in the gas

T,p = Absolute temperature and pressure

d = Distance between infinitely large plane-parallel surfaces of conducting or insulating material which form the boundaries of the gas-filled space.

f = A function, the form of which varies somewhat with the molecular structure of the gas but only very slightly with the nature of the material of boundary surfaces.

Depending on the conditions at the corona site, corona may start as intermittent corona and become continuous corona at higher voltages.

Thus the degradation of insulation is initiated by the presence of corona. The ultimate failure of insulation is usually caused by either:

i. the formation of a number of deep pits from which minute channels propagate through the material as a result of intense local stress concentrations at the points of impact of the charges;

ii. cumulative heating by the discharges; or

iii. tracking across the surfaces occurring due to a chemical reaction.

CHAPTER V

STUDY OF ELECTRICAL NOISE

5.1 Introduction

In the previous chapter we have discussed corona and its role in the degradation of insulation. Corona, in its wake, brings radio-noise which can be monitored and analyzed to give an indication of the condition of the insulator under stress.

Electrical noise measurements have been successfully used as a diagnostic tool in research in the field of reliability and failure mechanism studies. Noise measurements have been used to detect defects in semiconductor components and resistors. The principle in these studies is that the noise generated in any component can be predicted by empirical and theoretical formulae, but a defective component will generate noise which is considerably in excess of that produced by a defect-free component. To prove a case in point, such studies have been successfully performed in connection with life tests on resistors.[1] The drift in resistance in the value of resistors correlates very well with the noise produced by them. Those resistors having higher noise levels are those having larger drift in resistance. Excellent improvements in the failure rates of resistors

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[1] See Bibliography No. 1-64

were achieved by screening them using noise as a failure parameter.

Similarly, noise generated due to insulator corona could be a very effective parameter to predict the insulator behavior. It should be noted that the noise produced by resistors is proportional to the current density, whereas the noise produced by insulators is proportional to ionization. This chapter deals with the fundamental theory of electrical noise, and its role in screening transformers prone to failure.

5.2 Electrical Noise Generated on the Surface of an Insulator

The noise generated on application of electrical stress on an insulator results from the unevenness on the surface of an insulator. These defects are an inherent part of the insulator surface.

The stress on an insulator transmitting dielectric flux is directly proportional to the flux and inversely proportional to the ease with which the insulating material transmits flux. The electric stress in a solid and gas dielectric can, therefore, be written as:

$$E_{solid} = D/K_s \qquad (1)$$

$$E_{gas} = D/K_g \qquad (2)$$

from (1) and (2):

$$D = E_s\ K_s = E_g\ K_g$$

$$E_g = E_s\ (K_s/K_g) \qquad (3)$$

where,

E_{solid} = Electrical field stress in solid dielectric

E_{gas} = Electrical field stress in gas dielectric

D = flux density

K_s = permittivity of solid

K_g = permittivity of gas

When two dielectric materials such as a gas and a solid are in series transmitting the same dielectric flux, the gas dielectric having lower permittivity will be stressed more than the solid dielectric in series with it. This higher stress will produce excited and ionized molecules which will generate electrical noise. Electrical noise will also be produced by the partial discharges occurring at the sharp edges.

The amount of noise generated on the surface of the insulator depends, among other things, upon:

(a) The applied electrical stress

(b) Surface condition (hydrophilic or hydrophobic)

(c) Surface area

(d) Ambient atmospheric conditions, like temperature, humidity, pollution, etc.

(e) Permittivity of the material of the insulator

Since the insulator corona or excitation also depends on all of these factors, it can be said that the electrical noise is directly related to the intensity and quantity of corona.

5.3 Types of Noise

The types of noise generally encountered in electrical systems are:

(a) "Thermal" noise caused by random motion of the current carriers

(b) "Shot" noise resulting from the drift of current carriers caused by applied field

(c) "$\frac{1}{f}$" noise resulting from slow fluctuation in conductivity

(d) Noise occurring due to excitation or ionization.

(a) Thermal Noise (White Noise):

A resistor in thermodynamic equilibrium exhibits random fluctuation in voltage at its terminals which are known as thermal or Johnson Noise. It can be shown that a resistor in thermal equilibrium at an absolute temperature T°K has available noise power given by:

$$P_{nt} = \frac{hf}{\left(\exp\left(\frac{hf}{KT}\right) - 1\right)} \cdot \delta f$$

where k = Boltzman's constant
T = temperature in °K
f = frequency in H_z
δf = specified frequency interval in H_z, called Band width
h = plank's constant

For normal room temperature at microwave frequencies:

$$\frac{hf}{KT} << 1$$

$$P_{nt} = KT . \delta f$$

The equation for thermal noise-voltage is:

$$E_{th} = (4KTBR)^{\frac{1}{2}}$$

where B and R are band-width in cycles/second and resistance in ohms respectively.

The noise spectral density of thermal noise is independent of frequency and has an amplitude distribution which is Gaussian. The thermal noise generated within a component can therefore be calculated if the temperature and resistance are known.

(b) Shot Noise:

The noise resulting from the random passage of carriers across discontinuity such as a diode junction, under the influence of an applied bias, is termed "shot" noise. Shot noise as defined by Schotky appears as a noise current generator in parallel with the discontinuity.

The shot noise current generator is expressed as:

$$I_{shot} = (2qI_{dc}B)^{\frac{1}{2}}$$

(c) "$\frac{1}{f}$" Noise:

If a current is passed through a conducting material, a noise is generated. This noise has a power spectral density nearly proportional to the reciprocal of the frequency and proportional to the magnitude of the current.

For this reason it is usually referred to as "$\frac{1}{f}$" noise. It is also referred to as "current noise" or "excess noise."

The empirical equation is:

$$E_{\frac{1}{f}} = \left(\int_{f1}^{f2} KI^{\alpha} f^{\gamma} \, df \right)^{\frac{1}{2}}$$

α normally lies between 1.8 to 2.2 and $\gamma \approx -1$.

An insulator can be looked upon as a very high resistance. When a voltage is applied a very small current is produced. Noise is also produced on account of discharge in gaseous cavities of the insulator, as also on the surface, on account of ionization. Hence, if the voltage is increased across the insulator an increase in noise can be predicted due to higher leakage current and higher magnitude of discharge in gaseous cavities.

When an a.c. voltage is applied to an insulator, the radio noise level increases with the applied voltage. This is because as soon as discharge inception voltage is reached, partial discharges will be initiated. In the absence of any stress reducing or grading devices the noise level increases rapidly with voltage. However if these devices are used, large reduction in the radio noise level occurs.

5.4 Effects of Humidity and Pollution on the Corona Noise

Test conducted in a controlled humidity chamber showed that radio noise increased with relative humidity. However radio noise is found to decrease as its duration time in a humid atmosphere increased. Initially, when insulators in dry condition are put in such a humid atmosphere, larger amount of water vapor in air could enhance the corona discharges leading to increase in the noise level. But as the duration in such an atmosphere increases, the moisture penetrates within, reducing electrical resistivity. Hence corona intensity decreases.

A clean and dry insulator surface exhibits very high leakage resistance; hence, normally the leakage current is very low. The insulator surface can be polluted with substances like dirt, inorganic salts, etc. In the presence of humidity certain pollutant films absorb the moisture and form a wet film which as a result reduces the leakage resistance of insulators. Due to reduced leakage resistance, leakage current tends to flow on the surface. Thus, surface temperature increases, leakage current increases and hence temperature of the lattice increases further. This happens cumulatively and when temperature reaches a sufficiently high level, it dries the surface at one point. Due to increased resistance at this point, leakage current tends to flow through the remaining wet area. Thus, these dry spots eventually expand to form dry bands. The extension of the dry bands increases with the applied voltage and the degree of pollution, due to increased thermal effects. These dry bands may be overstressed and corona may occur.

CHAPTER VI

NOISE MEASUREMENTS UNDER HIGH ELECTRIC STRESS

6.1 Introduction

In the previous chapters we have discussed the fundamentals of corona and the adverse effects it has on insulating materials. It is therefore necessary to find a practical and meaningful way to detect the presence of corona in dielectrics.

The electrical noise generated on application of electrical stress is a good way to detect the presence and intensity of corona. The broad areas of detectable defects in transforming insulators are:

(a) air pockets and voids
(b) inadequate drying or other processing
(c) contaminants or foreign objects
(d) improperly applied insulation
(e) loose connections

There are different kinds of insulations in a transformer. The measurements of noise generated under electric stress have been restricted to the major insulation between the high voltage and low voltage windings.

6.2 Theory

From previous chapters it can be concluded that radio noise level is directly related to the intensity of corona. When the insulator is subjected to a moderately high electric stress, radio noise will be generated. The origin of this noise is on account of the minute air pockets in the bulk of the material and on the surface. These defects are almost invariably left in the manufacturing process. These air gaps which are in series with the solid dielectric material will be stressed much more than the solid (dielectric constant of solid is greater than unity) under the influence of electric stress. This produces excited and ionized molecules, which results in the generating of radio noise.

The noise generated in an insulator, therefore, depends on the degree of defect, under the same electric stress. That is, the defective insulator, due to pinholes or depressions, will produce more noise for the same applied stress than a relatively non-defective insulator. Since the level of radio noise increases with electrical stress, it can be concluded that a defective dielectric will generate a particular noise level at a lower level of applied electrical stress than a relatively non-defective specimen. Hence the noise generated from a given insulating material can be used as a parameter to determine the insulator condition.

This method can be applied to screen out those transformers which are too noisy, by considering such excessive noise levels as precursors of early failure.

6.3 Objectives of the Experiments

The objectives of the experiments are to:

(a) develop a suitable technique to measure the radio noise generated due to corona

(b) subject the entire sample (301) to an electric stress, and measure the voltage stress level at which a predetermined noise level (5S units) occurs

(c) analyze the data statistically by applying principles of sampling theory

(d) subject some of the specimens to accelerated life tests to verify screening results

6.4 Circuit Arrangement for the Measurement of Radio Noise

In practice, radio noise is measured as the radiated signal received on an antenna or as the voltage produced at a given frequency at the terminals of the noise generating specimen. The first method has been utilized for the experiments. Unless special precautions are taken, the use of this method will not be accurate, because the antenna may pick up noise signals generated by other equipment in the laboratory.

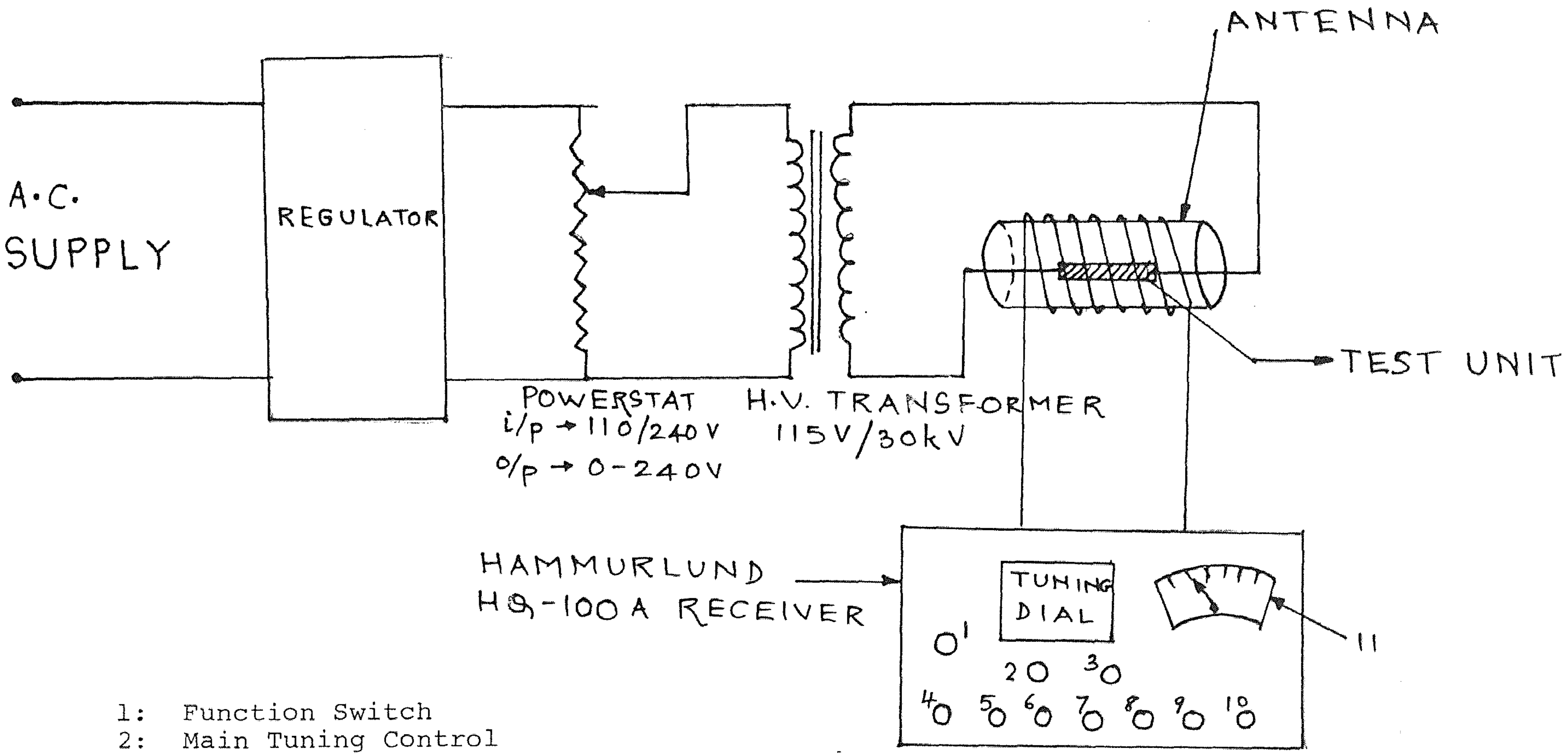
All leads have been soldered on to alligator clips, to eliminate loose connections, which may generate noise on application of high electric stress. All measurements have been done in a shielded room.

The circuit arrangement is shown in Figure 6.1.

A highly sensitive Hammerlund HQ100A receiver is used to detect the noise signal. The noise signal was monitored by the antenna wound around a plexiglass tubing, inside which were inserted the test specimens. The high voltage was applied across the major insulation between the HV and LV windings of the transformer. The voltage was varied with the aid of a variac as shown in Figure 6.1. The magnitude of the noise generated is monitored from the S-meter in the receiver. The S unit calibration is linear and an increase in each S unit corresponds to a 6 dB increase.

The radio noise generated by the receiver is the noise generated by the insulator together with the background noise. The true noise generated by the insulator cannot be obtained by simple subtraction of the two levels because measuring equipment may not respond with equal sensitivity to the two noise levels. Moreover, the measuring set adds noise of comparable levels from more than one source in an arithmetical manner, but it records the highest level only when the levels are of considerably different levels. In order to achieve the accurate noise readings, it is necessary that background noise should be as low as possible. However at higher applied voltages, generally the noise levels are widely different, and the background noise level becomes unimportant and its effect on the measuring equipment may be neglected.

The voltage stress measurements to produce 5S units of noise are shown in Table 6.1.



1: Function Switch
2: Main Tuning Control
3: Band Spread Control
4: Antenna Trimmer
5: Sensitivity Control
6: Band Selector
7: Man.-AVC Switch
8: Noise Limiter Switch
9: Gain Control
10: Selectivity Control
11: S-Meter (Noise Level Meter)

Fig. 6.1 Circuit Diagram for Noise Measurement.

Table 6.1

Transformer No.	Voltage	Transformer No.	Voltage
1	2000	26	1500
2	2000	27	1800
3	2400	28	2000
4	1300	29	1450
5	1500	30	1875
6	1600	31	2100
7	1600	32	1700
8	1650	33	1400
9	1900	34	1700
10	1500	35	1450
11	1400	36	1800
12	1775	37	1800
13	1900	38	1600
14	1600	39	1200
15	1600	40	1600
16	1800	41	1700
17	1875	42	1700
18	1900	43	1800
19	1675	44	1600
20	1700	45	2100
21	1700	46	2200
22	1475	47	1500
23	1800	48	1750
24	1900	49	1400
25	1375	50	1500

Transformer No.	Voltage	Transformer No.	Voltage
51	1500	76	1375
52	1500	77	1800
53	1700	78	1250
54	2000	79	1900
55	1200	80	1800
56	1400	81	1700
57	2100	82	2000
58	1400	83	1900
59	1500	84	1800
60	1600	85	1675
61	1600	86	1750
62	2050	87	1700
63	1700	88	1650
64	1900	89	1550
65	1500	90	1950
66	1650	91	1300
67	1550	92	1800
68	1350	93	1700
69	1800	94	1700
70	2000	95	1500
71	1900	96	1600
72	1400	97	1700
73	1900	98	1700
74	1700	99	1550
75	1500	100	1700

Transformer No.	Voltage	Transformer No.	Voltage
101	1600	126	1700
102	1850	127	925
103	1600	128	1500
104	1800	129	1550
105	1700	130	1550
106	1475	131	1875
107	1800	132	1700
108	1725	133	1700
109	1500	134	2050
110	1500	135	1550
111	1650	136	1500
112	2000	137	1500
113	1850	138	1400
114	1400	139	1600
115	1900	140	1800
116	1600	141	1600
117	1600	142	2150
118	1700	143	1250
119	1700	144	1500
120	1750	145	1850
121	1700	146	1700
122	1700	147	1900
123	1800	148	1400
124	1850	149	1475
125	1900	150	1750

Transformer No.	Voltage	Transformer No.	Voltage
151	1625	176	1400
152	1325	177	1600
153	1700	178	1650
154	1700	179	2200
155	1600	180	1250
156	1475	181	1300
157	1450	182	1500
158	1775	183	1675
159	1450	184	1500
160	1875	185	1700
161	1325	186	1600
162	1500	187	1450
163	1550	188	1700
164	2000	189	1650
165	1800	190	1700
166	1900	191	1875
167	1600	192	1700
168	1600	193	1650
169	1700	194	2000
170	1600	195	1800
171	2100	196	1700
172	1700	197	1150
173	1450	198	1500
174	1600	199	1700
175	2000	200	1600

Transformer No.	Voltage	Transformer No.	Voltage
201	1600	226	1900
202	1900	227	1400
203	2150	228	1750
204	1800	229	1600
205	1700	230	1750
206	2100	231	1600
207	2100	232	1900
208	1600	233	1700
209	1800	234	1475
210	1700	235	1400
211	1900	236	1700
212	1700	237	1750
213	1550	238	1700
214	1600	239	1750
215	1800	240	2100
216	1950	241	1400
217	2400	242	1600
218	2000	243	1500
219	1500	244	2200
220	1600	245	1700
221	1775	246	1800
222	1500	247	1975
223	2050	248	2200
224	1750	249	1800
225	1600	250	2150

Transformer No.	Voltage	Transformer No.	Voltage
251	2000	276	1550
252	1650	277	2000
253	2100	278	1800
254	1850	279	1900
255	1800	280	1900
256	2000	281	1700
257	1475	282	1700
258	2100	283	1700
259	2100	284	1700
260	1550	285	1500
261	1750	286	2250
262	1900	287	1700
263	1700	288	1800
264	1300	289	1600
265	2100	290	1400
266	1500	291	1700
267	1900	292	1900
268	2100	293	1500
269	1650	294	1900
270	1900	295	1800
271	1600	296	1900
272	1300	297	1500
273	1400	298	1700
274	1800	299	1950
275	1900	300	1875
		301	1750

CHAPTER VII

STATISTICAL SAMPLE ANALYSIS

7.1 Introduction

An important development in modern science and engineering is the study of systems in a probabilistic rather than a deterministic framework. The modern engineer is becoming increasingly aware that deterministic models are inadequate for designing or evaluating the complex equipment of the twentieth century. Supposedly identical systems differ to some extent on account of many factors. An engineer cannot trust his intuition alone. Intuitiveness lacks in statistical rigor and is frequently biased by the subjectivity of the man. Hence the engineer must be concerned with statistical models that describe the variations in system or component performance.

Probability and statistics are related fields. In problems in probability we make statements about the chances that various events will take place, based on an assumed model, whereas in problems in statistics we have some observed data and wish to determine a model that can be used to describe the data. Once a model is obtained, its parameters can be estimated and it can be used to predict future performance.

In this chapter we discuss certain concepts in very brief form, and present the analysis of the noise measurements.

7.2 Sample Distribution

In the manufacture of any component it is quite improbable that each item manufactured will be identical in all respects. Some will definitely be different from the designed ideal. It is also conceivable that, for a particular parameter, the values of the components may be scattered over a wide range. If the parameter values are plotted against the frequency of occurrence, the resultant curve is bell shaped, which is referred to as a "normal curve," and the distribution is called "Normal Distribution."

Theoretically speaking, this bell shaped curve should extend from $-\infty$ to $+\infty$, but in our case negative values are meaningless and therefore not possible. Thus, in the strictest sense, the theoretical normal distribution curve does not exist for our example. However, from the engineering and practical point of view this distribution looks like a bell-shaped curve or the so-called "Normal Distribution." Hence, the mathematical analysis developed for the normal distribution curves can be utilized.

7.3 Central Values of Distributions

The best known measure of central tendency is the expected value, more frequently called the "arithmetic mean," or sometimes just the "average: or "the mean."

For n discrete values, the mean by definition is:

$$\overline{X} = \frac{\sum_{i=1}^{n} Xi}{n}$$

where X_1, X_2 ..... X_n are the individual values of the total of n items.

"Median" is the value of the half way item; that is, there are as many items having a value below the median value as there are above it.

"Mode" is the most frequently occurring value in a frequency distribution.

7.4 Histogram

A plot of the frequency distribution with rectangles propositional in height to the class frequencies in the sample on the ordinate against the corresponding values of the random variable on the abacissa is called a "histogram."

7.5 Other Descriptive Measures of Distributions

(a) Moments:

Moments can be used to define a given mathematical curve and likewise the goodness to fit of a curve can be judged from looking at an observed datum and then by taking its suitable moments compared with a standard type of curve. Thus by these methods goodness to fit can be judged.

(b) Moments about the mean:

At times taking the moment about the arithmetic mean has special significance in a practical case. Here, the r_{th} moment about the mean is named μ_r.

$$\mu_r = \frac{1}{N} \sum_{i=1}^{n} fi \ (X_i - \overline{X})^r$$

where 4 may have any value 1, 2, 3 .... n and fi is the frequency of occurence

(c) Variance and standard deviation:

The second moment about the mean is:

$$\mu_2 = \frac{1}{N} \sum fi \; (X_i - \overline{X})^2 = \sigma^2$$

This is called the population variance and it is a measure of dispersion. The square root of the variance is called the standard deviation, and is denoted by σ.

(d) Skewness and kurtosis:

The third moment about the mean, related to the asymmetry of a distribution, is called the skewness.

The fourth moment about the mean, related to the peakedness or flatness of a curve is called the kurtosis.

(e) Quantiles and percentiles:

A way of summarizing information about a distribution is by its quantiles. The "i"th quantile is that value of the random variable that has a proportion i of the cumulative distribution below it. Thus, for a continuous random variable with probability density f(X), the i th quantile is that point (i) such that:

$$\int_{-\infty}^{z(i)} f(x) \, dx = i$$

The term percentile or percentage point is used to refer to the .01, .1, etc. quantiles when expressed in percent form. Differences between two percentiles are on occasion used as measures of dispersion.

7.6 Probability Plots

The assumption of a particular statistical model to represent physical phenomena is very important, because an incorrect assumption would lead to serious error if predictions based on the assumed model are made.

Probability plotting is a subjective method in that the determination of whether or not the data contradict the assumed model is based on a visual examination, rather than a statistical calculation. The method is quite simple and can provide a great deal of useful information in addition to an evaluation of the appropriateness of the chosen model.

The technique of probability plotting can be found in any standard textbook of statistics. In brief, it can be said that probability plotting is accomplished with a probability axis which is constructed for each distribution. From the plot, parameters of the distribution are estimated, and a best fitting line is drawn. If assumed distribution is correct, the plotted points tend to fall in a straight line.

The probability density functions for the various distributions are:

Distribution	Density
Uniform	$\frac{1}{B-A}$; $A < B$
Exponential	$\frac{1}{B} \exp\left(- \frac{(X-A)}{B}\right)$
Normal	$\frac{1}{\sqrt{2\pi}} \exp\left(- \frac{(X-A)^2}{2B^2}\right)$

Lognormal	$\frac{1}{\sqrt{2\sigma^2}} \exp\left(- \frac{(\log X - \mu)^2}{2\sigma^2} \right)$
Weibull	$ABX^{B-1} \exp(-AX^B);\ X \geq 0$
Logistic	$\frac{B \exp(-(A+BX))}{(1+\exp(-(A+BX)))^2}$

```
                     Simple Statistics

        N                    =301.
        Total                =512450.
        Mean                 =1702.49169435
        Median               =1700.
        Variance             =51172.9374308
        Std Dev              =226.214361681
        Min                  =925.
        Max                  =2400.
        Range                =1475.
        Skewness             =0.148826779245
        Kurtosis             =3.28559286252
        3rd Moment           =1714248.35982
        4th Moment           =8546808215.65
        Coeff of Var         =0.132872519984


Censored: Lt=   0   Rt=   0    Trimmed: Lt=   0   Rt=   0
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Fig. 7.1 Histogram

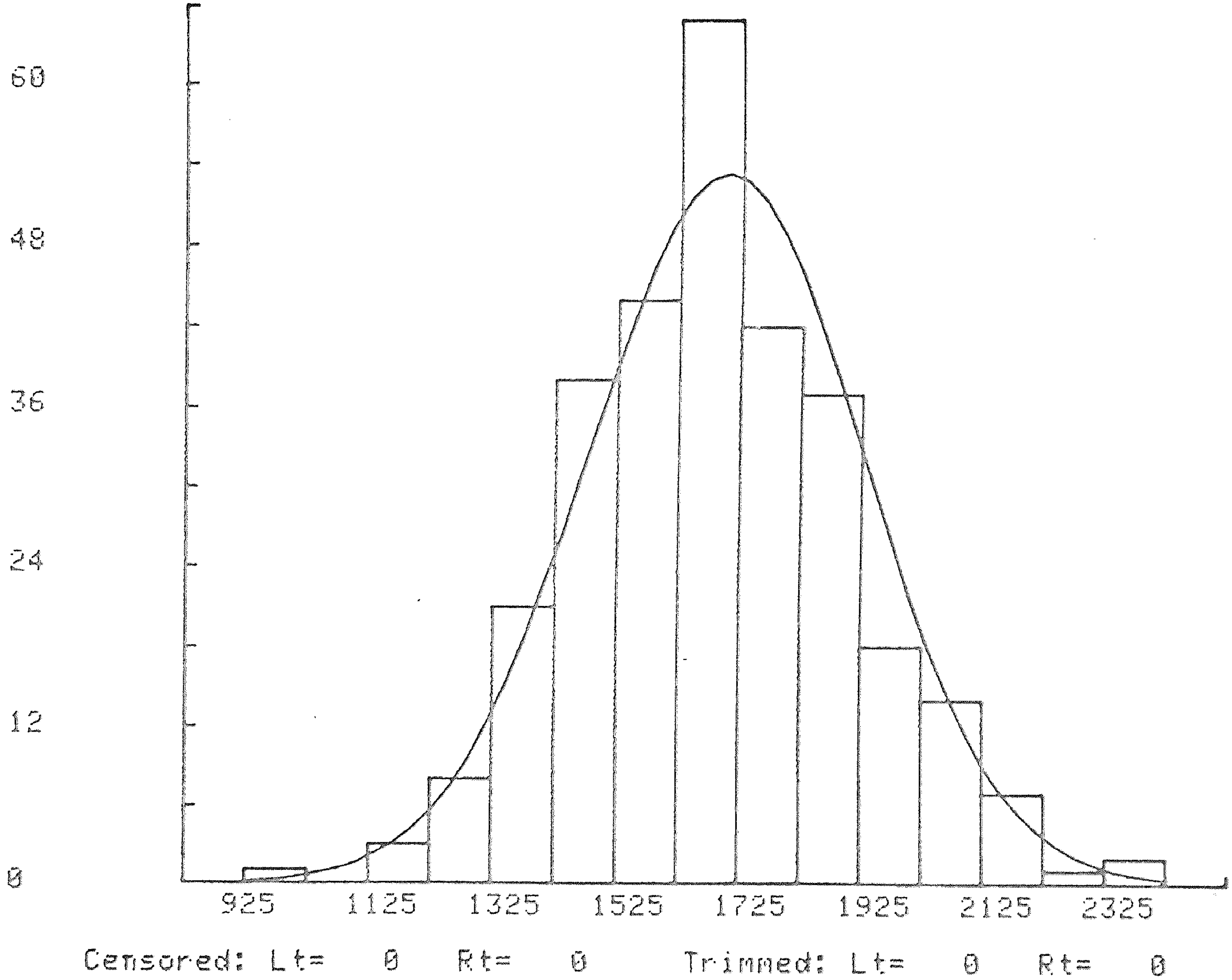


Fig. 7.2 Cumulative Histogram

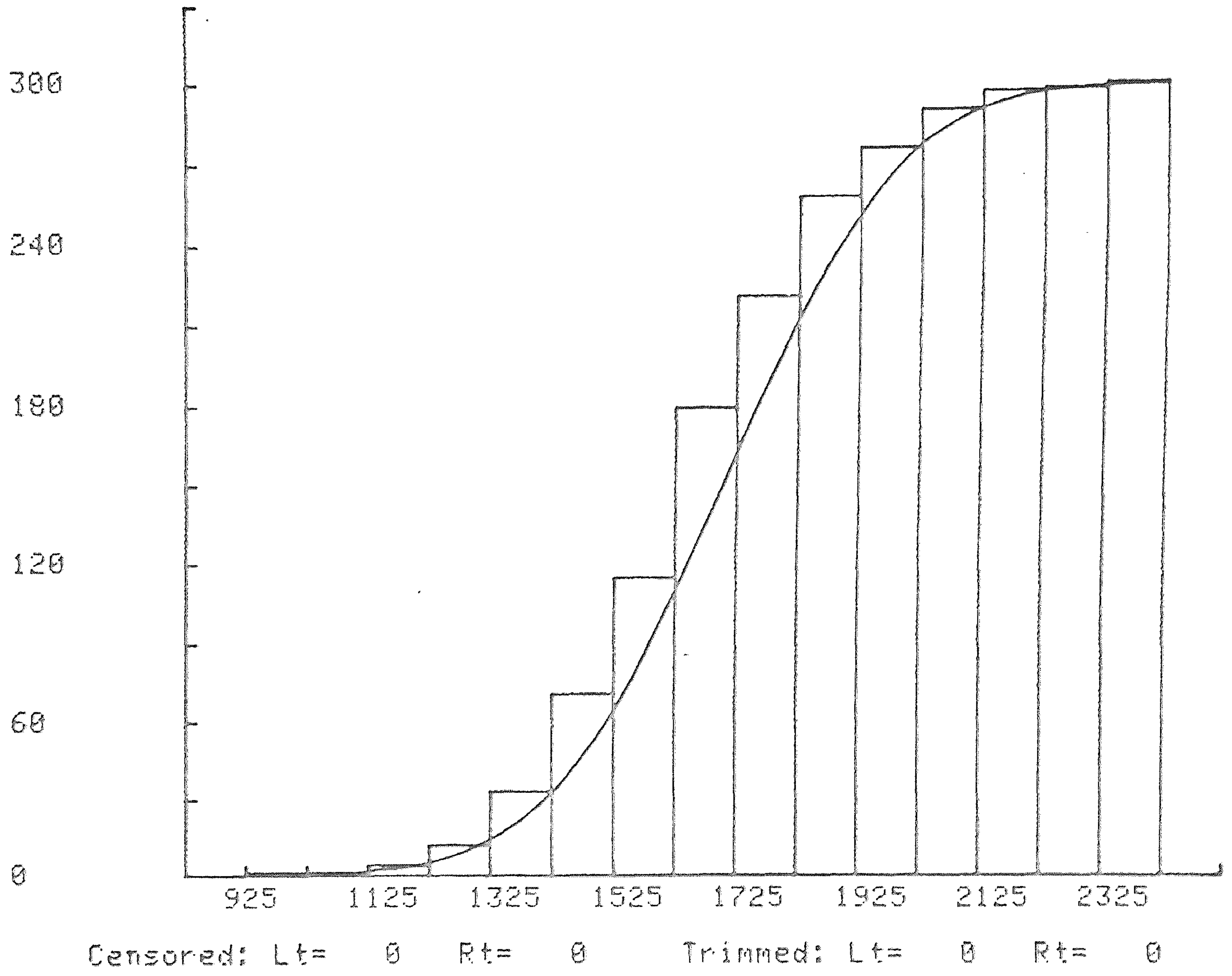


Fig. 7.3 Normal Plot

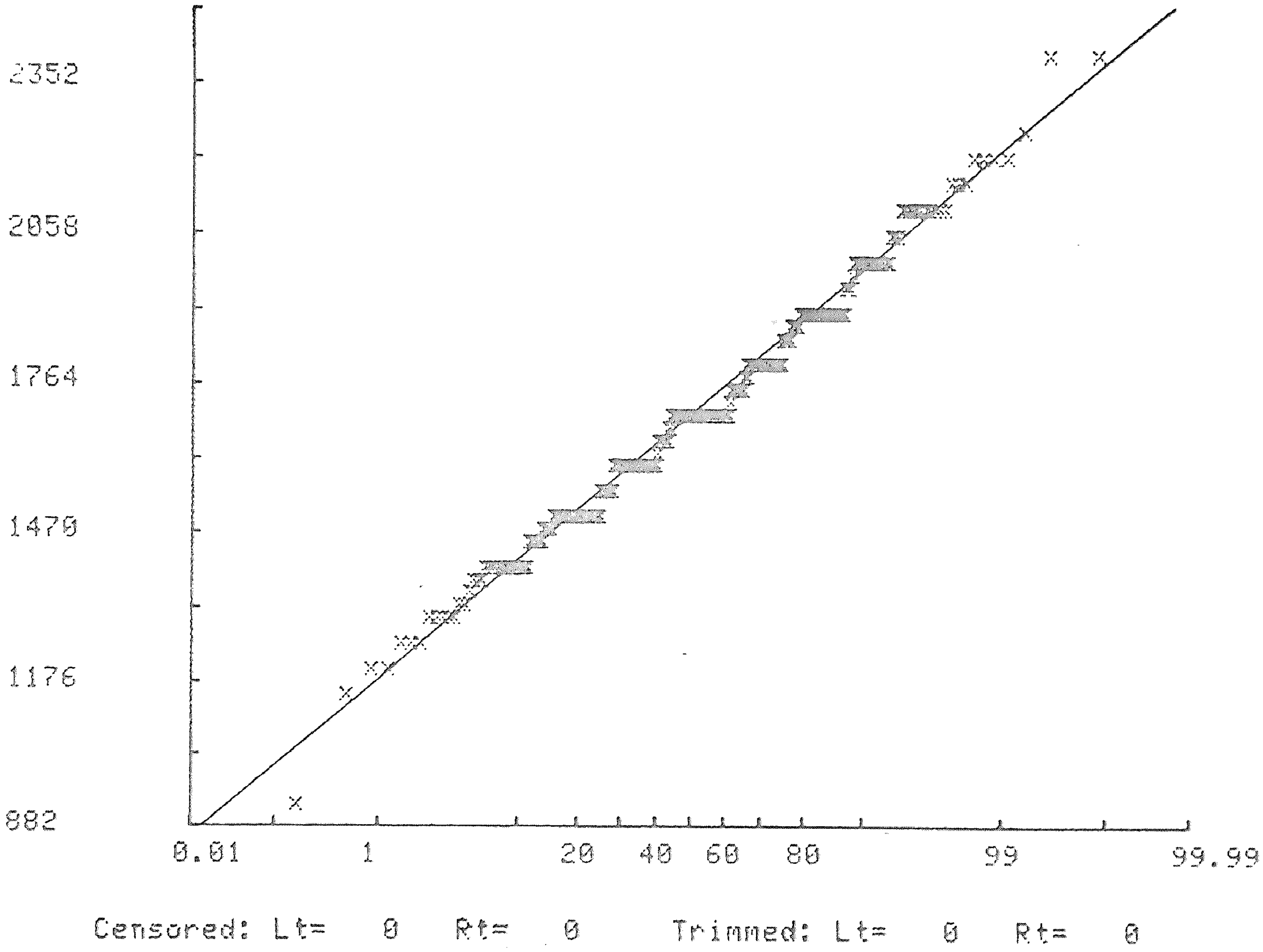


Fig. 7.4 Log Normal Plot

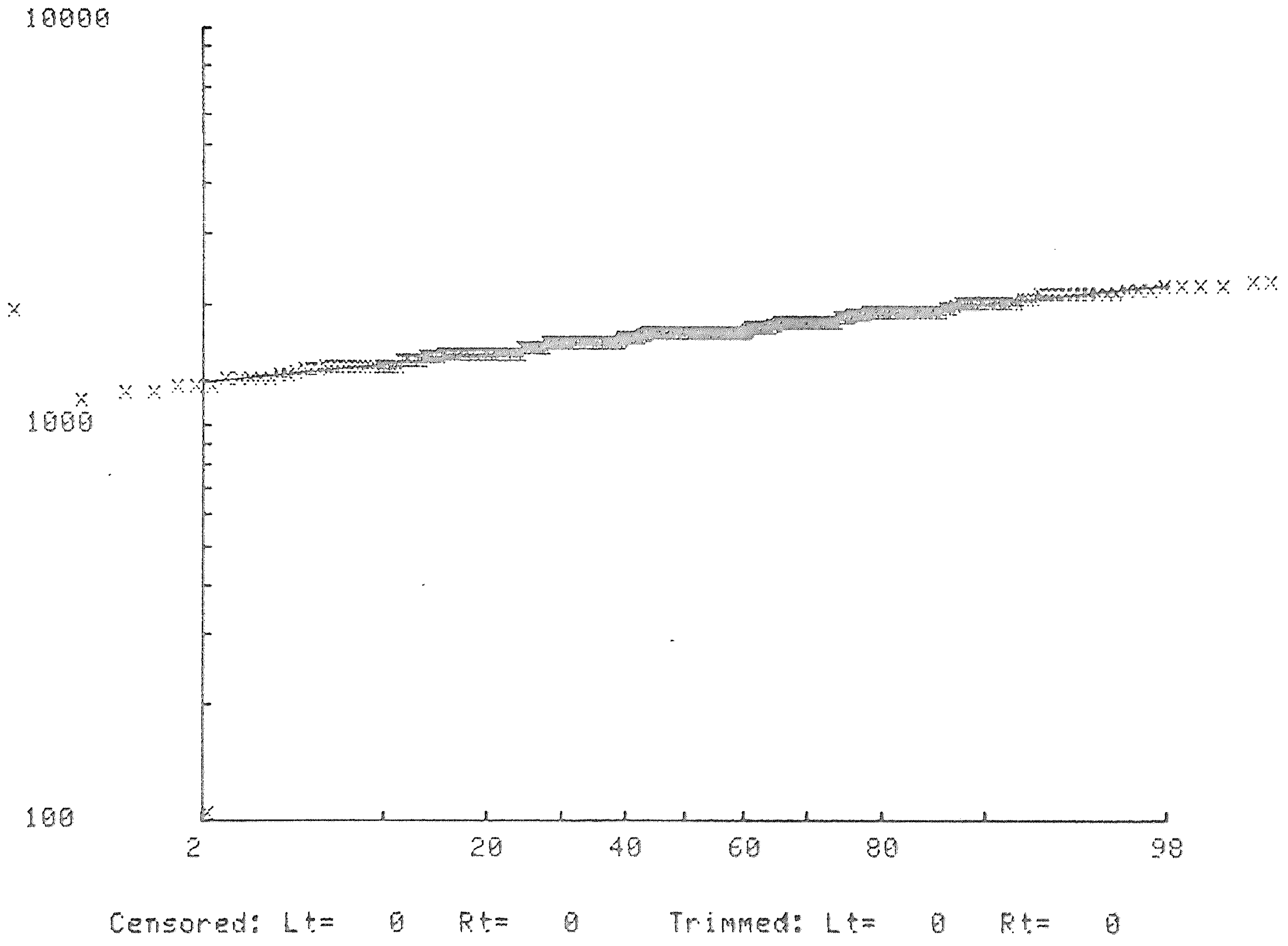
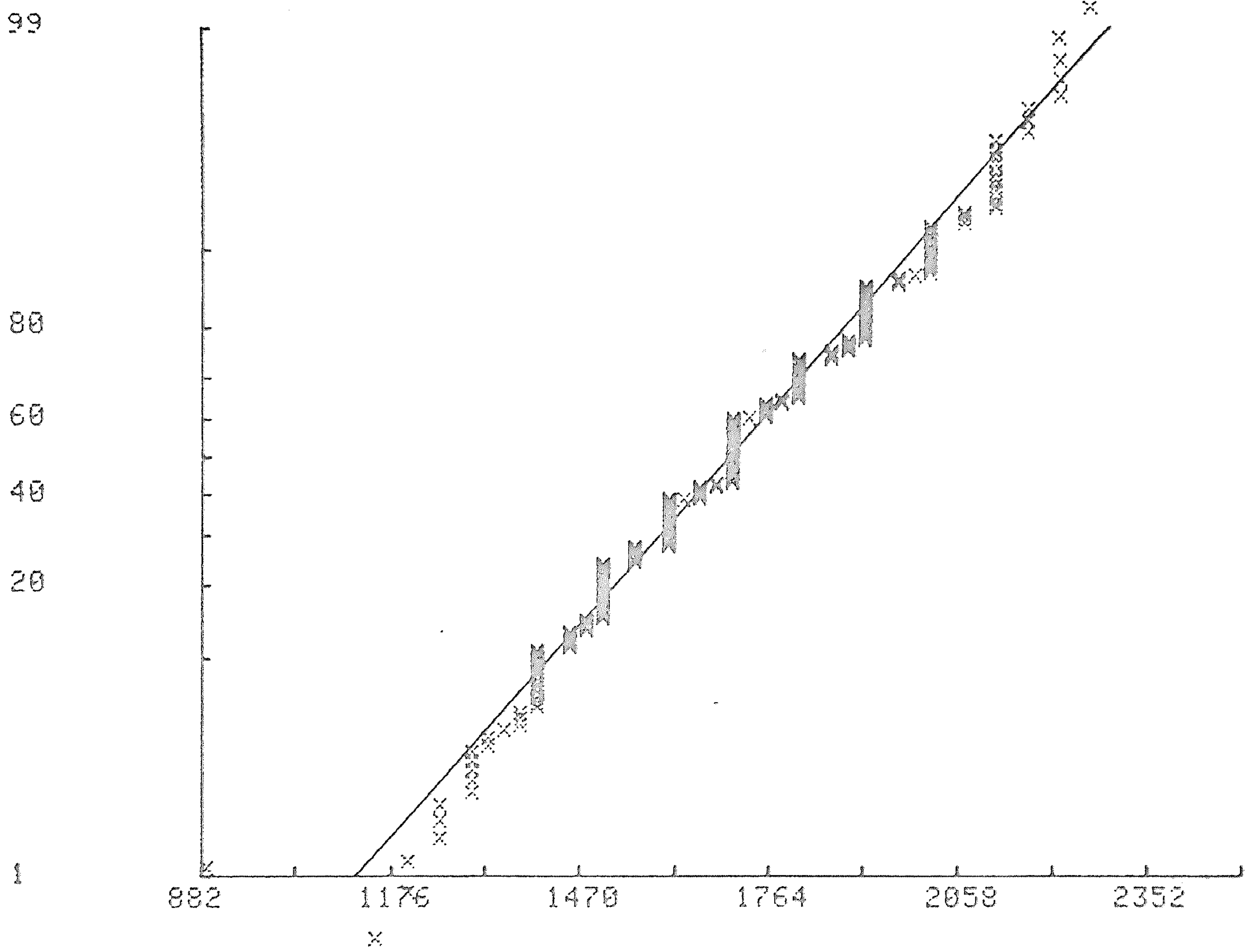
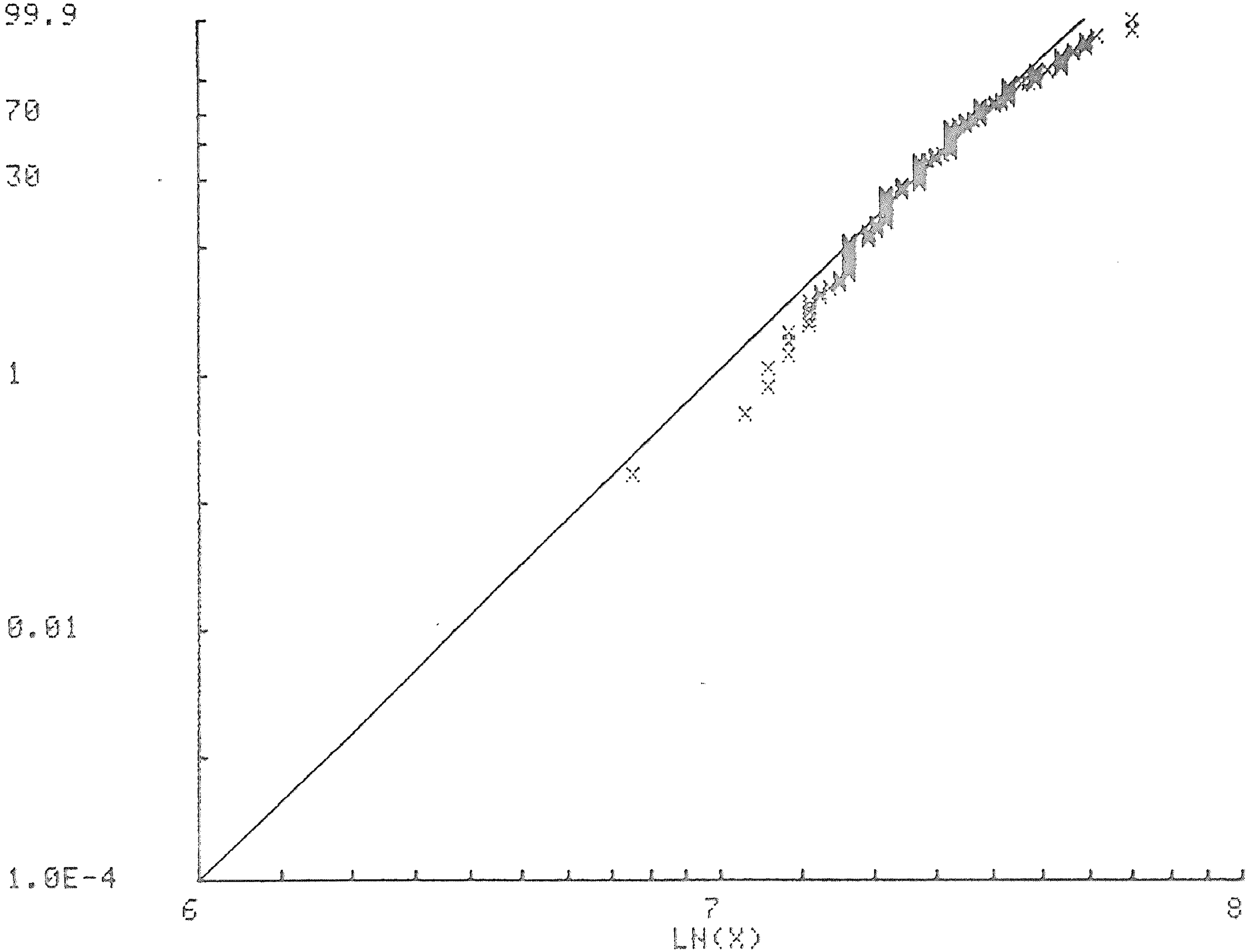


Fig. 7.5 Logistic Plot



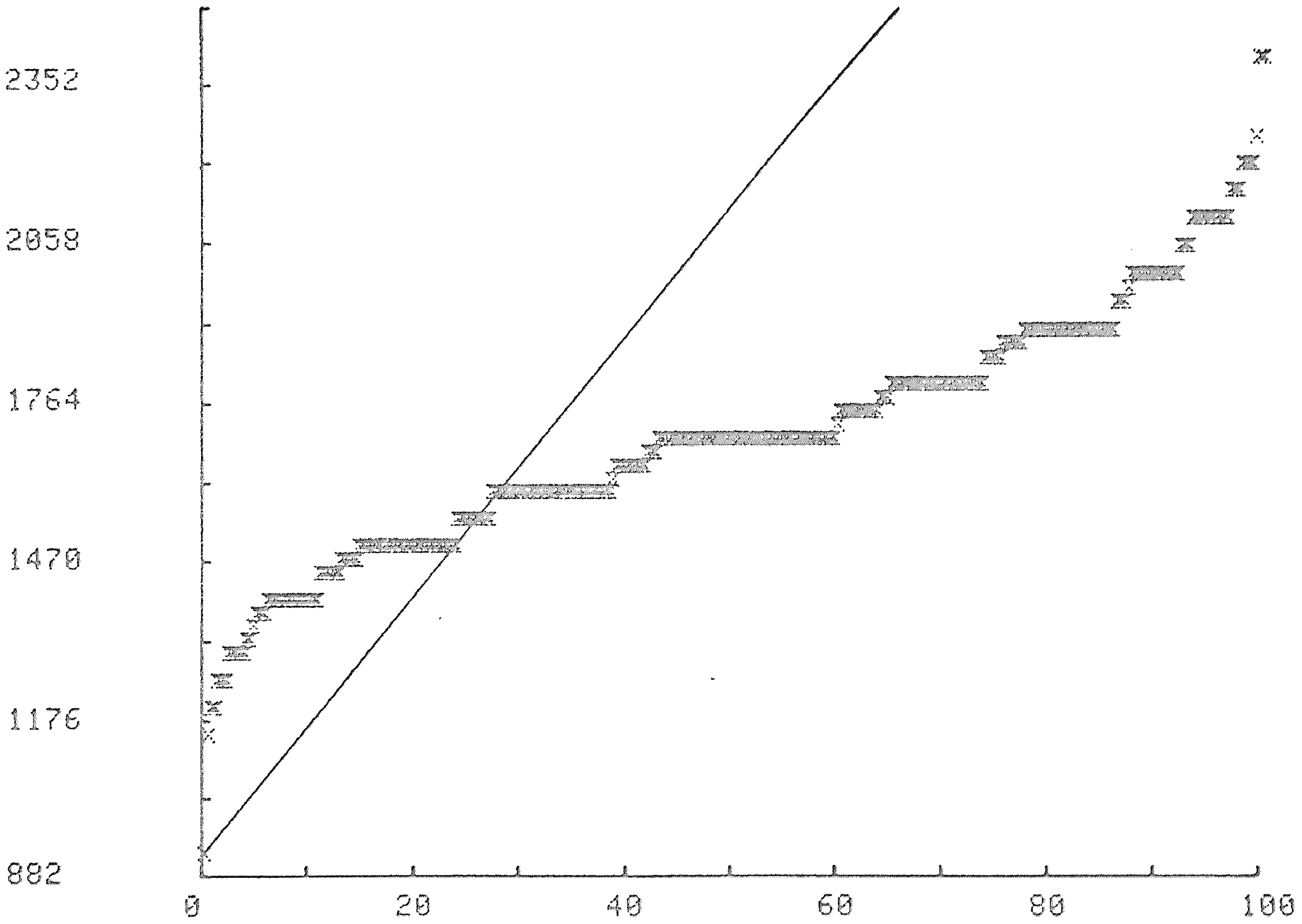
Censored: Lt= 0 Rt= 0 Trimmed: Lt= 0 Rt= 0

Fig. 7.6 Weibull Plot



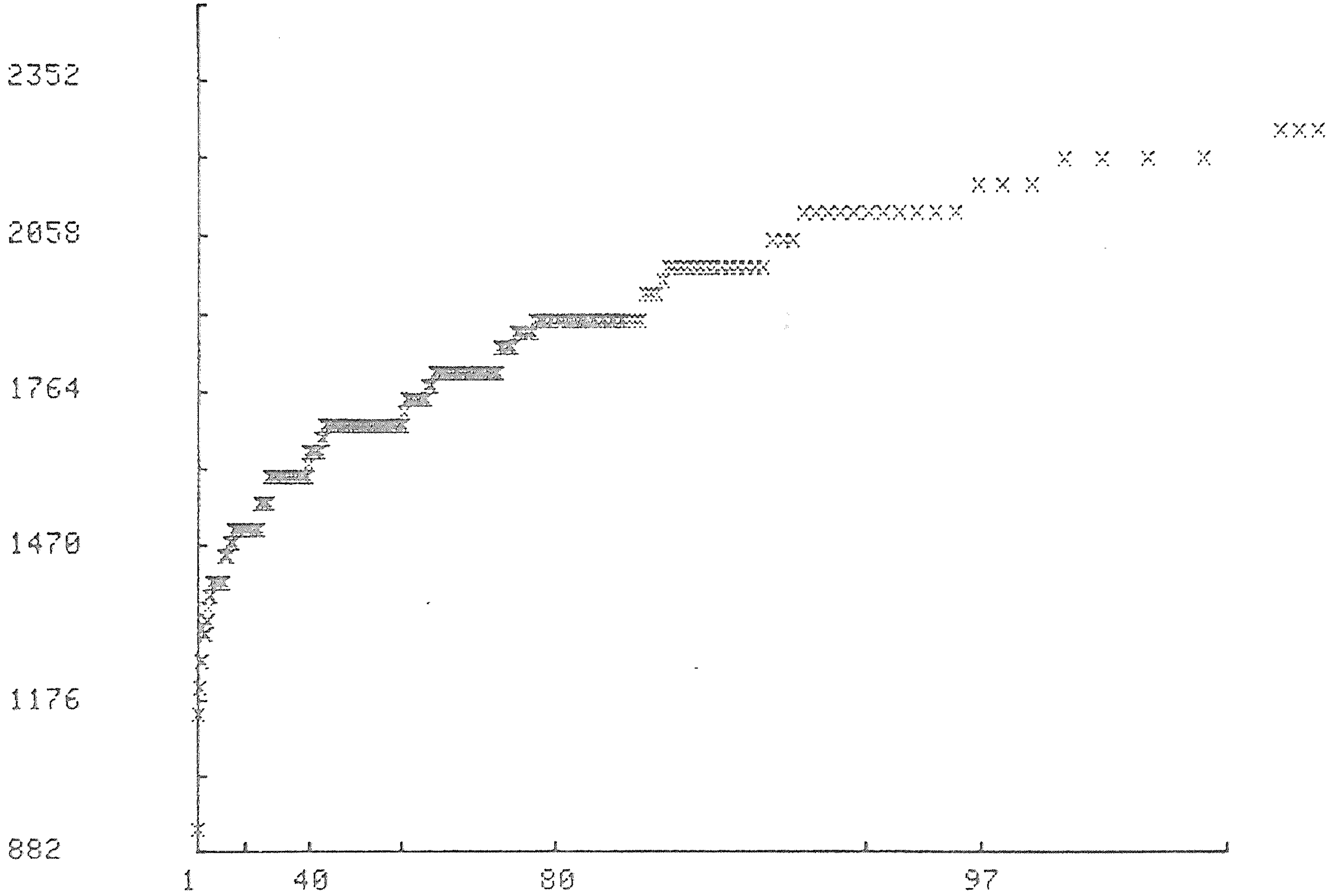
Censored: Lt= 0 Rt= 0 Trimmed: Lt= 0 Rt= 0

Fig. 7.7 Uniform Plot



Censored: Lt= 0 Rt= 0 Trimmed: Lt= 0 Rt= 0

Fig. 7.8 Exponential Plot



```
The Exponential cannot be fit
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```

```
                 Population Percentiles

       %                 Normal

      0.1          1007.41534383
      1.0          1179.23712431
      2.0          1240.55167695
      2.5          1261.646247
      5.0          1332.52234061
     10.0          1414.23809002
     50.0          1702.49169406
     90.0          1990.74529869
     95.0          2072.4610481
     97.5          2143.33714171
     98.0          2164.43171175
     99.0          2225.74626439
     99.9          2397.56804488

            A=1702.49169435
            B=224.925417097

Censored: Lt=   0   Rt=   0     Trimmed: Lt=   0   Rt=   0
```

CHAPTER VIII

CONCLUSIONS

It has been observed that significant electrical noise is generated at the sites of inhomogeneities inside the insulation, when it is subjected to an electrical voltage stress. The cause of this noise can be attributed to the minute air bubbles in the cracks or voids in the insulation. Since the dielectric constant of air is considerably less than the dielectric constant of solid insulation, these pockets of air will be stressed more than the solid dielectric. As a result excitation or ionization takes place. These excited or ionized molecules generate electrical noise. This electrical noise which has been generated has been monitored for a sample of three hundred transformers.

For the same level of magnitude of noise to be reached, it has been observed that the amount of electrical stress required varies for the different units. Hence, the amount of stress required to produce the same amount of electrical noise is an indication of the condition of the insulation. Hence, the insulations producing the same level of noise at lower voltages can be considered to be inferior to those producing that same level of noise but at higher applied voltages. These voltage stress readings have been analyzed statistically and have been found to have a normal distribution.

Units from the right extremity of the distribution have been categorized as high voltage (and hence low noise). The units from the left extremity of the distribution have been categorized as low voltage (and hence high noise). The reason is that if we had applied a fixed electrical stress (voltage), the units from the right extremity would have produced a lower noise level as compared to those in the left extremity of the distribution.

These few units ($n_{low} = 7$, $n_{high} = 7$) have been subjected to accelerated life tests. Approximate times of failure were noted, for the same amount of stress applied to all the units.

The observations from the life tests on high and low voltage specimens have been found to be quite significant from the statistical inferences worked out.

The coefficient of correlation has been found for the pairs of measurements. This calculated value for the linear regression coefficient of correlation has been found to exceed the critical value of the coefficient of correlation for the appropriate degree of freedom and significance level, thus making the formulation of regression equation very meaningful.

The regression equation has been formulated. By applying the F-test of significance on the regression equation it has been found that the regression equation which has been formulated is statistically significant.

8.1 Future Scope

The units can be subjected to different stresses of lower magnitudes to obtain more accurate failure times. By decreasing the level of these stresses, the acceleration factor would be smaller. Also, new failure modes which are not present in normal operation could be minimized.

The Arrhenius or Eyring model for accelerated testing could be used to extrapolate the data to normal operating conditions.

It is also possible to verify whether true acceleration exists from the Arrhenius plots for the applied stress levels.

A degradation parameter could be established and used for life test readings without inducing complete failure. Reliability screening can then be done on the basis of a linear discriminent.

The Modified Arrhenius Equation,

$R \propto A\exp(-\frac{E-C\xi}{KT})$, as proposed by Dr. Misra in EE 641, could be used for the analysis of life test data.

R = Reaction Rate

C, A = Constants

K = Boltzman's Constant

E = Activation Energy

T = Absolute Temperature

ξ = Electric Field

APPENDIX

Accelerated life tests have been performed on transformers from the extremities of the voltage stress distribution. Seven transformers which have low voltage readings and seven transformers which gave high voltage readings have been subjected to a voltage stress of 2.5 KV and temperature stress of 80°C. The time it takes for the leakage current to exceed 10 MA has been considered as the time to failure. Hence a 10 MA fuse has been connected in series with the insulation under stress. The approximate time to failure has been noted. The total time to failure has been considered as the cumulative time of the observations with the fuse intact plus the mean of the time from the last observation with the fuse intact to the time of observation when the fuse has blown.

The readings are as shown in Table A.1.

Table A.1

Transformer No.	Voltage for 5S Units of Noise (KV)	Time to Failure (hours)
217	2.4	63
197	1.15	13
127	.925	11
143	1.25	17
55	1.2	14
180	1.25	12
45	2.1	39
46	2.2	38
39	1.2	12
78	1.25	16
3	2.4	40
179	2.2	42
244	2.2	42
286	2.25	39

A.1 Significance

To find the significance of the observed data in Table A_1 we segregate the data into two categories -- high noise and low noise. To find the statistics the following formulae have been used:

$$\overline{X} = \frac{\Sigma x}{n}$$

$$s = \sqrt{\frac{\Sigma (x-\overline{x})^2}{n-1}}$$

$$\text{estimated} \quad = \frac{s}{\sqrt{n}}$$

Low Noise

V in KV	L = life
2.4	63
2.1	39
2.2	38
2.4	40
2.2	42
2.2	42
2.25	39

$\bar{V}_l = 2.26$ KV $\bar{L}_l = 43.29$ hours

$S_{vl} = 0.10$ $S_{ll} = 8.83$

estimated $\sigma_{vl} = 0.04$ $\sigma_{ll} = 3.34$

High Noise

V in KV	L = life
1.15	13
.93	11
1.25	17
1.2	14
1.25	12
1.2	12
1.25	16

$\bar{V}_h = 1.18$ KV $\bar{L}_h = 13.57$ hours

$S_{vh} = 0.12$ $S_{lh} = 2.13$

$\sigma_{vh} = 0.05$ $\sigma_{lh} = 0.81$

$$\Delta\bar{x} = 43.29 - 13.57 = 29.72$$

$$\sigma D = 3.34 - 0.81 = 2.53$$

$$\frac{\bar{x}}{\sigma_D} = 11.75$$

From the notes of Professor Misra in EE 641, it can be concluded that the result is significant.

A.2 T-Test

If the distributions of 2 independent random variables have means $\bar{x}_1$ and $\bar{x}_2$ and variances S_1^2 and S_2^2, then the distribution of their sum or difference has the mean $\bar{n}_1 + \bar{n}_2$ or $\bar{n}_1 - \bar{n}_2$ and variance $S_1^2 + S_2^2$.

According to the above theorem $S_{\bar{x}_1-\bar{x}_2}$ represents standard deviation of sampling distribution of difference between the means.

Test - statistic "t" given by:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{(S_{\bar{x}_1-\bar{x}_2})}$$

$$S_{\bar{x}_1} - \bar{x}_2 = \left(\frac{S_1^2}{n_1-1} + \frac{S_2^2}{n_2-1} \right)^{\frac{1}{2}}$$

$$= 3.71$$

$$t = \frac{29.72}{3.71}$$

$$= 8.01$$

From t-distribution table t.005 for d.f. = 12 is 3.055.

Calculated t is greater than 3.055; hence the result is significant.

A.3 Regression and Correlation

From the accelerated life test data we see that we have pairs of measurements. Each pair has a measurement in one classification, namely voltage and a corresponding measurement in another classification, namely time to failure. We are now going to check the consistency of the relationship of these pairs, finding an index of this consistency called the coefficient of correlation. If the sample coefficient of correlation appears to be significant, we shall then attempt to work out an equation that will enable us, given one member of a pair, to predict the other member.

We have compared the means of the high and low noise samples to see if these samples were significantly different. We are now going to determine whether the differences between the members of pairs suggest a relationship that is significant.

We shall approach the problem from a hypothesis-testing point of view, the null hypothesis being that there is no significant relationship, the alternative hypothesis being, of course, that there is a significant relationship.

A.3a Correlation Coefficient

We are trying to find out whether the pairs of measurements we have from the population of pairs show relationships that are more consistent than we should expect from a pairing of the members of the population by chance.

This sort of relationship of relationships was called correlation by a late Nineteenth Century biologist named Weldon. He also designed what is called a "coefficient of correlation."

The actual correlation r_a is given by:

$$r_a = \frac{n\Sigma xy - \Sigma x \Sigma y}{\sqrt{n\Sigma x^2 - (\Sigma x)^2}\ \sqrt{n\Sigma y^2 - (\Sigma y)^2}}$$

This value of r_a must then be compared with the critical coefficient r_c for the appropriate degrees of freedom and desired level of significance. If the calculated coefficient of correlation exceeds the appropriate critical value, we may then proceed to calculate the regression equation, with the conviction that the correlation is probably significant.

A.3b <u>Regression Equation</u>

When there is a significant relationship, then it would be useful for prediction purposes to have an equation for this regression line. We seek it in the form:

$$y = bx + a$$

All we need to know is a and b. But we would need calculus to get the a and b for the regression line that has the minimum sum of the squares of the vertical distances of the points from that line. The following formulae have already made use of the calculus. We substitute in them at once. All the information we need is in the table we set up for x, y, x^2, y^2 and xy.

$$a = \frac{\Sigma y \Sigma x^2 - \Sigma x \Sigma xy}{n\Sigma x^2 - (\Sigma x)^2}$$

$$b = \frac{n\Sigma xy - \Sigma x \Sigma y}{n\Sigma x^2 - (\Sigma x)^2}$$

Table A.2

x	y	x^2	y^2	xy
1.15	13	1.32	169	14.95
.93	11	.86	121	10.23
1.25	17	1.56	289	21.27
1.2	14	1.44	196	16.8
1.25	12	1.56	144	15.0
1.2	12	1.44	144	14.4
1.25	16	1.56	256	20.0
2.4	63	5.76	3969	151.2
2.1	39	4.41	1521	81.9
2.2	38	4.84	1444	83.6
2.4	40	5.76	1600	96.0
2.2	42	4.84	1842	92.4
2.2	42	4.84	1842	92.4
2.25	39	5.06	1521	87.75
23.98	398	45.25	15058	797.9

$$ra = \frac{n\Sigma xy - \Sigma x \Sigma y}{\sqrt{n\ (\Sigma x^2) - (\Sigma x)^2}\ \sqrt{n\Sigma y^2 - (\Sigma y)^2}}$$

$$= \frac{(14)(797.9) - (23.98)(398)}{(14)(45.25) - (23.98)^2 \quad (14)(15058) - (398)^2}$$

$$= 0.92$$

which is greater than $r_c = 0.661$ for $= 0.01$

Regression equation is of the form

$$y = bx + a$$

From the formula given above we now find the values of a and b:

$$a = \frac{(398)(45.25) - (23.98)(797.9)}{(14)(45.25) - (23.98)^2}$$

$$a = -19.22$$

$$b = \frac{(14)(747.9) - (23.98)(398)}{(14)(45.25) - (23.98)^2}$$

$$b = 27.82$$

SS due to regression

$$= \frac{(\Sigma xy - (\Sigma x)(\Sigma y)/n)^2}{(\Sigma x^2 - (\Sigma x)^2/n)}$$

$$= \frac{((797.9) - (23.98)(398)/14)^2}{(45.28 - (23.98)^2/14}$$

$$= 3209.57$$

Total corrected SS

$$= \Sigma y^2 - (\Sigma y)^2/n$$

$$= 15058 - (398)^2/14$$

$$= 3743.43$$

Table A.3

Source	d.f.	SS	MS
Total (corrected	13	3743.43	
Regression	1	3209.57	3209.57
Residuals	12	533.86	$S^2 = \frac{SS}{12} = 44.48$

Calculated F-value $= \frac{3209.57}{44.58} = 72.14$

A.4 F-Test for Significance of Regression

Calculated F-value $= 72.14 > 9.33$ (the critical F-value for $\alpha = 0.01$ and d.f. = 12); hence the regression is significant.

Standard error of slope $= \frac{S^2}{\sum (x_i - \bar{x})^2}$

$$= \frac{44.58}{4.23} = 10.54$$

Estimated variance of calculated y given by:

$$44.58 \left(\frac{1}{14} + \frac{x - 1.72}{4.23}\right)$$

Estimated standard error of calculated y is given by square root of variance.

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