BREAKDOWN TESTS ON COMPOSITE INSULATION

A DISSERTATION
submitted in partial fulfilment of
the requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Power Systems Engineering)

By
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CERTIFICATE

Certified that the dissertation entitled ''Breakdown tests on composite insulation'' being submitted by Shri Ashok Kumar in partial fulfilment for the award of the degree of Master of Engineering in Electrical Engineering (Power System Engineering) of the University of Roorkee, Roorkee is a record of student's own work carried out by him under our supervision and guidance. The matter embodied in this dissertation has not been published elsewhere nor submitted for the award of any other degree or diploma.

This is to further certify that he has worked for a period of six months from January 1979 to June 1979, for preparing this dissertation at this University.

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SYNOPSIS

The measurment of dielectric strength is generally beset with numerous difficulties, and the results depend to a large extent upon experimental conditions and sample geometry. In order to analyse breakdown test results which usually have a large scatter, it is necessary to apply statistical methods. Our experimental results were first tested for randomness and stationarity and then analysed statistically. The results follow the extreme value distribution (Gumbel I).

We used several solid insulating materials that were available. Special mention has to be made of Krempel (Class E) and Glass micanite since these are new materials. In general the results on these materials are quite encouraging.

Definition of Statistical Terms

1. **Variable.** : A measurable characteristic~~s~~ is called a variable.
2. **Variate.** : Individual measurments of a variable are called variates.
3. **Discrete Variable.** : If a variable can assume only specific values (usually integers), it is called a discrete or discontinuous variable.
4. **Continuous Variable.** : If a variable can assume any values whatsoever between certain limits, it is called a continuous variable.
5. **Measure of Central Tendency.** : Any measure indicating centre of distribution is called a measure of central tendency.
6. **Range.** : For a set of numbers the range is the difference between the largest and smallest numbers.
7. **Variance.** : The average of the squared deviations from the mean, called the variance, is used as a measure of dispersion.
8. **Standard Deviation.** : The square root of the variance is called the standard deviation.
9. **Random Data.** : is a collection of sets of observations, each of which represents only one many possible results which might have occurred.

10. <u>Sample Record.</u> : A single time history (of observations) representing a random phenomenon is called a sample record. It is observed over a finite time interval. It will also be called a set.

11. <u>Sample Function</u> : is a sample record taken over infinite time.

12. <u>Random Process</u> : The collection of all possible random sample records which the random phenomenon might have produced is known as random process.

12.a. Classification of Random Process: A. Stationary B. Non-stationary.

12.A. Stationary (i) ergodic (ii) Non-ergodic.

12.B. Non-stationary - Special classification of non-statonary

13. <u>Random Stationary Process.</u> : When the properties of random phenomenon can be hypothetically described at any instant of time by computing average values over the collection of sample functions which describe the random process, the process is known as random stationary process.

The mean value (first moment) $\mu_x (t_1)$ of a random stationary process can be computed at any time t_1 by averaging the instantaneous values $x_k (t_1)$ of each sample function of the random process at time t_1,

$$\mu_x(t_1) = \lim_{N \to \infty} \frac{1}{N} \sum_{k=1}^{N} x_k(t_1)$$

If this mean does not vary with time t_1, the process is said to be weakly stationary. For a weakly stationary function, the auto-correlation function $R_x(t_1, t_1 + \tau)$ defined as,

$$R_x(t_1, t_1 + \tau) = \lim_{N \to \infty} \sum_{k=1}^{N} x_k(t_1) \, x_k(t_1 + \tau)$$

is dependent only on the time interval τ.

If all possible moments of a random stationary function are time invariant, the function is said to be strongly stationary.

14. **Ergodic Random Process**: When in a random stationary process, the mean and auto-correlation function do not differ when computed over different sample function, the random process is said to be ergodic.

Ergodic random processes are an important class of random processes since all the properties of ergodic random process can be determined by performing time average over a single sample function. It is for this reason that the properties of an ergodic phenomenon can be measured properly from a single time history record.

15. **Self Stationary** : When a single sample record is stationary within itself i.e., the properties computed over short time

intervals do not vary significantly from one time interval to the next ('significantly' means that the observed variations are greater than would be expected owing to the normal statistical sampling variations), the sample record is said to be self stationary.

16. Basic Descriptive Properties of Random Data :

(a) Mean Square Value.

(b) Probability Density Functions.

(c) Auto-Corelation Function.

(a) **Mean Square Value** : It describes the general intensity of random data. In equation form the mean square value ψ_x^2 for a sample time history record x(t) is given by,

$$\psi_x^2 = \lim_{T \to \infty} \frac{1}{T} \int_0^T x^2(t)\, dt$$

It can be expressed in terms of two components:

(i) Mean value μ_x, which is the static or time invariant component because it is found simply by averaging the values,

$$\mu_x = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t)\, dt$$

and (ii) variance σ_x^2, which is the dynamic component, because it is computed by finding the variations of each value from the mean value.

$$\sigma_x^2 = \lim_{T \to \infty} \frac{1}{T} \int_0^T [x(t) - \mu_x]^2\, dt$$

$$\sigma_x^2 = \psi_x^2 - \mu_x^2$$

(b) **Probability density function** : It describes the probability that the data will assume a value within some defined range at any instant of time.

The probability that x(t) assumes a value within the range between x and x + Δx may be obtained by taking the ratio T_x / T when T_x is the total amount of time that x(t) falls within x and x + Δx during total observation time T. This ratio will approach an exact probability description as T approaches infinity.

$$\lim_{T \to \infty} \frac{T_x}{T} = \text{prob}\,[x < x(t) \leq x + \Delta x]$$

A first order density function p(x) can be defined for small Δx as follows

$$p(x)\,\Delta x \simeq \text{prob}\,[x < x(t) \leq x + \Delta x]$$

$$p(x) = \lim_{\Delta x \to 0} \text{prob}\,[x < x(t) \leq x + \Delta x]$$

$$= \lim_{\Delta x \to 0}\ \lim_{T \to \infty} \frac{1}{T}\left(\frac{T_x}{\Delta x}\right)$$

The probability density function p(x) is always a real valued non negative function.

P(x) is the probability that the instantaneous value of x(t) is less than or equal to some value x and is equal to the integral of the probability density function from $-\infty$ to x

$$P(x) = \text{Prob}\,[x(t) \leq x]$$

$$= \int_{-\infty}^{x} p(x)\,dx$$

P(x) is known as the distribution function or cumulative probability distribution function and is bounded by zero and one.

In terms of probability distribution function,

$$\mu_x = \int_{-\infty}^{\infty} x\, p(x)\, dx$$

$$\psi_x^2 = \int_{-\infty}^{\infty} x^2\, p(x)\, dx$$

(c) <u>Auto correlation function</u> : It describes the general dependence of the values of data at one time on the values of data at another time. An estimate of auto-correlation between the values x(t) at time t and t + τ is given by,

$$R_x(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t)\, x(t+\tau)\, dt$$

where is observation time.

$$R_x(0) \geq / R_x(\tau) / \quad \text{for all } \tau$$

$$R_x(-\tau) = R_x(\tau)$$

The mean value is given by $\mu_x = \sqrt{R_x(\infty)}$ and the mean square value by $\psi_x^2 = R_x(0)$ in terms of auto-correlations.

LIST OF SYMBOLS

E = electrical stress, breakdown strength in kV/cm.

$\bar{E}$ = mean breakdown strength in kV/cm.

$\vec{E}$ = electrical field vector.

E_m = modal value of breakdown strength in kV/cm.

f = observed frequency.

F = expected frequency.

i = number of class intervals = 1,2,...k

k = total number of class intervals.

= Bolt~~p~~zman's constant, thermal conductivity.

n = number of observations = 1,2,...N

= number of degrees of freedom.

N = total number of observations.

= number of dipole moments.

$p(x)$ = probability density function.

$p_0(x)$ = theoretical probability density function.

P = observed frequency.

$\vec{P}$ = polarisation vector.

P' = expected frequency.

$P(E)$ = probability distribution function.

r = number of runs.

= coefficient of variation.

R = cumulative frequency.

$R(E)$ = cumulative distribution function.

x = random variable.

$\bar{x}$ = mean value.

$\bar{x}^2$ = mean square value.

y = reduced variable of the extreme value distribution function.
$\bar{y}_N$ = theoretical value depending upon N.
α = level of significance.
= a parameter of the exponential distribution function.
= a measure of dispersion in the extreme value distribution function
= polarisability of dielectric.
β = a parameter of the exponential distribution function.
ϕ = probability density function.
= work function of the metal of the electrode.
= cumulative probability function.
ψ^2 = mean square value.
u = mean value.
σ = standard deviation.
= Surface tension of the liquid.
= electrical conductivity of the dielectric.
M = molecular weight in Kg.
= density in Kg/m^2.
K_r = relative permittivity.
K_0 = permittivity of free space.
T = absolute temperature.
J = Thermionic current density in the absence of the electrical field.

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1. INTRODUCTION

1.1 The Nature of the Problem

With the rapid increase in demand of electrical power in urban areas particularly, it is becoming necessary to bring higher voltages for the power transmission and distribution systems. In India for transmission purpose we are already using 400 KV transmission voltage and contemplating the use of 800 KV. Distribution of Electrical Power in heavily populated urban areas with such high voltage like 110 KV can only be achieved with the help of under ground power cables. The cities like LONDON and MOSCOW are having their distribution ring of 275 KV and above, which is mostly underground. There, one is forced to bring a voltage like 110 KV to the heart of the city to meet the high load density of 5 MVA/Km^2 and above.

Secondly the insulation content in the slots of rotating electrical machines varies between 100 to 300 Percent of copper area. By extensively testing the insulation system and evaluating the mechanical, electrical and thermal capabilities it is desired to achieve reduction in this insulation content for better utilisation of this space. This can also result in less temperature drop across the insulation wall and lesser material content. Adoption of higher temperature class of insulation can be restored for better space utilization and compactness. So insulating materials plays a very important role in this.

The insulating materials are extremely diverse in origin and properties. Many of them are of natural origin as for e.g. paper, cloth, paraffin wax and natural resin. Wide use is made of inorganic insulating materials such as glass, ceramics and mica. Many of the insulating materials are man made products manufactured in the form of resin, insulating film etc.

During the second World War, there was an explosion in the number of synthatic materials made commercially available - both PLASTOMERIC and ELASTOMARIC. Only a few of these materials proved technically suitable for use as cable insulants, and the field was further narrowed down when factors such as cost, availability and ease of processing were considered. The final choice can generally be limited to the following:

Plastomers:- Polyvinyl chloride, polyethylenes (both low and high density) polypropylene, and co-polymers.

Elastomers:- Styrene - butadienerubber, butyl rubber, ethylene propylene rubber, cross-linked polyethelene.

In recent years wide use is made of new materials whose compositions and properties place them in an intermediate position between inorganic and organic substances. There are the synthetic organo - silicon coumpounds, generally termed as silicones.

Paper insulated cable has been widely used as a high voltage power cable . But with the development of XLPE as cable insulation material around 1960, those areas are gradually being replaced by XLPE insulated cable and provides following advantage:-

1. No specialized technique such as oil impregnated paper tape wrapping or wiping is required in joining cables.

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1. No specialized technique such as oil impregnated paper tape wrapping or wiping is required in joining cables

2. Since a metal sheath is not employed, problems due to fatigue phenomena are eliminated.
3. Light weight permits long cable spans.
4. The maximum normal operating temperature of XLPE is 90°C, thus providing larger current carrying capacity.
5. Requires no additional systems such as oil feeding tank and alarm system.
6. May be employed without special devices to routes having large height variations.
7. Easy maintenance.

Because of certain extra ordinary qualities, plastic insulated power cables are fast replacing the conventional type paper insulated lead covered cable up to 33 KV. With the present day extrusion techniques, cables with extruded polythelene (PE) up to 225 KV have already been laid in France and Japan, where as in West Germany and U.S.A. hundreds of Km of 138 KV cross link PE cable are in service.

Insulating materials have a great responsibility in providing for reliable and successful operation of electrical equipment. After a switchgear equipment passes its initial tests, and operates for short period without untoward incident, it will be usually continue in safe, reliable and successful operation for many years. Analysis of the failures of electrical insulation have indicated that serious thermal ageing is the most general cause of the insulation failure. The exceptions are usually where there has been serious contamination of the insulation or where mechanical damage has occurred from some external cause.

It is obvious that as we are thinking about extra high voltage, we have to think about insulating materials also. Now our further efforts will be to evaluate the insulating materials individually and in combination with a view to select an insulating system according to our requirements in future.

1.2 Discussion of Available Literature

There are many kinds of materials for electrical purposes. These materials range from oils, resin, organic fibres, minerals and ceramics. There is only a common and a very significant characteristic to all insulating materials, namely their characteristic by a scarcity of free electrons in their physical structure. This means that while they can conduct electric current, when subjected to electric stress, the currents are relatively minute and require relatively very high voltage to produce them. The ability of an insulating material to withstand electric stress without rupture is a very important characteristic. When an insulator is stressed at a voltage sufficiently high to produce rupture, the voltage at which such breakdown occurs, is defined as the electric breakdown voltage (the electric strength being defined as breakdown voltage divided by the distance). Such electric breakdown strength depends on many factors including RRV, the time of voltage application, the frequency of applied voltage, the atmospheric condition and the thickness of the materials, as well as the temperature and the electrode configuration.

Narasimhan, et.al.[1] has reported the values of the moisture absorption by weight and maximum electric strength for different values of relative humidity, for glass epoxy, glass filled phenolic, resin impregnated wood and oil impregnated wood.

Suleebka[6] has discussed in her report about gap length between the electrodes, electrode shape and electrode material. According to her the variation of the gap length does not affect the form of the statistical distribution, but the modal value and dispersion of break down strength are higher at smaller gap length. The electrode shape affects the distribution to a large extent. The dispersion of breakdown strengths decreases as the field configuration of electrode is varied from uniform field, to point plane. The modal value of breakdown strength is smaller with uniform field electrodes than with sphare-sphare electrodes perhaps because of the area effect.

Brass has a normalising effect on the distribution of breakdown strength. The modal values as well as the dispersion using brass electrodes are smaller than those using stainless steel electrodes.

Zaky, et.al.[17] give results of the effect of a very wide range of additive concentrations (5×10^{-4} to 0.4 molar) on the gassing properties of mineral oil. Benzophenone, naphthalene, tetralin and quinoline were used under four gas phases, H_2 , N_2 , O_2 and air, and stresses ranging from 36 to 64 KV/cm.

Tangen, et.al.[18] have performed experiments on sphere/plate and plate/plate electrode embedded in epoxy resin and got the following results:
Tests on 0.2 and 0.35 mm sphere electrodes support the hypothesis of an area dependent breakdown strength.
It has been found that the curing condition is also of importance.
The breakdown strength limit, seems to decrease with increase in exothermic temperature. Hence extrapolations from small test specimens to larger ones are not permitted.
So far it has not been possible to establish a breakdown criterion generally valid for a specific resin.
Long time tests have shown that the breakdown strength limit is lowered by ageing processes.

1.3 Author's Line of Attack

In the light of the above discussion we have to plan our experimental work. Depending on the availability of insulating materials apparatus, facilities and on the strength of initial exploratory experiments, we have to decide which parameters we can control and which parameters are not controllable so that our experimental work will give some useful and accurate information.

The broad aim of the work is to study the electrical breakdown behaviour of solid insulating materials and transformer oil, individually and in combinations that are prevalent in practice. Statistical techniques will be used for processing the test results, and use will be made of the available computing facilities if necessary.

1.4 Arrangement of the Thesis

This thesis is devided in seven sections which is arranged in the order in which the work was done.

Section 1 gives the introduction which explains the nature of the problem, discussion of available literature, author's line of attack and the arrangement of this thesis.

Section 2 gives the review of the work done by other research workers in the field of electrical breakdown in solid and liquid insulating materials. Firstly, the introduction to this field is given, secondly, the electrical processes taking part in breakdown process are discussed. This is followed by the effect of various parameters on the breakdown strength. Lastly, the statistical studies that have been made till now are discussed.

Section 3 gives all the details about the automatic control system for the test equipment, and about the test procedure followed in the breakdown tests. The last subsection explains the statistical techniques used.

Section 4 gives the experimental results. The first part gives the list of parameters that are significant in breakdown tests on the solid insulating materials and transformer oil. The second part gives the properties of these materials and oil. The next part shows how a test procedure is decided upon with the help of exploratory experiments and statistical techniques. Since the test procedure is evolved on the basis of exploratory experiments, some of the discussion of results of exploratory experiments is included in this section. The last part gives the result of two main experiments.

Section 5 gives the analysis of the results. A sample calculation of each statistical test is also included.

Section 6 gives the discussion of the experimental results and section 7 gives the conclusions. The numbering of the figures and tables corresponds to the number of the subsection where it appears.

2. BREAKDOWN MECHANISM OF SOLID AND LIQUID DIELECTRICS

2.1. Introduction:

Power systems are continuously increasing in their generating and transmission capability to cope with the ever increasing demand of electric power. A definite feature of the present day industrial progress is that the generating stations through out the country are getting linked up in ''regional grids and super grids''. This has helped in the proper production of the electrical energy and ease of transporting from the point of production centres and places where they are mostly needed. This necessitates the adoption of higher system voltages.

The live conductors and those high voltage are required to be electrically supported at their potentials from electrically earthed objects which are at zero potential. Insulating materials serve the function of insulating and supporting these electrically live conductors against their coming in contact with the earthed object. Very literally speaking, the insulating materials offer very very high resistance to the flow of current from the live conductor to earth. The leakage current would be inappreciable in comparison with the main current flowing through the conductor of the windings of the generator, motor, transformer or the conductors of the overhead transmission line or under ground cables.

In order to understand the mechanism of failure of these insulating materials, a brief study of the electrical insulating material is essential.

From the down of electrical engineering till 1830 A.D., electrical experimentors and inventors used readily available materials for the insulation requirements of the equipments they handled. But with growing need of the technical complexities of various equipments, some insulating materials like rubber, asphalt, mica, cotton, shellac, varnished cloth etc. came in practical use. Thus prior to the second world war, mica, asbestos, bitumen shellac and synthetic materials had also forced their entry into the insulation industry. The post war development of the insulating materials has brought in polythene, P.V.C., plasticates, polynamides, polycarbonates, polystyrene, polytheylene into picture.

2.2 General Properties and Failure of Insulating Materials

In general, the weakest link in an insulation system is an interface between two different materials, especially when there are tangential electrical stresses along this interface. When the interface is solid to air (or gas) and the tangential stress is sufficiently high, corona discharges takes place if dust collects on the interface, tracking would occur during the period when moisture condensation is taking place on the surface.

With time and temperature, or due to the effects of ultraviolet light, solvents, vibration or other disruptive influence, the insulation would fail mechanically after which it would lose its electrical property. The actual final breakdown is associated with the condensation of moisture at the physical defect.

Power loss in a dielectric is a function of permittivity, loss tangent, frequency and electric stress or potential gradient ($p \alpha Kr. \tan\delta . f E^2$). If the voltage is applied continuously, the heat evoved should be dissipated by the outside surface. If the permittivity or the loss tangent increases rapidly with temperature, the rate of heat evolution increases and a runaway condition may occur with resultant failure of the insulating materials.

Properties of an insulating material for a particular use are given below in the relative order of importance.

1. Mechanical behaviour
2. Thermal behaviour
3. Chemical characteristics
4. Electrical properties and
5. Economic factors.

2.2.1 Mechanical behaviour of the insulating materials:- In general, toughness is the main requirement, stiffness modulus should be high for a rigid structure or low for a wire insulation. A slot liner sheet material has to be stiff enough to expand against the inside surface of the slot, should be able to crease without breaking and should be able to withstand burr on the edge of the slot lamination, vibration, chemical action of the impregnated varnish, effect of high temperature, absorption of moisture etc. The overhang of the coil should have high abrasion resistance or a very low coefficient of friction. The insulating varnish should have adhesion to the wires, sufficient elasticity to expand and contract with the copper as its temperature changes. Thus the mechanical requirements on an insulation are different for each application.

2.2.2. Thermal behaviour :- Many insulation applications Require the material to be exposed to the excessive temperatures for a short period of overheads. Physical properties of materials generally drod off to lower values with the rise in temperature. Tensile strength should not drop to the point where excessive deformation and creep would occur. A thermoplastic material must not be exposed to a temperature in excess of its melting point even for a short time.

When materials are exposed to temperature for longer period of time, they change their chemical composition. This chemical change with resultant change of physical properties from permissible state to non-permissible state lead to ageing of the material. It is now well established a fact that for most insulating materials, the service life can be related to temperature as an approximately linear slot of log of life versus the reciprocal of absolute temperature.

2.2.3. Chemical behaviour:- Chemical behaviour relates to the effect of the enviroment on the insulating material. The most common environment is air containing moisture. The oxygen in the air can oxidise the insulation at a temperature until it loses its necessary physical properties detrimentally. It can also hydrolyse and degrado some insulations. It can collect on the surface and give low insulation resistance. Ultraviolet resistance is of importance in those applications where the material is exposed to the radio active elements. Resistance to corrosive atmosphere, such as salt spray is equally important. Effects of solvents can be disastrous. The different insulations used in contact with one another can have disastrous effect on the thermal stability of one another.

2.2.4. Electrical properties :- of all the properties, dielectric strength is the most important. The measured value of dielectric strength is a function of electrode size, ambient medium in which the test is conducted, the shape of the electrode, the rate of rise of voltage, voltage wave shape and frequency, the relative humidity and temperature and the length of time to which the sample has been exposed to these conditions. There is no relationship between the measured value of the dielectric strength and the value of potential gradient at which the material can be used in practice. A judiciously selected value of factor of safety is the only guide. These values are of great importance for quality control and as research tools. A few uses where the properties are critical are (a) insulation for microwave cable where tanδ should be low for efficient transmission and (b) high voltage capacitors and high voltage oil/gas filled cables where insulations are stressed to much higher voltage gradients.

In machines upto 3.3 KV, the thickness of insulation is decided on the basis of mechanical strength, abrasion, etc. and the voltage gradient is calculated as a check.

Among the other electrical properties corona or discharge resistance and surface tracking resistance are important for high voltage transmission.

2.2.5. Economics factors:- The best insulation design is a part of overall design of an equipment/system which give the maximum performance per rupee of overall cost. This does not mean that the entire effort should be concentrated on minimising cost per unit weight of the given material for the desired equipment/system. If by spending more for one or more elements in a system, the whole system can be reduced in size and material savings for other than the insulation, more than over balances the insulation cost, it is wiser to use the more expensive insulation. All pros and cons of the problem must be studied along with cost per unit weight, fabrication and tooling, changing design to accomodate higher temperature.

2.3. Mechanism of Failure of Insulating Materials

(a) During operations, heat ageing causes embrittlement of the materials and thermal cycling products mechanical stresses.

(b) Vibration develops any tendency of the insulation to crack.

(c) Condensation of moisture which occurs during the non operational period enters the cracks.

(d) The voltage applied on restarting detects the moisture field cracks.

In the functional test, discussed in Appendix (A) a model of the equipment is subjected to a cycle of heat ageing, vibration, exposure to 100 Percent relative humidity by a test voltage. The temperature at which heat ageing is carried out are chosen above the operating temperature in order to obtain results in a reasonable period of time. The test voltage is used is little above the operating voltage in a humid atmosphere.

The test results (life in hours and temperature) are plotted in the form of graph fig.2.3.1. The life of the system at the classification temperature at an agreed life can be extrapolated. Thisfunctional test is useful because it makes if possible for the mechanism of failure to be observed in some detail. This can serve as a very useful tool for the classification of insulation systems, evaluation of insulating materials and improvement in the design of the equipment.

2.4. Molecular Properties of Dielectrics

A dielectric material can react to an electric field because it contains charge carriers that can be displaced. Electrically speaking, matter consists of positive atomic nuclei surrounded by negative clouds. Under the action of an external electric field, electrons are displaced slightly with respect to nuclei. Induced dipole movements result and cause the electronic-polarisation of materials. When atoms of different types form molecules, they would not normally share their electrons symmetrically because the electron clouds would be displaced ecentrically towards the stronger binding atoms. Thus atoms acquire charges of opposite polarity and an external field acting on these net charges would tend to change

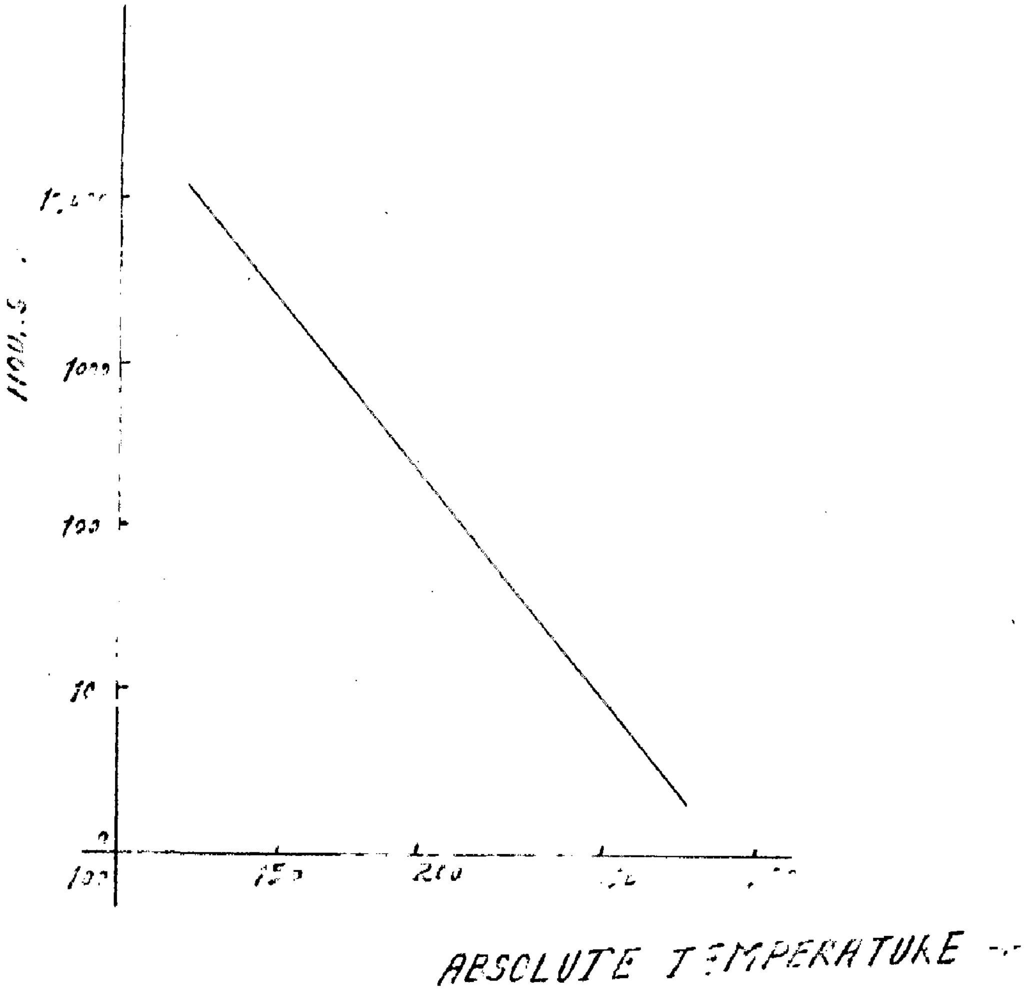


FIG NO 2.3-1

the equilibrium positions of the atoms themselves. By this displacement of changed atom or groups of atom with respect to each other, a second type of induced dipole moment is created. It represents the atomic polarisation of the dielectric. The asymmetric charge distribution between the unlike partners of a molecule gives rise to permanent dipole moments which exist even in the absence of external electric field. Such moments experience a torque in an applied field, that tends them to orien them in the field direction. Thus an orientation polarisation comes into picture.

These three mechanism of polarisation, characterised by an electronic polarisability (α_e), an atomic polarisability (α_a) and an orientation or dipole polarisability (α_d) are due to charges that are locally bound in atoms, in molecules or in the structure of solids and liquids. Besides, charge carriers usually exist can migrate for some distance through the dielectric. When such charges are impeded in their motion, either because they become trapped in the material or on interface, or they cannot be freely discharged or replaced at the electrodes, space charges and the overall field distortion result. This leads to the "space charge (or interfacial) polarisation," characterised by a "space charge" (or interfacial) polarisability (α_s), thus the total polarisability of a dielectric material would be given by :-

$$\alpha = \alpha_e + \alpha_a + \alpha_d + \alpha_s \qquad (1)$$

We know that for a dielectric, the Polarisation vector

$$\vec{P} = (K_r - 1)\, K_0\, \vec{E} \qquad (2)$$

where K_r = relative permittivity

K_0 → permittivity of free space.

$\vec{E}$ = Electrical field vector.

Also

$$\vec{P} = N\, \alpha\, \vec{E}' \qquad (3)$$

where N = No. of dipole moments.

α = Polarisability.

$\vec{E}'$ = Locally acting electrical field vector.

This field vector $\vec{E}'$ would normally differ from the applied field vector $\vec{E}$ due to the polarisation of the surrounding electrica medium.

If the external field is of alternating nature, a temporary phase shift may occur between the external field and the resultant polarisation and a loss component of current would appear. Under this condition α becomes a complex number

$$\vec{P} = (K_r^{*} - 1)\, K_0\, \vec{E} = N\, \alpha\, \vec{E}' \qquad (4)$$

Taking into account the effect of the locally acting fields: (a) field from the free charges, (b) field from the free - ends of the dipole - chains and (c) field due to the individual action of the molecules on the reference molecules. Mosotti obtained a relationship for polarisation per unit volume in terms of permittivity of the dielectric given by equation (5)

$$\frac{N\alpha}{3K_0} = \frac{K_r - 1}{K_r + 2} \qquad (5)$$

In other cases, as long as the molecules themselves are the dipole carriers, it would be convenient to eliminate the dependence of the polarisation on the density of the material by referring to polarisation per mol. (i.e. Avogadro's number).

∴ No. of molecules per mol.

= No

$$No = \frac{NM}{\rho} = 6.023 \times 10^{23} \qquad (6)$$

where M = Molecular weight – in Kg.

ρ = density in Kg per M^3.

∴ Molar Polarisation (i.e. Polarisability per Mole)

$$= \frac{N_0\alpha}{3K_0} = \left(\frac{K_r - 1}{K_r + 2}\right)\frac{M}{\rho} \qquad (7)$$

Equation (7) is known as the Clausius Mossotti equation.

From the above, it can be noted that the molecular properties of a dielectric can have great influence on the permittivity. The permittivity can be shown to be related with the capacitance, loss tangent etc., the important characteristics of a dielectric. It would be worth while to study the effect of temperature, pressure, voltage etc. On the permittivity of a dielectric before we embark upon the phenomenon of ionisation and breakdown of dielectrics.

2.4. The Experimental and Physical Parameters

In addition to the processes taking place in the liquid itself, the breakdown strength is also very sensitive to some external factors which are introduced by the test procedure. These factors are the experimental and physical parameters. In view of the large number of test necessary for a statistical appraisal, the experimental and physical parameters should be identified properly and rigorously controlled.

2.4.1. The physical parameters

:- The physical parameter can be listed as follows:-

(a) Pressure
(b) Temperature
(c) Humidity
(d) Frequency of applied voltage
(e) Voltage
(f) Viscosity
(g) Molecular weight

(a) Pressure :- For those dielectric obeying clausius - Mosotti equation, the permittivity would increase as pressure is increased if the density is increased too simultaneously. For non-polar gases, permittivity is directly proportional to the pressur

$$K_r = 1 + \frac{p}{T}\left\{2H + \frac{\delta E}{p}\left(\frac{10160}{T} - 0294\right)\right\} \times 10^{-6}$$ ①

where p = Pressure in mm of Hg.
δ = Air density factor
T = Absolute temperature
E = Pressure of vapour saturating the air mm
H = Height of a place above sea level (in Km).

Equation ① is the Volport's formula for air permittivity to be calculated with various values of pressure, temperature and humidity.

The permittivity of liquid and solid dielectric are also affected by pressure, e.g. permittivity of glycerol (at 5 °C and frequency 10^6 Hz) at one ata is 49.3 but is 53.2 at 4070 ata and again decreases to 33.6 at 9500 ata. Water has its increasin permittivity upto pressure range of 6000 ata.

Pressure applied during the process of testing also changes the permittivity of the dielectric under test.

(b) Temperature :- Temperature does not affect the process of electronic polarisation. Thus the separate molecules are not affected. Due to thermal expansion of substance, the quantity of molecules to be polarised per unit of dielectric volume decreases if the temperature is increased. Permittivity in such cases is also decreased (e.g. Permittivity of paraffin decreases when it is changed from solid state to liquid state).

In cases of solid ionic (non-ferro electric) dielectrics, permittivity increases with temperature (e.g. ceramics). In Polar dielectrics initially at low temperatures, easy dipole orientation leads to dipole ionisation and permittivity increases with temperature [e.g. nitrobenzene - melting point (5.7°C)].

Incidentally, it may be mentioned that in order to get capacitance independent of temperature, i.e. a thermo-compensated condenser, either the system of two capacitors with temperature coefficient of permittivity of opposite sign are to be connected in series or in parallel, or a condenser with composite dielectric (which is actually a mixture of two dielectrics having opposit signs of temperature coefficients of per-mittivity) is to be adopted.

The temperature coefficient of permittivity is obtained by obtaining $(\frac{dK}{dT})\ T = T_a$ of the curve $K = f(T)$

(c) Humidity :- Permittivity of hygroscopic dielectrics increases with humidity content. For some simple gases, clausius - Mossotti equation can be used but, in general, it is difficult to calculate the value of Permittivity of humidified dielectric. Humidity increases permittivity, decrease resistivity or increases conductivity, increases losses and decreases dielectric strength.

(d) Frequency :- The time of setting (i.e. relaxation of time) of electronic or ionic polarisation is very little in comparison with the time of variation of the sign of the voltage (i.e. one half period of alternating voltage) even for the highest frequencies is completely set. Thus the frequency does not much influence the permittivity of a dielectric, if, somehow or other, the Polarisation has not set completely before the voltages has changes its sign, the permittivity would decrease (i.e. if $\mathcal{T} < \frac{1}{2f}$).

If non-uniform dielectrics (having water inclusions), the interfacing or space charge polarisation would take place since this type of polarisation is very slow (may require minutes and hours). The higher frequency with higher water scope content would weaken the insulation and decrease the permittivity as well. Phenomenon of dependence of permittivity on the frequency is called or dispersion of permittivity.

(e) Voltage :- For linear or non ferroelectric materials, permittivity does not depend on the voltage. For Ferroelectric materials, the permittivity depends upon the voltage. Ferroelectricity arises from vibration states. The displacement of certain ions from their equilibrium posistions strongly unbalances the equilibrium of permanent moment. By a proper structural arrangement, this upset induces a motion of the neighbouring ions in a supporting sense which increases the original displacement by feedback. The tendency to bring the vibrations of neighbouring ions into ordered phase relations exists at the curie point against the random agitation. The equilibrium position of the critical ions shifts to one side because the whole effect was made possible only by the displacements of these ions. The old balance of the permanent moments is destroyed and a polar axis is created by the transformation of induced moments into additional permanent moments.

Thus for the ferroelectric crystal, the possibility of reversal of the induced moments into additional permanent moment is inherent because the axis evolves at the curie point from a state of higher symmetry. Thus this response to pressure and voltage leads to the increases of permittivity.

For polar liquids and gases, due to the effect of saturation, permittivity would decrease a little with the increase of voltage. Further the effect of saturation is very little for non-ferro-electric dielectrics (e.g. water) than for a ferromagnetic materials.

(f) Viscosity :- A change in viscosity of liquid should affect the speed of propagation of breakdown disturbance if the breakdown involves a vapour phase. It has been shown that the ratio of time to breakdown to viscosity remained constant over the whole range of viscosities for hexachlorodiphenyl (Krasucki, 1966)[6].

(g) Molecular Weight :- The breakdown strength is related to the molecular structure of the liquid. Sharbough, Crowe and Bragg, 1954,[6] reported that the breakdown strength of aliphatic hydrocarbons increases with molecular weight. As the molecular weight increases, the surface tension and the permittivity decreases, so that the stress required for the propagation of breakdown disturbance would be higher[6].

2.4.2 <u>The experimental parameters</u>:- The experimental parameters can be listed as follows:-

(a) Rate of rise of voltage
(b) Arc duration
(c) Magnitude of the breakdown current
(d) Time interval between two tests
(e) Polishing and cleaning of the electrodes
(f) Liquid purification
(g) Gap length.

(a) <u>Rate of Rise of Voltage</u> :

Salvage, 1951,[19] reported that the change of rate of rise of voltage had no effect on breakdown strength. But Brignell, 1963,[20] has shown that the effect of rate of rise, though small, is not insignificant. He has demonstrated the rate of rise effect using ramp voltages of different rates of rise and has explained this effect on the basis of variation of breakdown strength with pulse duration (Crowe, 1956)[6]. Since the time lag is a sharply decreasing function of stress, the breakdown stress would be a gently decreasing function of time available. Therefore breakdown stress would be a gently increasing function of the rate, which is the inverse of time. But the changes in the rate within one sequence of observations drastically alter the distribution of breakdown strengths towards the normal distribution. Therefore a rigorous control of the test method is needed if the distortion of the distribution is to be avoided. In fact, one of the difficulties in correlating the result of different workers arises because they have either not controlled the rate of rise of voltage to close limits or have used different rates.

(b) Arc Duration :

The arc duration decides the extent of deterioration of the liquid medium under test and of the electrode surfaces. If the extent of deterioration is large, the subsequent breakdown values are more susceptible to the earlier breakdown history Therefore the extent of deterioration must be limited by fixing the arc duration to a small constant value. Lewis, 1953,[21] reported that by employing a hydrogen thyratron bypass circuit, the dispersion in the measurements was much reduced, and many more measurements on a particular sample were possible.

(c) Magnitude of Breakdown Current:

The magnitude of breakdown current also decides the extent of deterioration. It can be kept constant by using a variable resistor whose magnitude at any instant would be proportional to the test voltage. Generally, the current is limited to a low value by providing a suitable current limiting resistor.

(d) Time Interval Between Two Tests:

The time interval between two consecutive tests must be of a duration sufficient for the condition of liquid to stabilise fully after a breakdown has taken place (Gosling, 1960)[6]. Time intervals of one minute or more are sufficient (Darwenize, 1959)[6].

(e) Polishing and Cleaning of the Electrodes:

Metal electrodes, polished mechanically to a mirror finish are employed almost universally. Polishing and cleaning of electrodes was emphasised too much about 15 years back. It was felt that a better polishing and cleaning would give a better surface and thus the electrode effects would be reduced, giving a reduced scatter in the breakdown voltages. But experience has not substantiated this feeling. Mechanically polished electrodes, rinsed with the test liquid and stress conditioned, give as satisfactory results as rigorously polished, electrolytically cleaned and baked electrodes (Lewis, 1959)[6].

The oxide layers on the electrode surfaces affect the breakdown strength to a large extent. Kao and Higham, 1961,[6] have suggested that the conditioning effect is primarily governed by oxide layers of electrodes. Hancox, 1957,[6] explained the greater scatter in breakdown voltages obtained with copper electrodes on the basis of uneven oxidation of electrode surfaces. Swan and Lewis, 1961,[6] conducted extensive studies on the effect of oxidation of electrodes on breakdown strength. They oxidised the electrodes of different metals at room temperature, varying the time of oxidation. The breakdown strength did not vary with time of oxidation for platinum and gold electrodes because they do not get oxidised at room temperature. For stainless steel and brass electrodes, a maxima occurred since they get oxidised very quickly, and with more oxidation time, the breakdown strength decreased. For aluminium electrodes, the breakdown strength decreased very sharply with time of oxidation, because immediately after polishing or during polishing, an oxide layer would have formed on it. The effect of oxidation of electrodes on breakdown strength is different for anode and cathode.

(f) Liquid Purification

None of the liquids, as available in the market, would be pure. Removal of all the impurities from the liquid before conductivity or breakdown measurements is absolutely necessary because of the deterimental effect of impurities.

The strength of the liquid would be increased and scatter would be decreased when solid particles are removed from the liquid. The presence of particles result in premature breakdown because of particle oscillation and bridge formation. Gosling, 1960,[6] has reported this kind of breakdown at 300 kv/c in transformer oil, and has photographed the bridge formation successfully. On crossing this region of stress, it was possible for him to maintain a field of 1000 kv/cm. the particle activity gradually subsiding.

The test cell and electrodes are usually rinsed with the clean liquid so that they donot introduce any impurities. The liquid purification system and the test cell are generally arranged in a closed system.

(g) Gap Length:

The breakdown strength of n-hexane increases as the gap length decreases and there is an apparent intercept of about 1000 for zero gap length. Gap lengths less than about 30 μm have not yet been explored. For purified transformer oil, the breakdown strength of 700 kv/cm for a 200 μm gap, rises to 1500 kv/cm for 28 μm gap (Gosling, 1960)[6]. At larger gap lengths (1 mm - 5 mm), the breakdown strength does not depend on gap length (Hancore and Tropper, 1958)[22].

2.5 Control of Parameters:

It is thus clear that the experimental and physical parameters affect the breakdown phenomenon to a large extent. The manner, in which the variation in a parameter affects the breakdown strength when all other parameters are kept constant, can lead to an explanation of the breakdown phenomenon. This can be done when all the parameters can be controlled rigorously. In the previous works, a rigorous control was not adopted, therefore many discrepancies about the results of breakdown tests arose. The importance of rigorous control has been realised now, and in recent works (Brignell, 1964)[6], the better experimental techniques adopted have given better consistency of results. 'Better consistency' means that the same results are obtained when the experiment is repeated under the same conditions, andnot that the scatter in the values of breakdown strengths in a series of tests is reduced. The scatter of breakdown strengths isnot decreased by adopting better experimental techniques, on the contrary, less scatter may mean poorer experimental techniques like rough electrodes, presence of impurities or faulty statistical selection (Brignell, 1966)[20].

2.6 Statistical Studies

An attempt to formulate a correct statistical model of the breakdown theory necessitates the determination of the distribution of breakdown strengths since the observations in breakdown tests in variably have a large scatter. The idea that breakdown studies on liquids should be approached from the point of view of statistics has been long recognised, but the use of mean and variance was made more as a matter of convenience in summarising the test results than as a result of rigorous statistical analysis.

To apply statistical technique to breakdown test results, the problem is appreached from the basic principles of statistics. A set of readings should satisfy the fundamental statistical conditions, namely randomness and stationarity, if the set is to be used to determine the distribution of breakdown strength. Such a set is obtained only when the breakdown test is designed properly, on the basis of statistics, by performing exploratory experiments.

2.6.1 Basis of selecting readings from a sample record :

All the readings in a sample record may not satisfy the conditions of randomness and stationarity. For example, in a sample record of say 10, 100 or 1000 readings, there will be a rising or falling trend of breakdown values in the initial part due to conditioning, thereafter the breakdown values will be comparatively stable and in the last part there will be a falling trend of values due to deterioration of oil and of electrodes. Fig.2.6.1 shows such a trend. Of course the actual values of breakdown voltage will be randomly distributed about this line showing the trend.

Can all the readings in such a sample record be selected for statistical analysis ? Most of the researchers have not reported about selection of readings though they have presented their results in terms of means and variances.

From the very definition of conditioning, i.e., change of breakdown voltage with successive breakdowns, it is clear that the initial part of a sample record representing conditioning cannot be statistically stationary. Similarly, the last part, representing deterioration cannot be stationary. Therefore the middle part can be selected for statistical analysis. The observations in this part can be subjected to a statistical test of stationarity.

2.6.2. Theories of breakdown phenomenon of liquid dielectrics:

The breakdown phenomenon of liquid dielectrics is not so perfectly understood as that of the gaseous or solid dielectrics. One of the methods states that the electrons are emitted from the cathode either by field emission or by the field enhanced thermionic effect (i.e. Schottky effect). These electrons bring in avalanche ionisation of the atoms of the liquids dielectrics as in the case with gaseous dielectrics.

Second method is based upon the formation of bubble in the liquid and its effect upon the breakdown of the liquid dielectric.

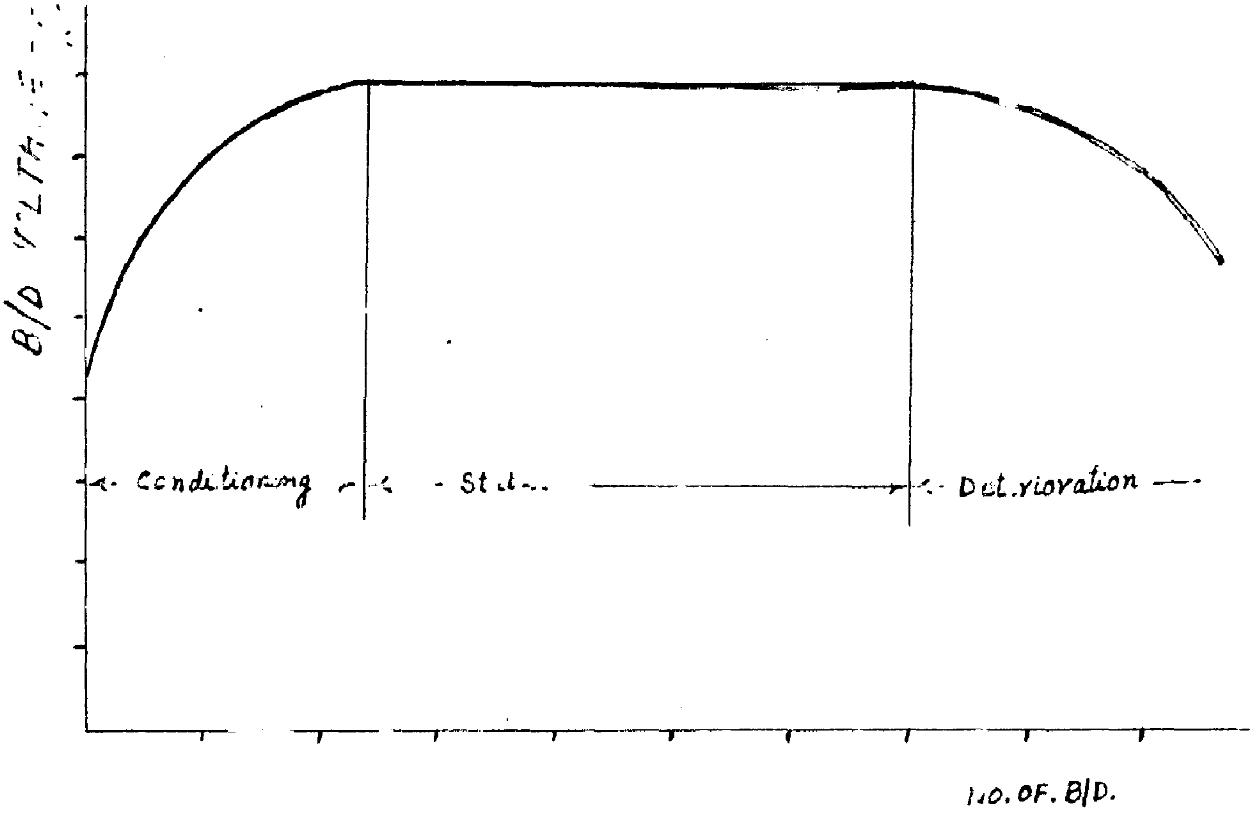


FIG. NO. 2.6-1

The suspended foreign particles are also held responsible for the breakdown of liquids. The suspended particles are equivalent to the polarisable sphere of permittivity higher than that of the liquid. Under the action of the external field, these particles experience an accelerating force enabling them to reach the electrode (anode). Surface irregularities of the electrodes help the particles to be accumulated in the inter-electrode region tending to form the bridge across the gap. This finally leads to the breakdown of the dielectric.

(a) Electronic Breakdown of Liquid Dielectronics: conduction in liquid dielectric increases with the voltage gradient (i.e. the applied electrical field intensity) and the temperature but the permittivity decreases with the increase of temperature. The conductivity because of the decrease of viscosity and consequent increase of ion mobility. Detailed study of conduction activity of liquid dielectrics has indicated that the experimental results agree with the Schottky's equation of electron emission from metallic cathodes and of electronic conduction through the liquid dielectrics. The current density is given by:-

$$J = J_s \, e \, \frac{e}{KT}\sqrt{\frac{eE}{4\pi \, K_r \, K_0}} \quad \text{Amp/ m}^2 \qquad (1)$$

where J_s = Thermionic current density in the absence of the electric field

= $AT^2 \, e^{-\phi e/KT}$

K = Boltzman's constt.

ϕ = Work function of the metal of the electrode.

e = charge of the electron

T = absolute temperature

K_r = relative permittivity of the liquid dielectric

$K_0 = \frac{1}{36\pi} \times 10^{-9}$ farads

E = Voltage gradients in (V/m)

$$\therefore \quad J = J_s \, e^{0.44\sqrt{E/T}} \text{ Amp} / m^2$$

Where E is expressed in volt/ cm

$$= J_s \, e^{4.4\sqrt{E/T}} \text{ Amp} / m^2 \qquad (2)$$

Due to field emission augmentation of the thermionic electronic conduction process, the electron conducted increases manifold. This factor is taken into account by multiplying the actually applied potential gradient (E_a) by a multiplication factor (M) to obtain the value of the Potential gradiant (E) to be used in equation 2. For polished surfaces, M may be of the order of 10.

Statistical result of experimental studies of the effect of temperature on the breakdown V indicate that the breakdown V is more or less independent of temperature. This indicates that the cathode process postulated in the electronic breakdown mechanism is really the field emission rather than the thermionic emission.

Further it is assumed that the electron released from the cathode gets accelerated by the applied electric field , gains more energy from the field than it losses during collisions with the molecules of the liquid dielectrics and after ionising the molecules, an avalanche is launched leading to the breakdown of the dielectric.

The electronic theory satisfactorily explains the breakdown strength values but does not explain the time lags well. The observed formative time lags in liquids are much longer than the predicted time by the electronic theory of breakdown.

(b) Cavitation Breakdown of Liquid Dielectrics

Due to the liquid head over the electrode head, the bubbles are supposed to be formed in the liquid. The formation of bubble is helped by.

(a) The gas pockets on the electrode surface.

(b) Electrostatic force being greater than the force due to surface tension.

(c) Dissociation of liquid molecules in strong electric field and

(d) Corona-type discharge at the electrode surface due to surface irregularities etc.

The 'bubble' breakdown strength has been given by Kao is

$$E = \frac{1}{K_1 - K_2} \left\{ \frac{2\pi \sigma (2 K_1 + K_2)}{r} \left(\frac{\pi}{4} \sqrt{\frac{V_b}{2rE}} - 1 \right) \right\}^{1/2} \qquad (3)$$

Where

σ = Surface tension of the liquid.

K_1 and K_2 = Permittivity of the liquid and bubble respectively.

r = radius of the sphere formed by the bubble (the spherical shape is assumed to remain constant although it depends upon the pressure & temperature)

V_b = Voltage deop in the bubble.

The cavitation breakdown of liquid dielectrics primarily depends on the lower permittivity of the bubble compared with that of the liquid dielectric. When two dielectrics electrically in series have to with-stand the externally applied voltage, the failure of the overall system would be decided by the failure of the dielectric with lower permittivity alone. The formation of bubble is inevitable as long as these exists the large energy input into the liquid in the form of high electric field.

(c) Suspended Particle Theory of Breakdown of Liquid Dielectric:

The principal cause of conductivity increase of liquid dielectrics are contamination and chemical and electro-chemical reactions with the environment. Transformer oils are transferred through hoses . The best hoses have contamination effect. The oxidation of the liquid dielectrics also brings in foreign particles in the dielectrics.

Suspended particles may be treated to be equivalent to tiny sphere of higher permittivity than that of the liquid dielectric. These tiny spheres experience a force under the action of the applied field and they start accumulating between the electrodes. Ultimately the gap is bridged and the breakdown results. The breakdown time lag is a function of the concentration of particles and the liquid viscosity. The breakdown for short stress time is given by

$$t_b \, g^4 \, r^7 (E_b^2 - E_0^2) \, N = \eta^2 \times \text{constant} \qquad (4)$$

Where E_b = Short time breakdown strength

E_0 = Long time breakdown strength

t_b = Time required for breakdown

g = Enhancement or multiplication factor of the applied field (for lemispherical shape, $g = 3$).

r = Radius of sphere.

η = Viscosity of the liquid dielectric.

For long-time voltage application, we have

$$(g^2 - 1) \, r^3 \, E_0^2 = 2 \, KT \qquad (5)$$

Where K = Boltzman's constant

T = Absolute temperature.

for $g = 3$ or $g^2 = 9$, we have

$$E_0^2 = \left(\frac{2KT}{8r3}\right) = \frac{1}{4} \; \frac{KT}{r^3}$$

$$\therefore \; E_0 \propto r^{-3/2} \qquad (6)$$

i.e. the long time breakdown strength is proportional to $r^{-3/2}$ besides it also depends upon the temperature (7).

2.6.3. Theory of breakdown phenomenon of solid dielectrics:

The processes responsible for the breakdown of gaseous dielectrics are governed by the rapid growth of current due to the emission of electrons from the cathode, ionisation of the gas molecules and rapid advance of the electron avalanches. In solid dielectrics, the situation is quite different. The growth of current is a prolonged affair from the instant of the application of the voltage. The product of the breakdown voltage and the log of time of application of the voltage is almost constant i.e.,

$$V_b \times \log t \simeq \text{constant} \qquad (7)$$

The relationship is shown in fig. 2.6.3a.

In above fig. A denotes the region of intrinsic or electromechanical breakdown, B denotes the region of streamer breakdown, C is the region of thermal breakdown and D is the region of erosion or electrochemical tracking breakdown.

(a) Intrinsic Breakdown of Solid Dielectric:

Neglecting the effect of external influences, an insulator would breakdown for a large voltage applied across a thin specimen for a very short time. The dielectric strength would be exceptionally very large. The conditions existing are assumed to be ideal conditions of testing. The dielectric strength is known as the instrinsic dielectric strength of the dielectric when the electrons gain sufficient energy from the applied field so as to jump from the volency to the conduction band across the forbidden energy gap, the gain of energy by the electron from the field would be a loss of energy from the electron to the lattice. The conduction of electrons is responsible for the intrinsic breakdown of the solid dielectrics.

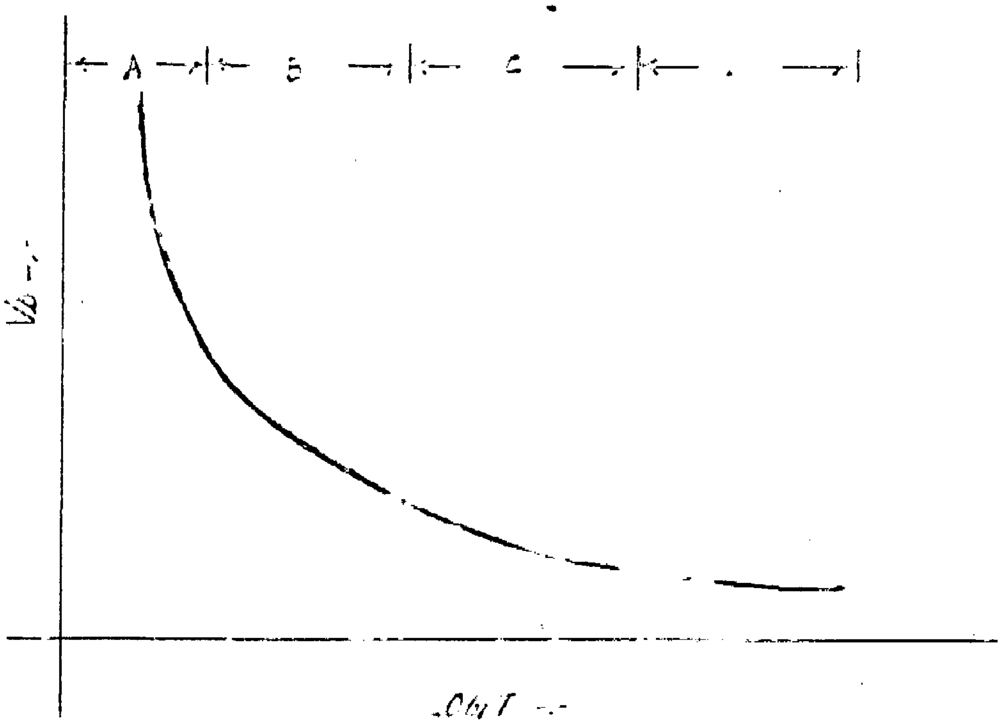


FIG. 10.2.6-A

(b) Electromechanical Breakdown of the Solid Dielectric:

When a (solid) dielectric is placed in an electric field with constant potential gradient, the atoms of the dielectrics are polarised or stretched by the action of the electric field. Since each atom is composed of positive and negative charges, a cloud of uniformly distributed negative charge would be assumed to be existing slightly shifted with respect to an equal and uniformly distributed cloud of positive charges. The negative charges by the mutual repulsion of the many particles set up an outward pressure in all directions. It tends to swell the small volume into the surrounding territory acting normally upon any boundary. The positive charges act likewise (this is very similar to be the Pascal's pressure at a point inside a liquid). This pressure is given by.

$$p_r = \frac{(K - K_0)}{2} E^2 \quad Nw / m^2 \qquad (8)$$

where K = Permittivity of the dielectric.

K_0 = Permittivity of the free space.

E = Magnitude of the electric field vector.

When an electrode is brought into contact with the solid dielectric, the pressure at the boundary would be of compressive nature and given by

$$p_c = \frac{D^2}{2K} = \frac{KE^2}{2} \quad Nw / m^2 \qquad (9)$$

Thus when this electrostatic compressive stress exceeds the mechanical stress, the failure of the solid dielectric would take place i.e. for equilibrium or threshold condition,

$$\frac{KE^2}{2} = Eym \quad \log\left(\frac{d_0}{d}\right) \tag{10}$$

where Eym = Young's Modulous of the dielectric material

d_0 = Initial thickness of the dielectric

d = Final thickness of the dielectric.

$$\therefore \frac{K_0 K_r}{2}\left(\frac{V}{d}\right)^2 = Eym \log\left(\frac{d_0}{d}\right)$$

$$V^2 = \frac{2Eym}{K_0 K_r} d^2 \log\left(\frac{d_0}{d}\right) \tag{11}$$

$$V = \sqrt{\left[\frac{2Eym}{K_0 K_r} \log \frac{d_0}{d_r}\right]} \; d \quad \text{Volts}$$

But $\frac{V}{d}$ = Breakdown potential gradient = E_b

$$\therefore E_b = \sqrt{\frac{2Eym}{K_0 K_r} \log \frac{d_0}{d}} \tag{12}$$

Differentiating equation 11 w.r. to d , we get

$$2V \frac{dV}{dd} = \frac{2\ Eym}{K_0\ K_r}\left[2d \log\left(\frac{d_0}{d}\right) - d^2\left(\frac{d}{d_0}\right)\left(\frac{d_0}{d^2}\right)\right] = 0$$

$$\therefore 2d \log\left(\frac{d_0}{d}\right) = d$$

$$\log \frac{d_0}{d} = \frac{1}{2}$$

$$\frac{d_0}{d} = e^{1/2}$$

or

$$d = e^{-1/2} d_0 = 0.6\ d_0 \tag{13}$$

For any real value of V, the reduction in thickness should not be more than 40 percent of the original thickness. For any increase of voltage corresponding to this ratio ($\frac{d}{d_0} = 0.6$), the thickness becomes unstable and the specimen breakdown.

The maximum value of dielectric strength would be obtained from equation 11

$$V = \sqrt{\frac{Eym}{K_0 K_r}} \sqrt{2 \log \left(\frac{d_0}{d}\right)} \; (0.6\, d_0)$$

$$\therefore E_b, \max = \frac{V}{d_0} = 0.6 \sqrt{\frac{Eym}{K_0 K_r}} \sqrt{2 \times 1/2}$$

$$= 0.6 \sqrt{\frac{Eym}{K_0 K_r}} \qquad (14)$$

The possibility of instability occuring for lower average field is ignored. In other words, the effect of stress concentration at irregularities, the effect of time and stress on young's modulus and also the plastic flow of the dielectric are not taken into account.

(c) <u>Streamer Breakdown of the Solid Dielectric:</u>

When a pointed electrode is placed on the surface of the solid dielectric, the electron from the cathode would drift towards the anode under the action of the applied field. This electrode would, in all probability, not be ideally embedded in the dielectric. Therefore, there would be two paths:

(a) Through the dielectric directly and (b) the ambient medium. The permittivities of the dielectric would be greater than that of the gaseous ambient medium. The breakdown of the ambient would, therefore, take place first leading to the ultimate breakdown of the dielectric. The ultimate breakdown is preceded by the local breakdowns at the teps of the electrode. The breakdown does not take place through the formation of a single discharge channel but assumes a tree like structure of fig. 2.6.3C

Because of the appearance of the discharge path very similar to that of a streamer breakdown of gaseous dielectrics, this is known as the streamer breakdown of solid dielectrics. The time required for breakdown is would be different and may vary from a few secs to a few minutes.

(d) Thermal Breakdown of Solid Dielectric:

Under the action of an electric field, the conduction current through a dielectric starts flowing. This current at room temperature is small but with the gradual flow of current, the dielectric gets heated and the conduction current further increases. This process, if not porperly checked by timely removal or dissipation of heat from the dielectric would be cumulative in nature and ultimately result in the thermal breakdown of the solid dielectric. The heat input (σE^2) must be equal to the heat dissipation {div(K grad T)} and the heat required for raising the temperature of the solid dielectric ($cv \frac{dT}{dt}$). Thus

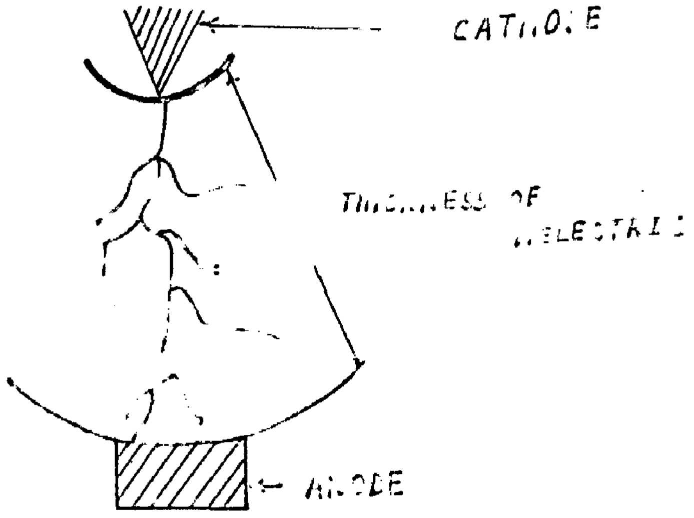


FIG. NO. 2.6.3C.

$$\sigma E^2 = \text{div}\,(K\ \text{grad}\ T) + C_v \frac{dT}{dt}$$

$$\sigma E^2 = \nabla\,(K \nabla T) + C_v \frac{dT}{dt}$$

For constant K = Thermal conductivity, we get

$$\sigma E^2 = K \nabla^2 T + C_v \frac{dT}{dt}$$

or

$$\nabla^2 T + \frac{C_v}{K} \frac{dT}{dt} = \left(\frac{\sigma}{K}\right) E^2 \tag{15}$$

where C_v = Specific heat per unit volume

K = Thermal conductivity of the dielectric

σ = Electrical conductivity of the dielectric

E = Magnitude of the electric field vector

T = Temperature of the volume.

With alternating voltage, the losses in the dielectric exceed much more than with unidirectional voltages due to loss in relaxation phenomenon of dipoles. The dielectric strength for alternating voltages is therefore lower than that for direct or unidirectional over voltages.

With comparatively thicker dielectrics with large electrodes, heat is carried by the electrodes and $C_v \frac{dT}{dt}$ tends to be zero in comparison with $K \nabla^2 T$.

The minimum thermal breakdown voltage is given by

$$V_m{}^2 = \int_{T_0}^{T_m} \left(\frac{8K}{\sigma}\right) dT \tag{16}$$

where T_0 = Temperature at the specimen's surface

T_m = Critical temperature at which the dielectric decomposes.

From thinner dielectrics, V_m is dependent upon thickness

$$V_m \times \sqrt{d} = \text{constant} \tag{17}$$

where d = Thickness of the specimen.

The limiting value of d is the thickness of the thicker dielectrics.

When $K \nabla^2 T$ tends to be zero in comparison with $C_0 \frac{dT}{dt}$, we have

$$C_v \frac{dT}{dt} = \sigma E^2 \tag{18}$$

The magnitude of E obtained from the SOLUTION of equation 18 is the impulse thermal breakdown strength of the dielectric. The electrons and ions are responsible for the electrical condition, the conductivity increases with temperature and breakdown results when the rate of heat evolution exceeds the rate of heat dissipation.

(e) Erosion or Electrochemical Tracking in Solid Dielectric Leading to Their Breakdown :

Due to defects in the manufacturing process, some cavities or voids are entrapped in the solid dielectrics. Electrically the cavities and the solid dielectrics are in series. The cavities or voids are having lower permittivities than that of solid dielectrics because these cavities contain gaseous molecules. Electrical breakdown of the cavities leads to the local thermal instability of the insulation surrounding the cavity. This promotes conduction in the dielectric by forming the channels and pits. Additional deterioration is due to the discharge of chemically active products (e.g. oz one oxides of N_2 etc.), leading to oxidation, nitration etc. of the solid dielectrics. In severe cases this deterioration may lead to breakdown by high conduction, thermal instability or mechanical failure.

The breakdown of solid dielectric with cavilices may take place relatively at a much lower voltage across the dielectr as a whole. This is one of the common methods of breakdown of solid dielectrics. The breakdown by erosion may take place in times ranging from a few days to many years.

3. EXPERIMENTAL SET UP AND TEST PROCEDURE

3.1. Development of Control System:

3.1.1. Introduction: The statistical approach towards breakdown tests demands high degree of consistency in the test procedure. Since mannual operation of the equipment used for breakdown tests introduces human errors, automatic control of the test equipment is neccessary. The experimental set up developed here has the following features

(1) A constant rate of rise of voltage of 0.69 Kv rms/sec.

(2) A time interval of one minute between two tests.

3.1.2. Method of test:

When determining the dielectric breakdown voltage of a material any one of three different methods may be employed for applying the test voltage. These are the short-time test for quick determination, and the step by step test and the slow rate of rise test, where duration of voltage application is important. In choosing the type of test, reference should always be made to the ASTM method applicable to the material to be tested.

3.1.3. Electrical Apparatus:

(a) Transformer :- The desired test voltage may be obtained from a step up transformer energized from an adjustable low voltage source. The transformer and its controlling equipment shall be of such size and design that, with the test specimen in the circuit, the crest factor (ratio of crest to effective) of the test voltage shall not differ by more than ± 5 Percent from that of a sinusoidal wave over the upper half of the range of the test voltage. The crest factor may be checked by means of an oscillograph, an oscilloscope, sphere gap, or a peak-reading voltmeter in conjunction with an rms voltmeter.

For test specimen of small capacitance, a testing transformer as small as 500 -V-A rating or a well-designed potential transformer may be adequate. For specimens of high capacitance or leakage, a transformer of ample kilovolt ampere rating must be used. Where the wave form can not be determined, a transformer having a rating of not less than 2 KVA has been found adequate for voltage not exceeding 50 KV and one having a rating of not less than 5 KVA for voltage exceeding 50 KV.

(b) Circuit Interrupting Equipment :- The test transformer circuit shall be protected by an automatic circuit breaker device capable of opening as quickly as practical on the current produced by breakdown of the specimen. Device capable of opening the circuit in five cycle or less are available. A pro-longed flow of current at the time of breakdown is undesirable as it causes unnecessary burning of the test specimen and pitting and heating of the electrodes, thereby increasing etc. work and time of testing.

(c) Voltage Control Equipment :- Control of voltage may be obtained by the use of a motor driven, variable-ratio auto-transformer or any device which gives at least as uniform rate of rise of the voltage without distortion of the wave form beyond the limit of 3.1.3a Preference should be given to equipment having an approximately straight line voltage-time curve over the operating range motor drive with variable speed control should be preferred to mannual drive because of the difficulty of maintaining a reasonably uniform rate of voltage rise with the letter.

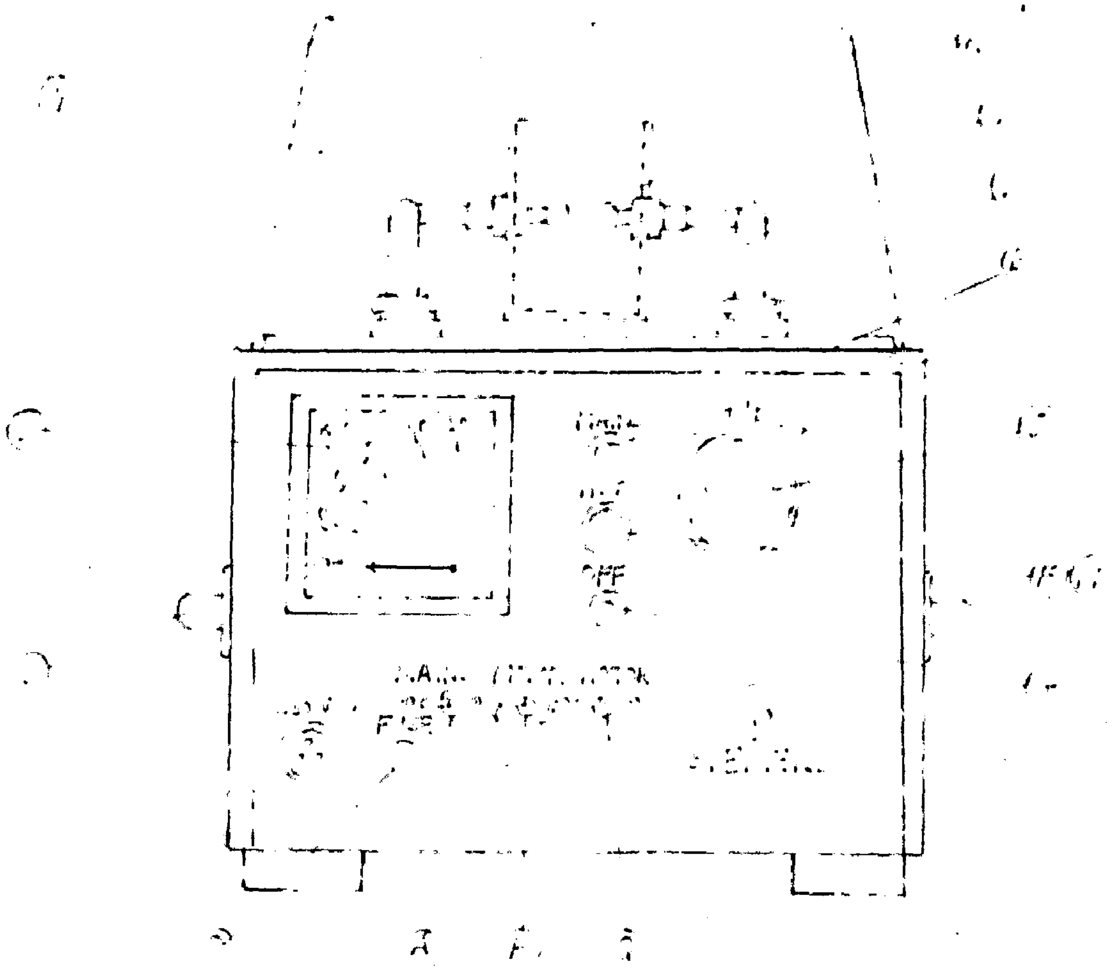
Assemblies to be done before commissioning the set:

Bakelite disc (1) to be fixed on the studs protruding from the bushings before fixing the electrodes (2). The electrodes should be al-igned such that the slots are in a straight line handle (3) to be fixed on the sides. Acrylic cover to be fixed on the hinges. Variac knob to be fixed on the shaft. This knob should not be used in the motorised units, unless the motor fails. In that case, the inner coupling should be disengaged before operating the knob. See fig. 3.1.3a

1. **Technical Data:**

Input voltage : 230 V, 50 Hz
Max generated test voltage between transformer terminals : 50 KV/60 KV rms
Capacity : 0.5 KVA (Short Time rating)
Dimension including handles, knobs, groments and acyclic cover. : Length 485 mm
Breadth 460 mm
Height 400 mm
Weight 47 Kg.

2. **Basic Design** : A low voltage 230 V, 50 c/s supply is transformed into a high voltage by a H.T. transformer, and the voltage is



A [illegible]

[illegible]

[illegible]

1·3

[illegible]

increased by a variable auto transformer which controls the primary voltage of the HT transformer. On the secondary of the H.T. transformer an oil vessel with electrodes is mounted and it contains the oil to be tested. The voltage is increased till the spark between the electrodes occurs. This flashover voltage can be read off by the voltmeter mounted on the sheet.

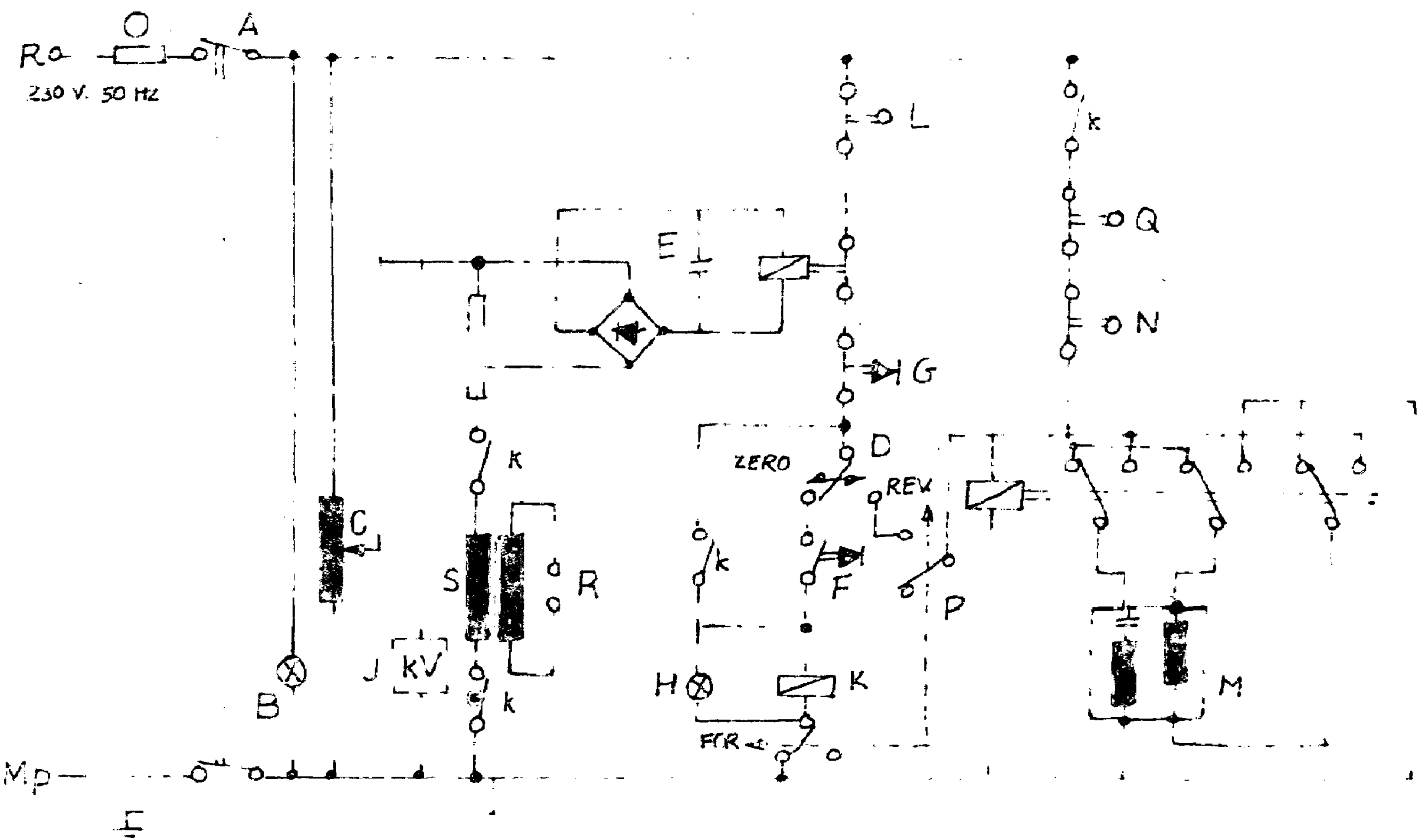
3. Design Features : For testing insulation of oils, the unit operates at variable test voltage, which is gradually increased until a flash over occurs between the electrodes of the oil pot. With this flashover the high voltage circuit is switched off automatically, but the voltmeter will indicate the voltage even after the H.T. is cut off. This enables the operator to concentrate on the oil pot without diverting his attention for observing the voltmeter.

As per ISS the electrodes are to be spaced 4 mm apart which can be done by using the gauge supplied with the equipment. The electrodes, oilpot and the gauges are supplied according to ISS.

The tripping relay is set such that it is insensitive to flashes at a value less than 8 KV. The unit has been so designed that the distortion wave form of the output voltage is extremely negligible. This is important because the breakdown occurs at the peak voltage while the measurements are taken in rms value. See fig.3.1.3.(b).

3.2. Test Cells and Electrodes:

3.2.1. Test Cell:- Two test cell ~~s~~ were used in this thesis. The main difference between the two is :-

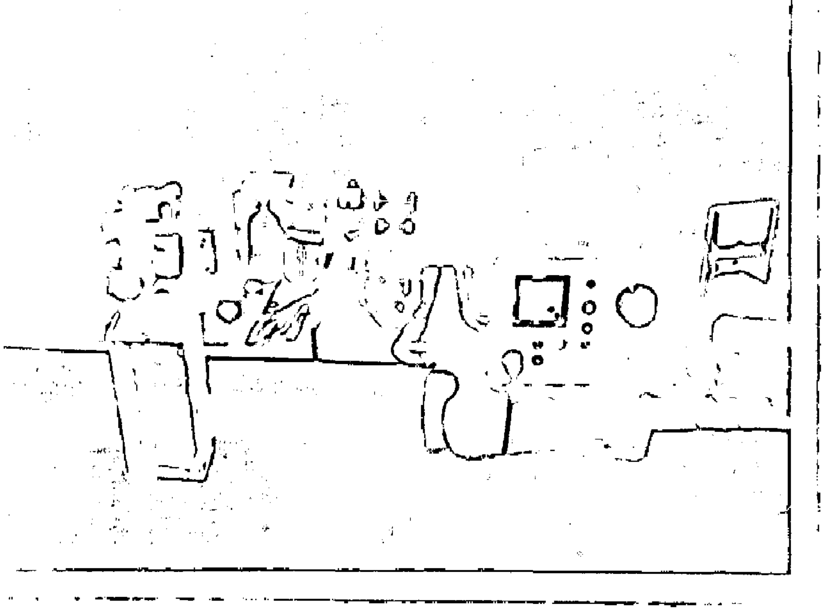


A	Main switch
B	Mains indicating lamp
C	Voltage regulator
D	Limit switch-zero end
E	Tripping relay
F	Push button ON
G	Push button OFF
H	Lamp HT
J	Voltmeter
K	Contactor
L	Cover switch
M	Motor
N	End switch - Motor
O	Fuse
P	Motor rev. switch
Q	Motor stop switch
R	Electrodes
S	H.T. Transformer

Fig. 3.1.3 (b)

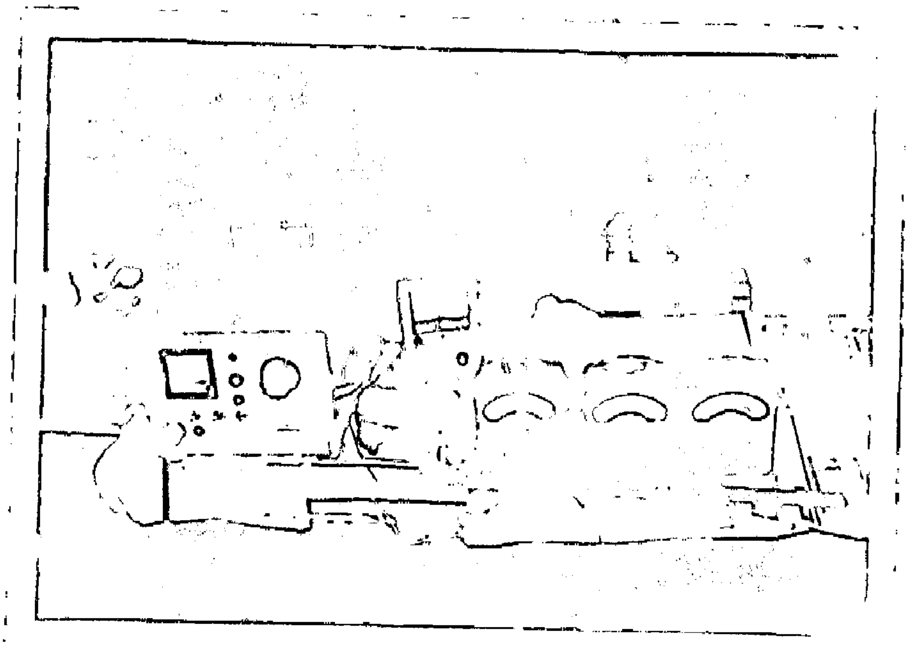
Circuit Diagram for
Oil Testing Set OTS.51/KOM

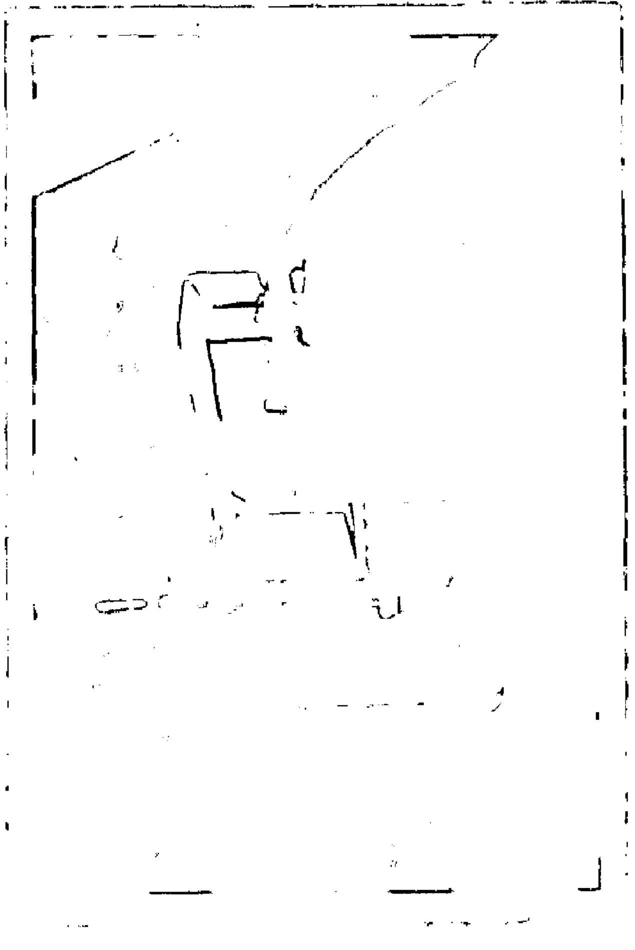
SIEMENS INDIA LIMITED



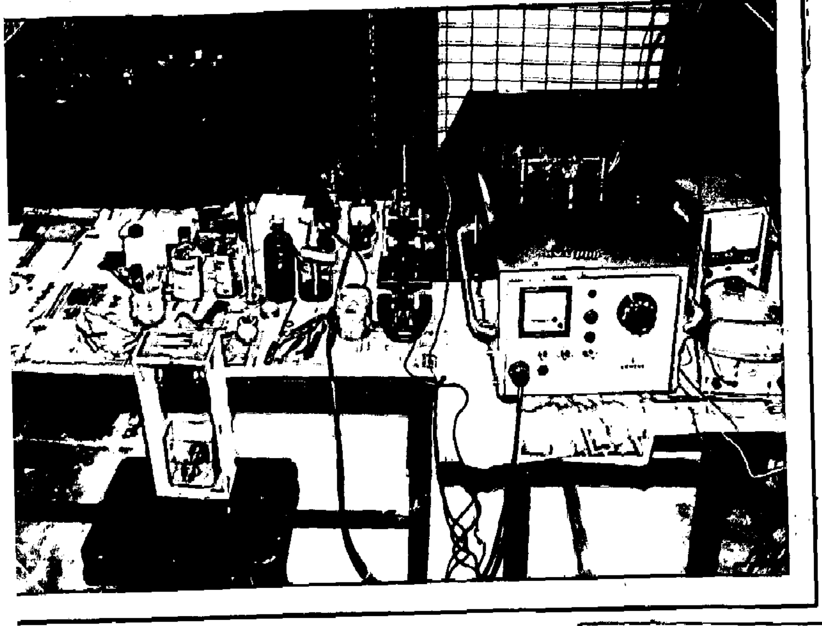
↑

PHOTOGRAPH A

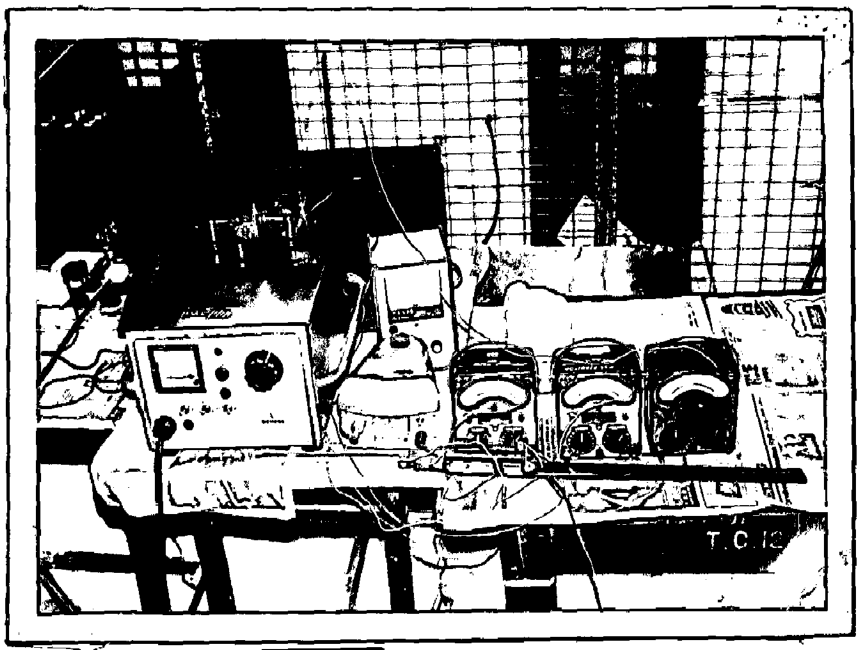


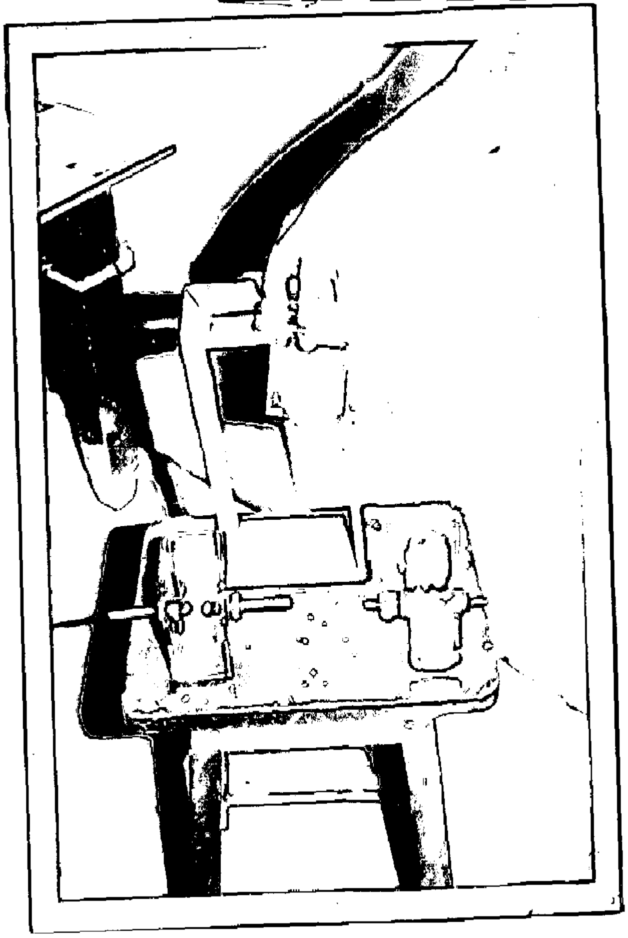


← PHOTOGRAPH B



PHOTOGRAPH A





PHOTOGRAPH B

The test cell which is with the Siemen set can be used only for oil testing. Because when we fit any sample between the electrode, we do not have proper arrangement to set it. Sometimes force applied on to the sample may be more or sometime less because it is done mannually; accordingly there will be error in our measurment. So we replaced another cell:-

This another cell is made of glass and have an such arrangement that we can easily apply approximately same force on the sample. The difference between the two cell can be seen from the photograph (b)

3.2.2. Electrodes:- The dielectric strength of an insulating material varies with the thickness of the material, the area and geometry of the test electrode, temperature, and humidity, tests were made with electrodes of brass in our experiments. The arrangement of the experimental work can be seen from the photograph (a).

3.3. Test Procedures:

The test material used for the experiments was empire cloth (impregnated); Elephantoid, Polyster film, Glass-micanite fibre, Glass fibre cloth (impregnated); Leatheroid paper and Krempel.

The test procedure as described below was the same for all the experiments reported in this thesis.

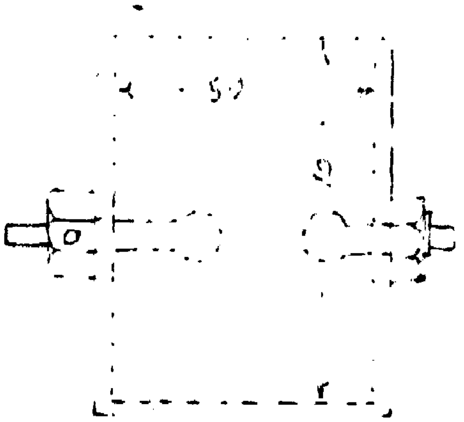
3.3.1. Treatment on the electrodes:- The electrodes were polished with Brasso readily available in the market and then rinsed twice or thrice in 10 cc carbon tetrachloride. They were then fixed in position in the test cell and rinsed with ccl_4 twice along with cell. After the cell become dry (in five minutes) it was rinsed with the test liquid.

3.3.2. Test specimen:- The specimen shall be representative of the material to be tested. Sufficient material shall be availabl to permit making satisfactory tests. In the preparation of the test specimen from solid materials care shall be taken that the surface in contact with the electrodes are parallel and as plane and smooth as the material permits. In our experiment we have used the specimen size of 5 x 5 cm, explained in (Appendix B). As seen in the experimental results it becomes necessary to design a holder in which we have to fix the material to be test. The design is given in Appendix B. The photograph (b) of this holder is given. The complete dimensions for the test cell and holder given in the fig.3.3.2.

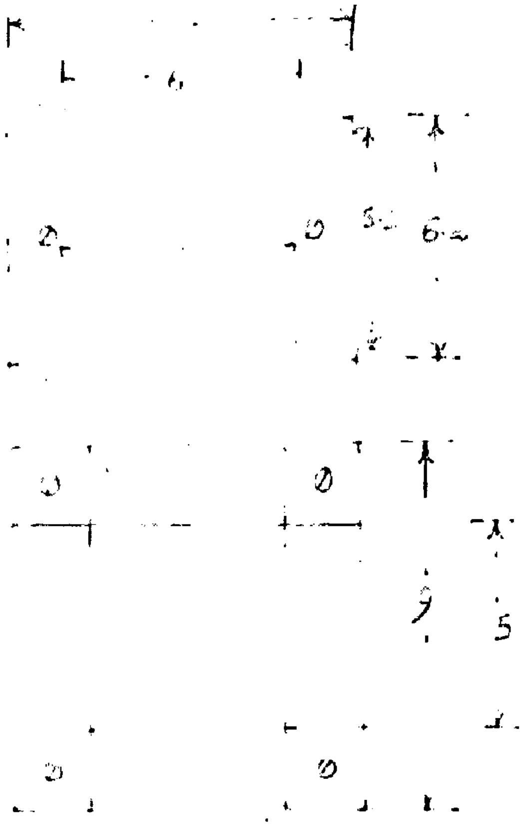
3.3.3. Thickness:- The thickness used in computing the dielectric strength shall be the thickness of the specimen measured as specified in the test method for the material involved. Measurmen of thickness is being done by micro meter. Its least count is ± .005. Measurments for the material used is given in Appendix B.

3.3.4. Method of filling the cell:- After fitting the electrode and specimen between the electrode in the cell; the cell was filled with transformer oil taken from the drum.

After removing the air bubbles from the oil by stirring continuously by means of glass road, we cover the cell by Acrylic cover.



TEST CELL



HOLDER

(ALL DIMENSIONS IN C.M.)

FIG. 5.3.2

3.3.5. Measurment of the Gap Length:- Measurment of the gap length is necessary when we are performing the experiment on transformer oil only; which is being done by gauge available with the Siemen's set.

3.3.6. Control of Pressure, Temperature and Humidity :- All the tests were done at atmospheric pressure. The range of the atmospheric pressure, at Roorkee for these days was 975 to 982. millibars

3.4 STATISTICAL TECHNIQUE USED

The inherent statistical nature of the breakdown phenomenon in liquid was discussed earlier. The results of breakdown tests must therefore be evaluated on the basis of statistics. Any set of reading can not be straight away analysed on the basis of statistics. It must satisfy two basic conditions (1) It must represent a random stationary process and (2) The number of readings must be sufficient so that the properties of the set can represent the properties of the parent population with good accuracy. To obtain such a set of reading, the experiment itself is to be designed on the basis of statistics.

The first step in designing a breakdown test to give results fit for statistical analysis is to as-certain that the set of readings represent a random stationary process. Here it must be emphasised that stationarity does not mean constancy of readings. The physical concept of a random stationary process is like this. If a sample record satisfies the tests of randomness and stationarity, it means firstly that the individual readings in that sample record are independent of each other, that is they are random and secondly, that all the reading belongs to the same parent population so that the properties of this sample record can represent the properties of parent populations. Such a sample record is said to be stationary.

A nonstationary random data can also be processed statistically but the statistical tools for its processing are complicated. In reality most of the physical phenomena, the breakdown phenomena also, represent stationary random process.

3.4.1. General Procedure:- The following four steps should be followed in conducting breakdown test on composite insulating materials.

(1) Identification of parameters and their control:- Since various parameters affect the breakdown phenomenon, a set of reading can not certainly satisfy the condition of randomness and stationarity unless these parameters are controlled fully. On the basis of previous knowledge about breakdown in these materials, a comprehensive list of all the parameter that can be significant in breakdown tests of oils should be made. As far as possible, all the parameters should be controlled. But some parameters, if their effect is considered negligible or random, can be left uncontrolled subject to experimental verification later.

(2) Randomness and stationarity:- From the results of the exploratory experiments, it should be as-certained whether the set obtained is random stationary. If the set is non-

random or non stationary, the most probable source could be the uncontrolled parameters. A search for the source could then be made, by repeating the exploratory experiments with these parameters controlled one by one till a random stationary set is obtained. If a random stationary set can not be obtained with all the known parameters fully controlled, a search has to be made for the unknown parameter (Main experiment).

(3) Sufficient number of reading :- The properties of the sample record can represent those of the parent population only when the number of readings in the sample record is sufficiently large. To decide upon the "sufficiently large" number of readings. The distribution of the sample record has to be ascertained first. For normal distribution the sufficient number of readings can be fixed easily. For other distributions, the procedure has to be decided separately for each specific case.

(4) The main experiment :- In main experimental work we selected three materials which should be used in combination with the transformer oil. Now test results are taken [illegible] when we fix the insulating material in holder which give the very good observations.

Secondly the materials are also tested for the different time of intervals which give little more detailed result on the effect of oil absorption by the materials on the breakdown voltage.

3.4.2. Statistical tests:

In Section 3.4.1, the general procedure that should be followed while conducting breakdown tests was discussed. Here, the actual statistical tests for determining various statistical properties are given.

1. Run Test:[16]

The run test is used to determine whether the readings are independent observations of the same random variable. Since in the beginning, the distribution of a sample record is not known, a distribution free procedure is to be used for determining the randomness of observations. The run test is one of the distribution-free tests.

Consider a sequence of N observations of a random variable x(k) where each observation is classified as one or two mutually exclusive categories, which may be identified simply by (+) or by (-). The sequence of (+) or (-) observations might be as follows in a set of 20 readings:

++ - +--- +++ - + --- ++++ -

1 2 3 4 5 6 7 8 9 10

In the above example, there are 10 runs. A run is defined as a sequence of identical observations that are followed or preceded by a different observation or no observation at all.

The number of runs that occur in a sequence of observations gives an indication whether the results are independent observations of the same random variable, i.e., the probability of a (+) or (-) result does not change from one observation to the next. The sampling distribution of the number of runs in the sequence is a random variable r(k) with a mean value and a variance as follows:

$$\text{The mean value } \mu_r = \frac{2N_1N_2}{N} + 1$$

$$\text{The variance } \sigma_r^2 = \frac{2N_1N_2(2N_1N_2 - N)}{N^2(N - 1)}$$

where N_1 is the number of (+) observations
and N_2 is the number of (-) observations.

If $N_1 = N_2 = N/2$, then,

$$\mu_r = (N/2) + 1$$

$$\sigma_r^2 = N(N - 2)/4(N - 1)$$

The hypothesis that the individual observations are independent observations of the same random variable can be tested at any desired level of significance and by comparing the observed runs r with the interval between $r_{n,1-\alpha/2}$ and $r_{n,\alpha/2}$ (given in reference 16). If the observed runs fall outside the interval, the hypothesis should be rejected at the α level of significanc Otherwise, the hypothesis should be accepted.

Most of the times a visual observation of the sample record indicates whether the set of observations are randomly distributed.

A sample calculation of the run test is given in Chapter 5.

2. Test for Stationarity:[16]

The test for stationarity is as follows:

(i) Divide the sample record in N equal intervals where the data in each time interval can be considered independent of one another.

(ii) Compute the mean value and the mean square, and align these sample values in time sequence as follows:

$$\bar{x}_1, \bar{x}_2 \text{------} \bar{x}_N$$
$$x_1^2, x_2^2 \text{------} x_N^2 .$$

(iii) Test the sequence of mean and square values for the presence of underlying trends or variations other than those due to expected sampling variations, by the run test.

The above test for stationarity is made on the following assumptions:

(a) If the data is stationary, then the statistical properties computed for each of the sequence of short intervals do not vary significantly from one time interval to the next. Here ‘‘significantly’’ means that the variations are greater than would be expected due to statistical sampling variations. If this assumption is accepted, then the proof of self stationarity for individual sample record can be accepted as the proof of stationarity for the random process from which the sample is drawn.

(b) The verification of weak stationarity can be accepted as the verification of stationarity. If this assumption is accepted then the verification of stationarity can be restricted only to the investigation of mean and mean square values of the data. This assumption can be accepted for two reasons (i) the most important data analysis procedures require only weak stationarity to be valid for analysing power spectra and autocorrelation function; (ii) most of the random data representing physical phenomenon will be strongly stationary if the data are weakly stationary. Also note that Gaussian process which is weakly stationary, becomes automatically strongly stationary, since all other higher moments are determined by the mean and the autocorrelation function.

(c) That, if the mean square value (or variance) of the data is stationary, the autocorrelation function is also stationary. It is because the variance equals autocorrelation function at time displacement $\tau = 0$. This assumption is valid because it is highly unlikely for a non-stationary data to have a time varying autocorrelation function without the value at $\tau = 0$ varying.

(d) That the sample length is very long as compared to the random fluctuation of the data time history. This correlation is necessary so that the short time averages will truely reflect average properties of the data and not just the random fluctuations of the time history.

It is necessary to note that the test for stationarity i based on the concept of randomness. In subjecting the sequence of mean values and of mean square values to the run test, we are accepting or rejecting the hypothesis that the sequence of mean values and of mean square values are each independent sample values of a random variable with a true mean μ_x and mean square value ψ_x^2. In fact the test for randomness itself constitutes the test for stationarity where the time history record is divide into equal time intervals, each interval containing one observation. This test is more powerful than the run test on mean values or mean square values since it is performed on more number of terms. A time history record that passes the test of randomness will pass the test of stationarity. Table 5.1.2 gives the results of run test performed on the means of subgroups of 5 readings of random sets.

If the terms $\bar{x}_1, \bar{x}_2 --- \bar{x}_N$ and $\bar{x}_1^2, \bar{x}_2^2 --- \bar{x}_N^2$ belong to the same time intervals, the outcome of run test either on $\bar{x}_1, \bar{x}_2 --- \bar{x}_N$ or on $\bar{x}_1^2, \bar{x}_2^2 --- \bar{x}_N^2$ will be the same. Therefore it suffices to test the sequence of means only for randomness.

3. Chi-Squared Goodness-of-Fit Test:

This test is used to compare the observed probability density function with a given probability density function (e.g., theoretical normal or exponential).

Consider a sample of N independent observations of a random variable x(k) with a probability density function p(x). Let the observations be grouped in k intervals, called class intervals which together form a frequency histogram. The number of observations falling within its class interval is called the observed frequency in the ith class and will be denoted by f_i. The number of observations which would be expected to fall within the ith class interval, if x(k) has a theoretical probability density function $p_0(x)$ is called the expected frequency in the ith class interval and will be denoted by F_i. Now, the discrepancy between the observed frequency and the expected theoretical frequency within each class interval is $(f_i - F_i)$. The square of the discrepancies in each interval are summed to obtain the sample statistic

$$x^2 = \sum_{i=1}^{k} \frac{(f_i - F_i)^2}{F_i}$$

The x^2 distribution has k-1 degrees of freedom.

Now a hypothesis test may be performed as follows. Let it be hypothesised that the variable x(k) has a probability density $p(x) = p_0(x)$. After grouping the sample observations into k class intervals and computing the expected frequency for each class interval assuming $p(x) = p_0(x)$, compute x^2. Since any deviation of p(x) from $p_0(x)$ will cause x^2 to increase, a one sided (upper tail) test is used. The region of acceptance is,

$x^2 \leqslant x^2_{n,\alpha}$ where $x_{n,\alpha}$ is a value given in the table ''Percentage points of x^2 distribution'' in reference 16.

If the sample value of x^2 is greater than $x^2_{n,\alpha}$, then the hypothesis that $p(x) = p_0(x)$ is rejected at α level of significance.

If $x^2 \leq x^2_{n,\alpha}$, then the hypothesis is accepted.

The x^2 test is used to find out whether:

(a) The normal probability function fits the observatio

(b) The exponential function of the type $\phi = \exp(\alpha E - \beta)$ fits the observations.

A sample calculation is given in Chapter 5.

4. To Fit an Exponential Distribution Function:

The exponential distribution function is fitted to the observations by the following method. Then the observations are compared to this fitted function by the x^2 test to find out how good the fit is.

Basic assumption:[6]

The distribution function ϕ depends on the increment in stress dE. The probability dp that the breakdown will occur during the increment in stress dE is given by,

$$dp = \phi \, dE$$

The probability function P(E) is given by the following equation:

$$P(E) = \phi \exp [- \int_0^E \phi \, dE]$$

$$\therefore \frac{P}{\phi} = \exp [- \int_0^E \phi \, dE]$$

$$\therefore \frac{d(P/\phi)}{dE} = \exp [- \int_0^E \phi \, dE] \, . \, \frac{d[- \int_0^E \phi \, dE]}{dE}$$

$$= \exp [- \int_0^E \phi \, dE] . [- \phi]$$

$$= - P$$

$$\therefore \quad \frac{P}{\phi} = -\int_0^E P\,dE + C \qquad \text{for normalised distribution} \quad C = 1$$

$$\therefore \quad \frac{P}{\phi} = 1 - \int_0^E P\,dE, \qquad \int_0^E P\,dE = R \text{ --- Cum. dist. function.}$$

$$\therefore \quad \frac{P}{\phi} = 1 - R$$

$$\therefore \quad \phi = \frac{P}{1 - R}$$

To fit a distribution function ϕ to the observed data of P and E, ϕ is calculated by the equation $\phi = P/(1-R)$ for each E. log ϕ is then plotted against E on a linear graph paper and a straight line is fitted by the method of least squares.

The cumulative distribution function R is calculated back from the values of ϕ obtained from this straight line at E by the equation,

$$R_k = \frac{\phi + R_{k-1}}{\phi + 1}$$

A sample calculation is given in Chapter 5.

5. <u>To Fit an Extreme Value Distribution Function:</u>

The extreme value distribution function[6] is represente by the following equations:

$$\bar{\Phi}(E) = \exp(-e^{-y})$$

$$\phi(E) = \exp(-y - e^{-y})$$

where $\Phi(E)$ = cumulative probability function

$\phi(E)$ = probability density function

and y = $\alpha(E - E_m)$ is the reduced largest variate where α and E_m are the parameters of the extremal distribution.

E_m is the modal (most probable) largest breakdown strength in a sample of size N and $1/\alpha$ is a measure of dispersion and is asymptotically the rate of increase of most probable largest value with natural logarithm of the number of samples N.

The value of y corresponding to the probability of E can be obtained from ‘‘probability tables for the analysis of extreme-value data’’[23]. E Vs y when plotted on a linear graph paper would give a straight line if the observations are followin extreme value distribution function. The points are plotted by taking for ordinates the observed E_n and for abscissa the values of y corresponding to probabilities $x_n = n/(N+1)$ $(n = 1,2,\text{----}N)$ The lowest strength is plotted at y corresponding to $N/(N+1)$. Since smallest values are dealt with, Φ is replaced by $(1 - \Phi)$ and y by $(-y)$ in the use of the tables.

A sample calculation is given in Chapter 5.

4. EXPERIMENTAL DETAILS

4.1. Identification of Parameters Significant in the Breakdown Test on Solid Insulating Materials and Transformer Oil:

Of all the parameters that could be significant in the breakdown tests on insulating material and transformer oil (table 4.1.1), only some are normally controlled or specified, whereas others are not.

In the present work, not only the exploratory experiment but the main experiment follow the table 4.1.1. All the experiment were performed in atmospheric conditions. We tried to take precaution as much as we can.

4.2. Measurment of the Properties of Transformer Oil Used:

These properties can be had from the manufacturer also. But the oil which we have used is taken from the Elect. Maintenance Section, University of Roorkee; so it is not necessary that the properties of the oil will be same as it comes directly from the manufacturer. So it becomes necessary to take some measurments which are possible here. Table 4.2.1 gives the properties of transformer oil used.

4.3. Measurment of Properties of Solid Insulating Material:

As seen the solid insulating material are not properly handled by the suppliers. . There may be scratches on the sheets; problem generally come when we handle micanite type of sheet. So it becomes necessary to take some measurments for these solid insulating materials for their properties. Only three measurements were possible. The results are given in table 4.3.1. There are so many other tests which are not possible due to shortage of time.

4.4. Exploratory Experiment:

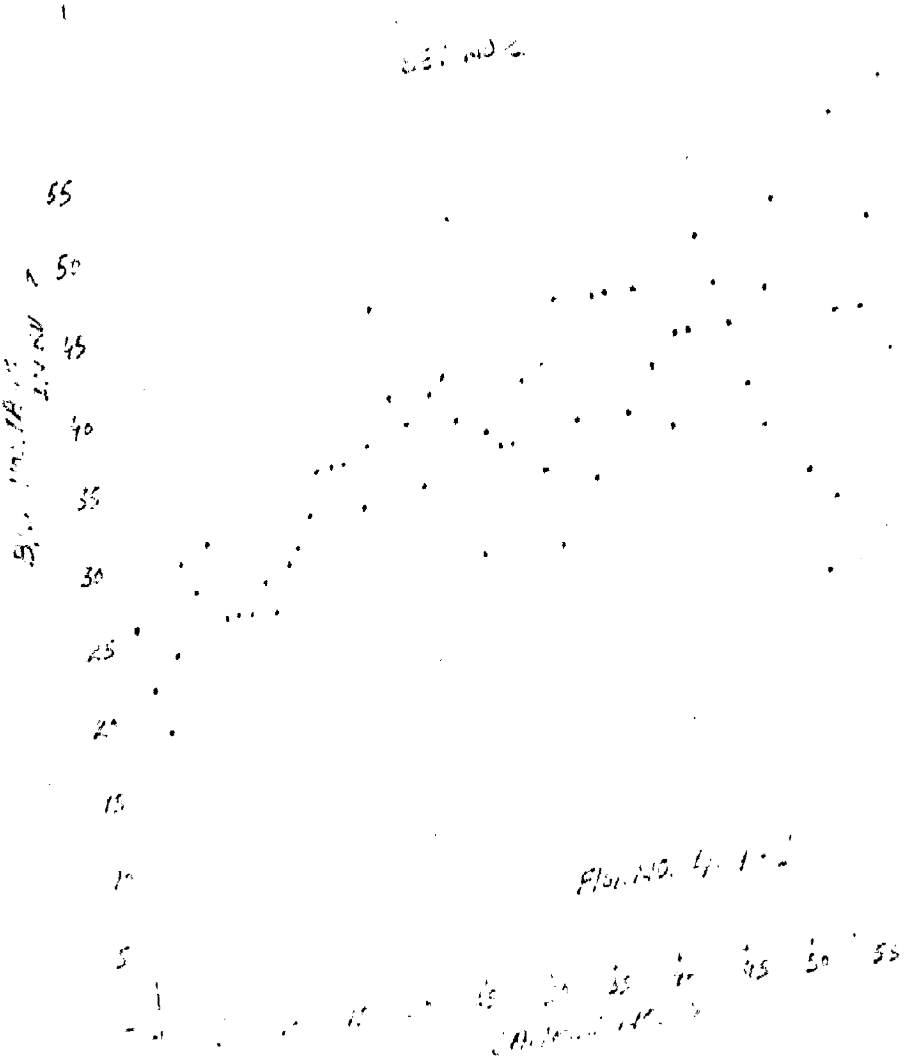
The aim of the exploratory experiments was to find out which materials we should select for the main experiments. How much reading we should take for the proper statistical analysis. In transformer oil it becomes necessary to take the sufficient reading for statistical analysis. Let us discuss some points in this aspect.

4.4.1. Randomness and stationarity:

None of the sets (1-3) represents a random stationary process. The analysis for the tests of randomness and stationarity for set 1 is given in section 5. Fig.4.4.1 and Fig.4.4.2 shows the increasing trend of breakdown voltages which is responsible for non randomness and non stationarity. This is conditioning process which is not over even in 100 readings. The conditioning process must be over after some finite number of readings after which the breakdown process can be expected to become random stationary. To find out after how many readings the conditions would be over, Set 4 and 5 consisting of 210 reading at gap length 1.06 mm was taken. Fig.4.4.3 shows that the conditioning (A) is over after 40 readings. Therefore to get a random stationary set, first 40 readings have to be discarded, which is impractical.

4.4.2. Sufficient number of readings:

The number of readings should be large enough so that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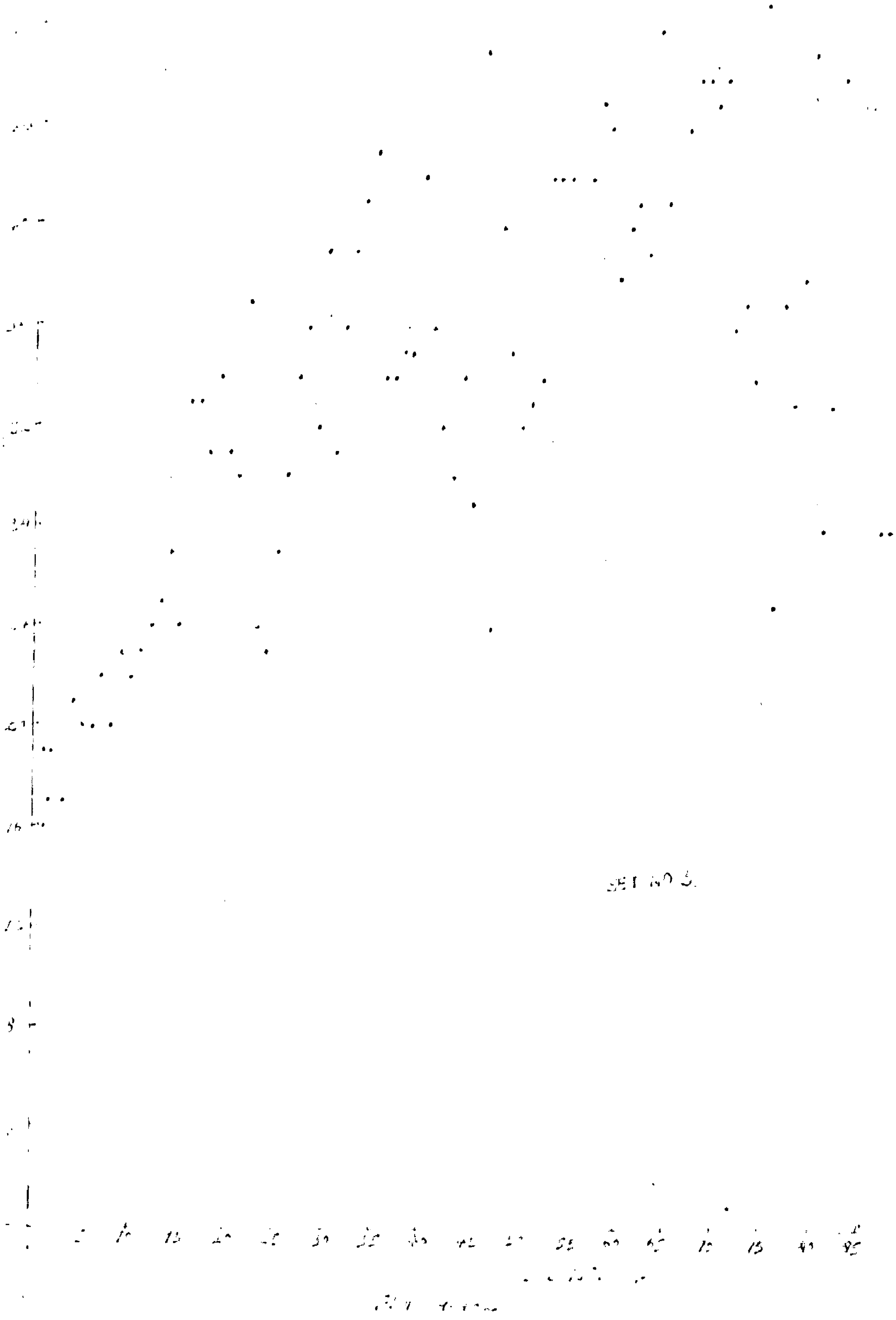
SET NO 5.
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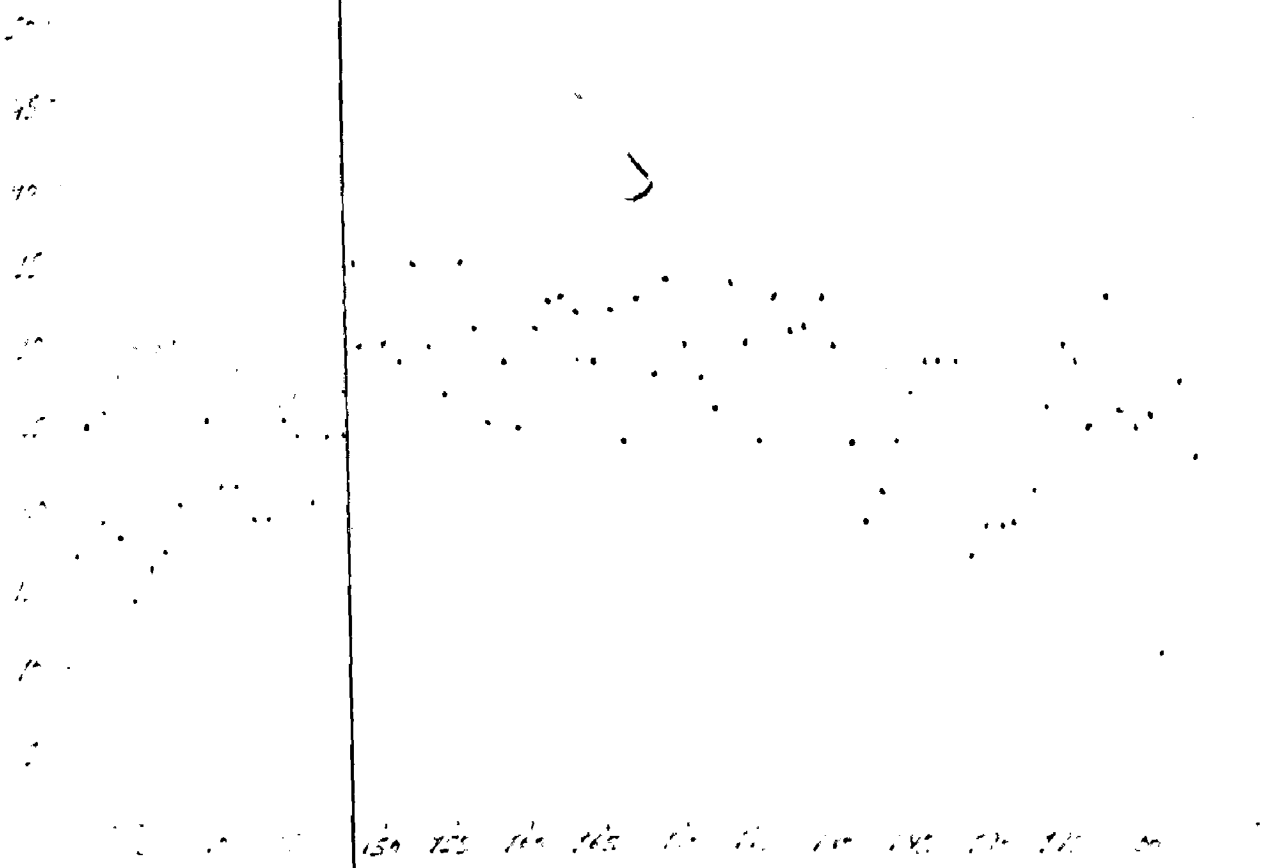
75
80
85

Table 4.1.1 : Parameters significant in the breakdown tests.

S.NO.	Parameter	Controlled/ uncontrolled	Choice in the present work	x Remarks
1.	Volume of the liquid	Controlled	300/350 ml.	b
2.	Electrode spacing	Controlled	1.06 mm to 4.0 mm	a
3.	Electrode shape	Controlled	Sphere-sphere	b
4.	Electrode material	Controlled	Brass	b
5.	Test material and oil	Controlled	Empire cloth, Krempol, elephentoid and transformer oil.	b
6.	Procedure of filling the cell	Controlled	Rinsing with ccl_4 and transformer oil.	b
7.	Electrode treatment	Controlled	Manual polishing with Brasso.	b
8.	Temperature	Controlled	31 °C to 32 °C	b
9.	Pressure	Controlled	Atmospheric	b
10.	Relative humidity	Controlled	13 to 76 Percent	b
11.	Voltage	Controlled	50 c/s sinusoidal	b
12.	Rate of rise of voltage.	Controlled	·69 KV/Sec.	b
13.	Interval between two breakdowns.	Controlled	1 min. to 30 min.	a
14.	Voltage Polarity	Not controlled		c
15.	Fluctuation of the supply voltage.	"		c
16.	Distortion of the voltage wave shape.	"		c
17.	Corona formation prior to breakdown.	"		c
18.	Influence of the surrounding object.	"		c
19.	Purity of the medium.	"		c

x (a) Effect investigated.
(b) Kept fixed due to considerations of equipment limitations.
(c) Effect not investigated but assumed negligible.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165

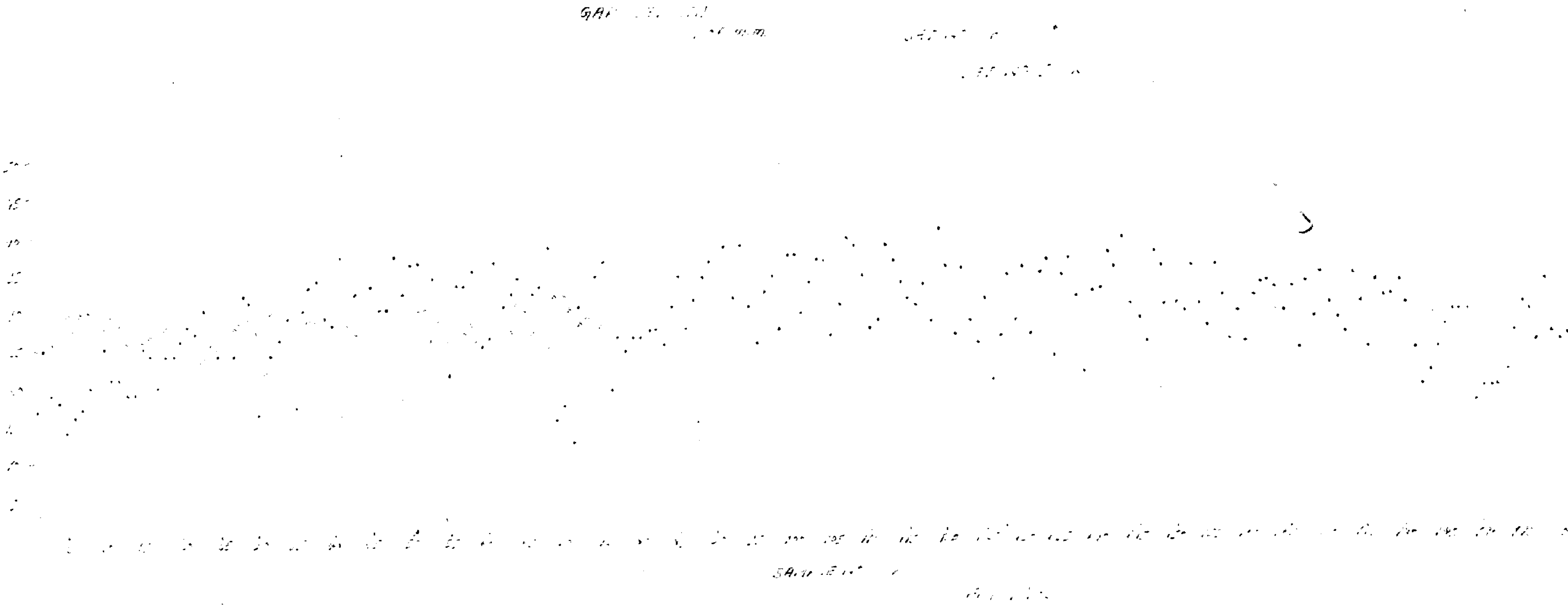


Table 4.2.1 : Properties of transformer oil used.

S.NO.	Property	Value	Method of Measurment
1.	Kinetic Viscosity CS	22.5 at 31 °C	D 445 - 74 [9]
2.	Refrative Index	1.4805 at 25°C	D 1218 - 61 (1973)[9]
3.	Density gm./CC.	0.873 gm/CC.	D 1298 - 67 (1972)[9]
4.	Specific gravity	0.8791	-do-

Table 4.3.1 : Properties of solid insulating materials.

S.NO.	Name of the Material	Property	Value	Method of Measurment
1.	Empire cloth	a. Thickness	.2178 mm	D 374-74[9]
		b. Substance	0.0233 gm/cm^2	
		c. Tensile strength	3.5 kg/cm	D 651-75[9]
		d. Oil absorption	0.1235 gm. (in 20 hours)	
2.	Krempel	a. Thickness	.2707 mm	
		b. Substance	0.0352 gm/cm	
		c. Tensile strength	23 Kg.	
		d. Oil absorption	.2092 gm. (in 20 hours)	
3.	Elephantoid	a. Thickness	1.2407 mm	
		b. Substance	0.1889 gm/cm^2	
		c. Tensile strength	56 Kg.	
		d. Oil absorption	.3022 gm. (in 20 hours)	

a sample record may represent the parent population with good accuracy. Before determining the sufficiency of number of readings, the distribution of the sample record must be ascertained.

The distribution of random stationary set 24 comes out to be normal (table 5.2.2) as shown by X^2 goodness-of-fit test for normality for a level of significance = 0.05. Neyneth and Csaki, 1963[6], has given a table giving the maximum value of percent coefficient of variation r_{max} for n number of readings being sufficient to represent the parent population. Their analysis is based on initial normal distribution. Table 5.5.1 gives the calculated values of percent coefficient of variation for different values of n for set 5,28,29 and 24. These values are much less than r_{max}. Therefore readings taken are sufficien to represent the population.

4.4.3. Measurment of breakdown voltage of insulating material in Air :

We were having ten different solid insulating materials. We screened the material taking in the view of breakdown voltage i.e. those material having breakdown voltage less than 5 KV, the were screened out. Now on remaining materials we have some breakdown measurments. The breakdown values are shown on the simple graph paper which can be seen in section 6. Fig6.2a to f

4.4.4. Measurment of breakdown voltage of selected insulating material in transformer oil :

In experimal sets 6,7,8,9,10,11,12,13,14 and 15 we selected only six materials which is having breakdown voltage above 5 KV. Now we saw the breakdown behaviour of these six materials (Empire cloth, polyster film, Krempel, Glasso micanite fibre, Elephantoid etc.) in transformer oil, and found that some material have more breakdown voltage when we immer-esed them in transformer oil. Difference between these subsection results can be seen from the graph attached in section 6. Fig 6.2a to f

4.5 Main Experiment:

The main experiment follow the aim of the author's line of attack. After having completed the design of the experiments to yield data fit for statistical analysis, we consider two points here. We have decided that only three insulating material out of all the material which we have used in the experiments, should be used in combination with the transformer oil. For this purpose we have taken some measurments for different time intervals because if we use these material in transformer than these will be immersed in oil for all 24 hours. So we want some conclusion on this basis also.

Second point which we think for main experiment the material which are not rigid, bend towards any one of the electrod which can give wrong information. For this we designed a fixer and have taken measurments fixing the material in this holder and we really got some better information by this arrangement.

The analysis of the results and the discussion follow in the subsequent sections.

5. ANALYSIS OF RESULTS

5.1 Tests for Randomness and Stationarity:

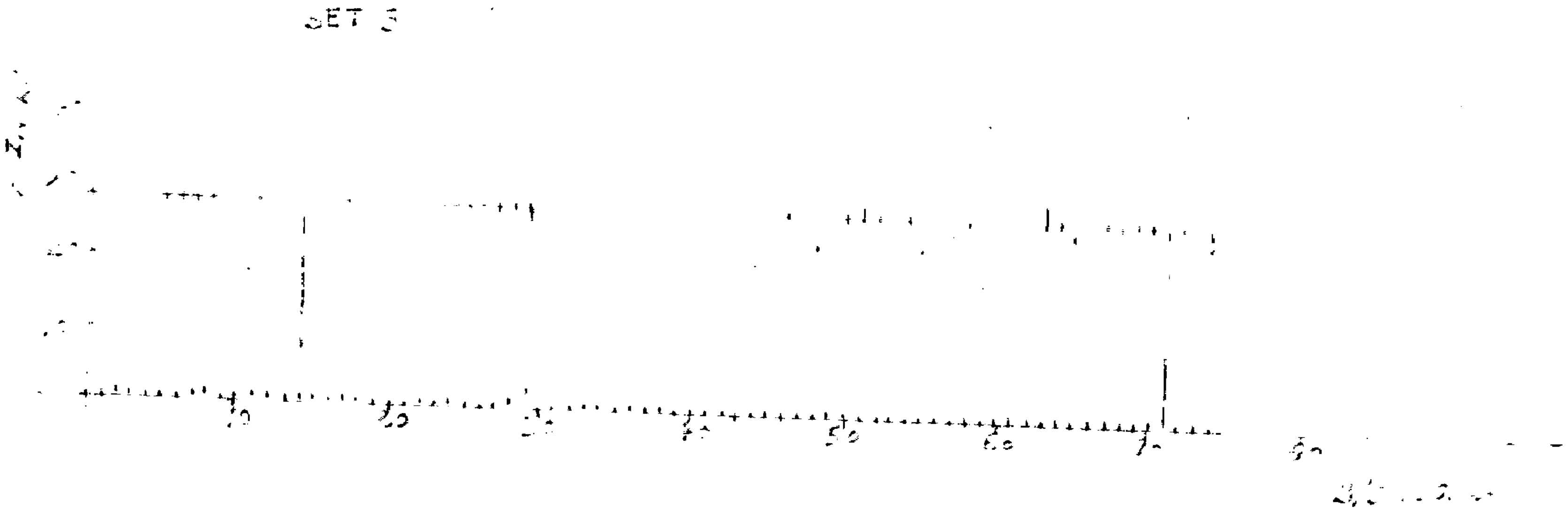
The theory, on which the run test for randomness and stationarity is based, is discussed in Chapter 3.4.2.

In the run analysis for the set of observations discussed in this thesis, the number of runs which occur in the variation of observations about their median value are determine From the table ''percentage points for run distribution'' given in reference[16], the acceptance region $r_{n,1-\frac{\alpha}{2}}$ to $r_{n,\alpha/2}$ is determined for n number of observations and α level of significance. If the observed number of runs falls in this region, the observations are randomly distributed.

Fig.5.1.1 shows the calculation for runs for set 5. For $n = 74$ and $\alpha = 0.05$, the acceptance region is 29 - 45. The number of runs for the set 5 is calculated to be 32. Therefor the observations of set 32 are random. The visual inspection of the voltage charts in Fig.5.1.1 would also give the same information.

Table 5.1.1 gives the results of the test for randomnes for all the sets at α=0.05.

The test of stationarity the run test on the means of subgroups of 5 readings is conducted the same way, and table 5.1.2 gives the results for all the sets which are random.


SET 5
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20
30
40
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60
70
80

[illegible]

Table 5.1.1

OUTCOME OF TESTS FOR RANDOMNESS

NO.	Set NO.	NO. of observations	NO. of runs.	Acceptance region	Out-come
1	1	50	14	18 - 33	Non-random
2	5	74	32	29 - 45	Random
3	28	40	23	14 - 27	Random
4	29	36	13	12 - 25	Random
5	24	18	13	5 - 14	Random

Table 5.1.2

OUT-COME TESTSFOR STATIONARITY

NO.	Set NO.	NO. of subgroups	NO. of runs	Acceptance region	Out-come
1	5	15	9	4 - 13	Stationarity
2	28	8	5	3 - 10	Stationarity
3	29	12	5	3 - 10	Stationarity
4	24	10	6	2 - 9	Stationarity

5.2. X^2 Goodness of Fit Test for Normality:

Table 5.2.1 shows the calculation of X^2 goodness-of-fit test for normality.

Fig.5.2.1 shows the histogram of set 24.

Table 5.2.2 shows the results of X^2 goodness-of-fit test for normality for all the sets.

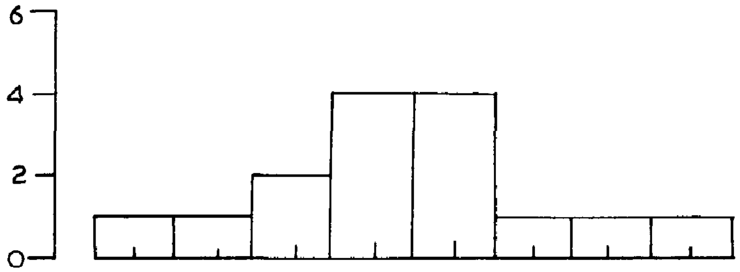


FIG. 5·2 -1 HISTOGRAM OF SET 24

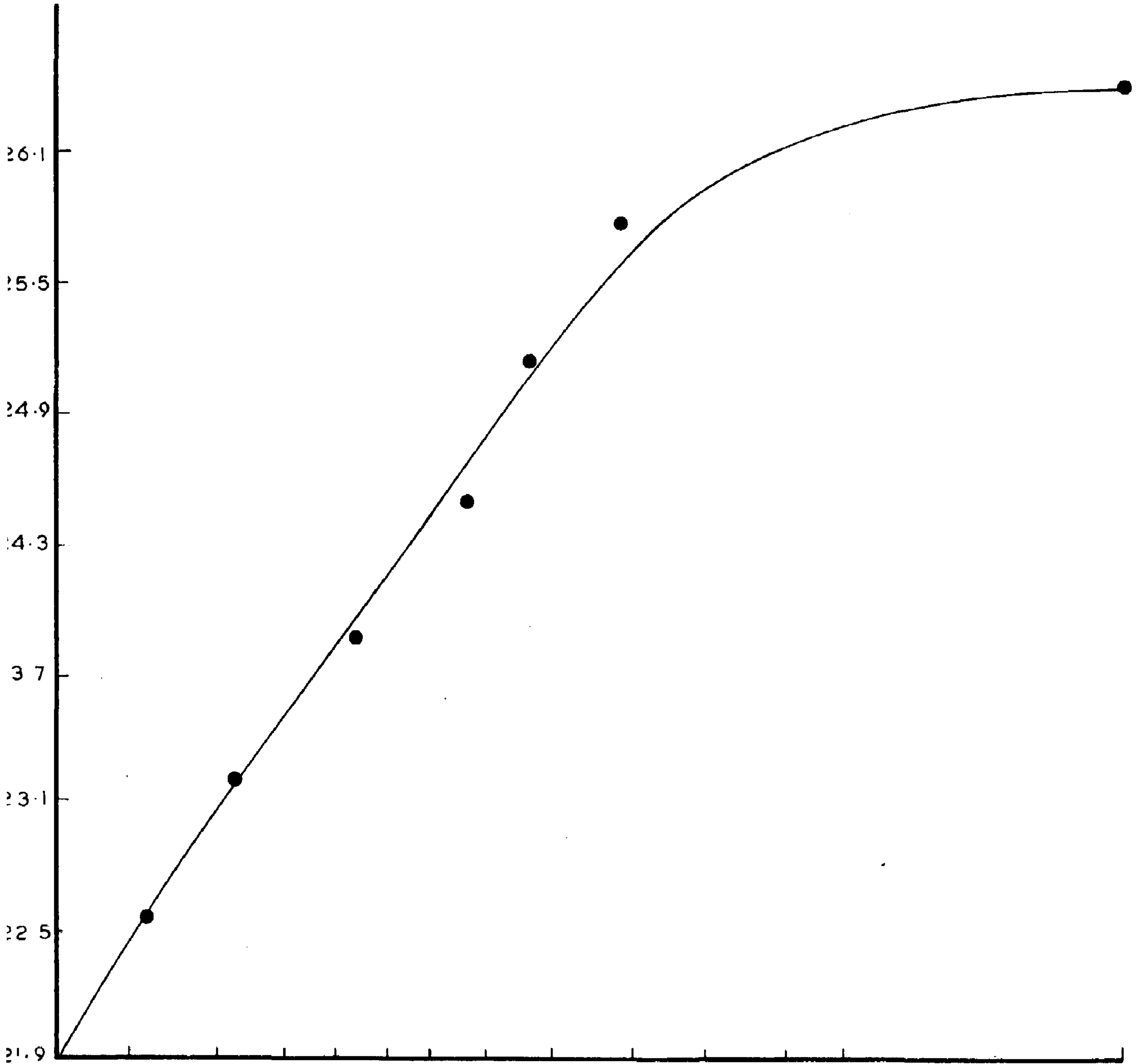


FIG. 5 2 -2 CUMULATIVE FREQUENCY PLOT ON NORMAL PROBABILITY PAPER SET - 24

Table 5.2.1

SAMPLE CALCULATION OF X^2 GOODNESS-OF FIT TEST FOR NORMALIT

Class No.	Interval x_i KV	to x_i+1 KV	Mid points x KV	f	$Z_{i+1}=\frac{x_i+1-\bar{x}}{s}$	A^*	F=NA	$\frac{(f-F)^2}{F}$
1	21.6	22.2	21.9	1	-1.75	00401	0.7	0.13
2	22.2	22.8	22.5	1	-1.23	0.0692	1.2	0.03
3	22.8	23.4	23.1	2	-0.70	0.1327	2.4	0.06
4	23.4	24.0	23.7	4	-0.18	.1866	3.6	0.04
5	24.0	24.6	24.3	4	+0.35	0.0654	1.2	6.53
6	24.6	25.2	24.9	2	+0.88	0.1738	3.1	0.39
7	25.2	25.8	25.5	2	1.4	.1086	2.0	0.0
8	25.8	26.4	26.1	2	1.93	0.054	1.0	1.0
								ΣX^2 8.2

N = 18 ; $\bar{x}$ = 24.2 KV , s = 1.14 , n = K-3 = 5 , α = 0.05, $X^2_{5,0.05}$ = 11.0

A^* A is the area under a standardised normal function p(Z) between the limits Z_i and Z_{i+1}

Table 5.2.2

Out Come of X^2 Tests for Normality

NO.	Set NO.	X^2	$X^{2*}_{n,\alpha}$	Out come
1	5	24.6	$X^2_{6,.05}$=12.59	Not normal
2	28	18.97	$X^2_{7,.05}$=14.07	Not normal
3	29	54.6	$X^2_{7,.05}$=14.07	Not normal
4	24	8.2	$X^2_{5,.05}$=11.07	Normal

* From reference 16

5.3 Fitting An Exponential Distribution Function:

Sample Calculation:

Table 5.3.1 and 5.3.2. give the calculations for fitting an exponential function to the data of set 5. Fig.5.3.1 shows the straight line $\log \phi = -13.01 + 0.471\,V$ fitted to the observed data and the corresponding exponential function $\phi = \exp(-13.01 + 0.471\,V)$ fitted to the observed data.

Table 5.3.1

SAMPLE CALCULATIONS FOR FITTING AN EXPONENTIAL DISTRIBUTION FUNCTI

NO.	V(KV) = x_1	P	R	1-R	$\phi = \frac{P}{1-R}$	log ϕ	log ϕ-2 = y_1
1	17	0.013	0.01	0.99	0.0131	-4.335	-6.335
2	19	0.013	0.03	0.97	0.0134	-4.312	-6.312
3	21	0.013	0.04	0.96	0.0135	-4.302	-6.302
4	23	0.122	0.16	0.84	0.1452	-1.929	-3.929
5	25	0.243	0.40	0.6	0.405	-0.903	-2.903
6	27	0.270	0.67	0.33	0.8181	-0.20	-2.201
7	29	0.243	0.92	0.08	3.0375	.111	-0.889
8	31	0.067	0.98	0.02	3.35	1.208	-0.792
9	33	0.013	1.00	0	0	0	

Fitting a straight line by method of least squares:

$\Sigma x_1 = 192$; $\Sigma x_1^2 = 4776$; $(\Sigma x_1)^2/n = 4608$

$\Sigma y_1 = 29.663$; $\Sigma x_1 y_1 = 632.667$; $(\Sigma x_1 y_1)/n = 79.08$

The equation to the line fitted by least squares is

$$y = a + bx \quad \text{where}$$

$$b = \frac{\Sigma\, x_i y_i - (\Sigma\, x_i\, \Sigma\, y_i)/n}{\Sigma\, x_i^2 - (\Sigma\, x_i)^2/n}$$

and $a = (\Sigma\, y_i - b\, \Sigma\, x_i)/n$

For the above set,

$$b = 0.471 \; ; \quad a = -15.01$$

$$y = -15.01 + 0.471\, X$$

$$\left.\begin{array}{l} \therefore \; \log \phi = -13.01 + 0.471\, V \\ \therefore \quad \phi = \exp\,(0.471\, V - 13.01) \end{array}\right] \begin{array}{l} \text{Shown in} \\ \text{Fig. 5.3.1} \end{array}$$

The calculations of ϕ for drawing the graph in Fig.5.3.1 are given in table 5.3.2.

Table 5.3.2.

CALCULATION FOR FITTING AN EXPONENTIAL DISTRIBUTION FUNCTION

NO.	V	log ϕ	ϕ	$\phi + R$	$\phi + 1$	$R_n = \frac{\phi + R_{n-1}}{\phi + 1}$
1	17	-5.003	.0067	-	1.0067	0.0067
2	19	-4.061	0.0172	.0239	1.0172	0.0235
3	21	-3.119	0.0442	.0677	1.0442	0.0648
4	23	-2.177	0.1134	.1782	1.1134	0.1600
5	25	-1.235	0.2908	.4508	1.2908	0.3492
6	27	-0.293	0.7460	1.1952	1.7460	0.6845
7	29	0.649	1.9136	2.5981	2.9136	0.8917
8	31	1.591	4.9086	5.8003	5.9086	0.9817
9	33	2.533	12.5912	13.5729	13.5912	0.9986

5.4. X^2 Goodness-of-fit Test For Exponential Function:

Sample calculation:

Table 5.4.1 gives the calculation of X^2 for fitting an exponential distribution.

Table 5.4.1

SAMPLE CALCULATION OF X^2 WHEN AN EXPONENTIAL DISTRIBUTED IS FITTE

Class NO.	Mid Value	P Set 5	* P^1	$\frac{(P - P^1)^2}{P^1}$
1	≤ 19	.3	2.35	1.79
2	21	1.3	4.13	1.94
3	23	12.2	9.52	0.75
4	25	24.3	18.92	1.53
5	27	27.0	33.53	1.27
6	29	24.3	20.72	0.62
7	31	6.7	9.00	0.59
8	33	1.3	1.69	0.09

Degree of freedom 8-1 = 7

$$\Sigma \frac{(P - P^1)^2}{P^1} = X^2 = 6.79$$

* Calculated from $\phi = \exp(0.471V - 13.01)$

Table 5.4.2 gives the values of X^2 for fitting an exponential distribution function and their corresponding probabilities.

Table 5.4.2

THE VALUES OF X^2 AND THEIR PROBABILITIES WHEN NORMAL AND EXPONENTIAL FUNCTIONS ARE FITTED.

NO.	Set NO.	X^2 *	X'^2 **	Exponential function fitted	Probabilities*** X^2	Probabilities*** X'^2
1	5	24.6	6.79	exp $(.471V-13.01)$	$<<.01$	$<.2$
2	28	18.97	65.16	exp $(2.2V - 27.24)$	$<.02$	$<<.01$
3	29	54.6	25.22	exp$(.94V-11.73)$	$<<.01$	$<<.01$
4	24	8.2	10.28	exp $(.904V-22.78)$	$<.3$	$<.2$

* for fitting a normal function.

** for fitting an exponential function.

*** From reference 15.

5.5 Sufficient Number of Readings:

Table 5.5.1 gives the calculated values of coefficient of variation $r = \frac{\sigma}{\bar{E}}$ for the sets which pass the test of normality. The value of r_{max} can be get from reference 6.

Table 5.5.1

SUFFICIENT NUMBER OF READINGS

NO.	Set NO.	NO. of observation	$\bar{E}$ KV/cm	σ KV/cm	$\sigma/\bar{E}$ $= r$	r_{max}
1	5	74	250.04	26.6	7.86	$\simeq 10.0$
2	28	41	440.8	24.01	2.23	$\simeq 7.47$
3	29	36	419.45	37.20	3.19	$\simeq 7.05$
4	24	18	195.0	9.19	0.85	$\simeq 2.48$

5.6 Fitting An Extreme Value Distribution Function

Table 5.6.1

SAMPLE CALCULATION FOR FITTING AN EXTREME VALUE DISTRIBUTION FUNCTION

Break-down Voltage KV	NO. of Obser-vation	Cululative Number n	Plotting Positions $X_n = \frac{n}{N+1}$	Reduced Variate y *
17	1	1	0.0133	- 1.5272
19	1	2	0.0267	- 1.3053
21	1	3	0.0400	- 1.1690
23	9	4 to 12	0.0533 to 0.1600	-1.0972 to -0.6057
25	18	13 to 30	0.1733 to 0.4000	-0.5721 to 0.0874
27	20	31 to 50	0.4133 to 0.6667	.1147 to 0.8782
29	18	51 to 68	0.6800 to 0.9067	.9528 to 2.3044
31	5	69 to 73	0.9200 to 0.9733	2.4843 to 3.4914
33	1	74	0.9867	4.1922
	N = 74			

* From reference 23.

For set 5, $\bar{X} = 250.04$; $\sigma = 24.3$

From reference 6, for $N = 74$, $\sigma_N = 4.69$ $\bar{y}_N = 0.50$

$$\frac{1}{\alpha} = \frac{\sigma}{\sigma_N} = 5.66 \quad ; \quad Z_n = \bar{X} + \frac{\bar{y}_N}{\alpha}$$

$$= 252.87$$

Table 5.6.2

PARAMETERS OF EXTREME VALUE DISTRIBUTION FITTED

NO.	Set NO.	$\bar{E}$ KV	σ	E_m	$\frac{1}{\alpha}$
1	5	250.04	26.6	252.9	15.66
2	28	440.8	24.01	445.0	–
3	29	419.45	37.2	419.4	6.52
4	24	195.0	9.19	194.2	3.81

6. DISCUSSION

In our experimental work measurment of breakdown voltage plays a very important role. Accuracy in taking measurment is important here. We have assumed an electrostatic voltmeter as substandard voltmeter and the calibrated the multimeter set. The calibration curve is shown in Fig.6. Now we will discuss about the other experimental work.

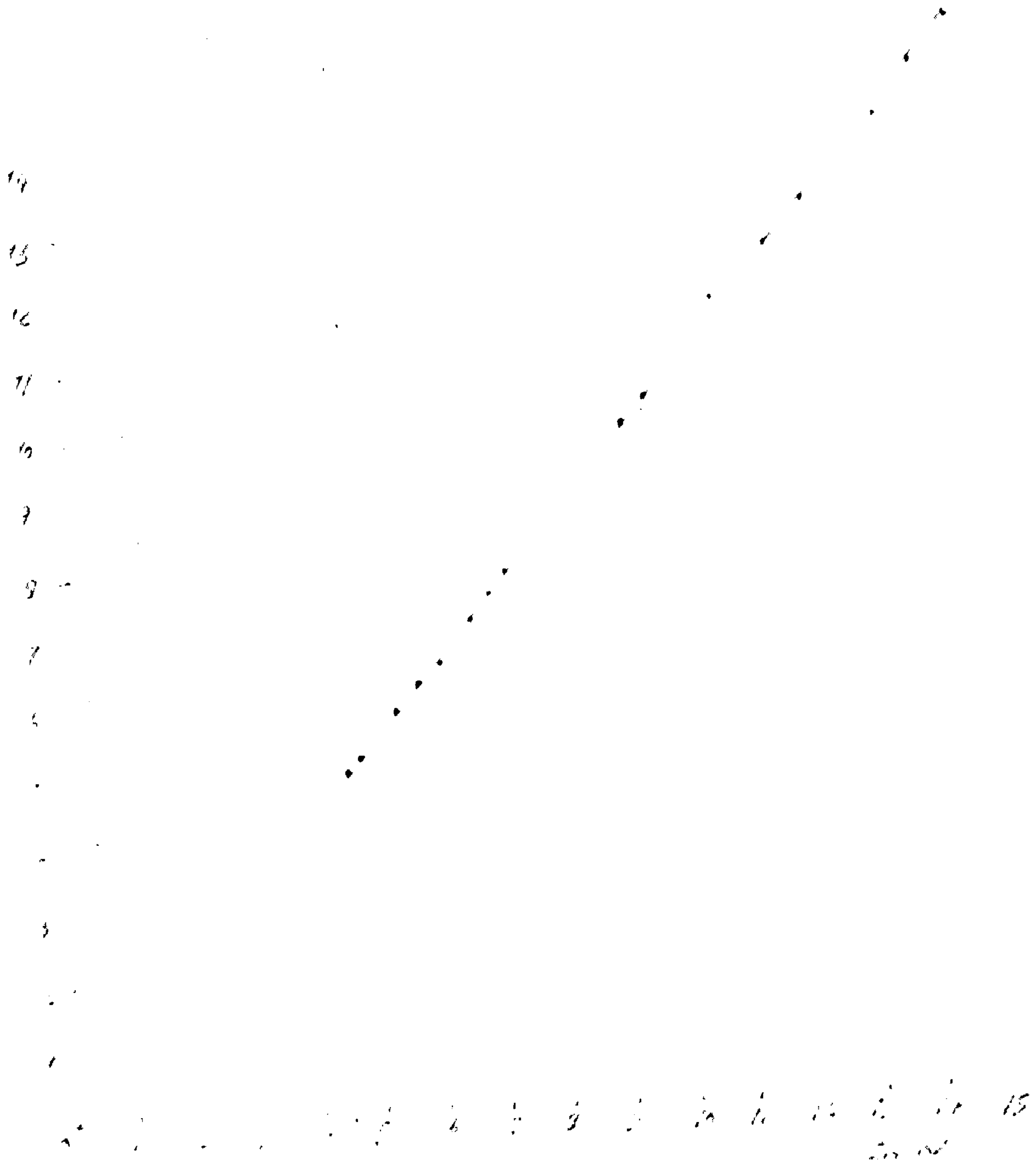
6.1 Randomness and Stationarity:

Randomness and stationarity are the two basic statistical conditions that the data must satisfy before it can be analysed with ordinary statistical techniques. We have seen in section 3.4 that the data can be considered as random-stationary if the individual time history are proved to represent random self stationary process.

Set 1 to 3 taken with the Siemen's test cell to check the properties of randomness and stationarity showed that the breakdown voltage increased gradually with successive breakdowns, till about 50 readings at a gap length of 4 m.m. The gradual decrease in breakdown voltage at the start of a series of measurments is quite common in dielectric breakdown studies and is referred to as 'conditioning' obviously the observations in such a set can not be random as confirmed by the analytical tests given in table 5.1.1. Normal statistical techniques cannot therefore be used to analyse such a set, special techniques are available for analysing time varying sets (such as representing

CALIBRATION CURVE FOR MULT[illegible]

[illegible]



MULTIMETER SET[illegible]

FIG. NO. 6

conditioning process). But an analysis of the conditioning region to get at the breakdown strength is meaningless the breakdown strength obtained for this region is strongly influnced by the electrode effects, impurities etc. and does not represent the characteristic of the medium. The representative value can be found from the breakdown test sequence only after conditioning is over, when the electrode effects would have stabilised. In this region the test can be expected to represent a random stationary process. A sufficiently large number of readings of this region can be analysed statistically to get the breakdown strength. The value of breakdown voltage quoted by by Brignell[6 and Sletter[6] have been obtained from this stationary region. This procedure is not only true for breakdown studies in liquids, but is true for breakdown studies on all media. The following factor may take part in conditioning.

6.1.1 Electrode surface:

The adsorbed gas layers on the electrode surface get destroyed with repeated breakdown voltage and thus the breakdown voltage goes on increasing. Similarly the oxide layers on the electrodes get destroyed giving rise to higher strengths. The out gassing of the electrodes at high temperature in vacuum is the usual method of removing the adsobved layer of gases. Weber and Endicott[24] avoided conditioning effects by automatically polishing the electrodes after every breakdown. In the present work, however, name of these have been used. The electrodes were cleaned by rinsing the electrodes with carbon tetrachloride and transformer oil before each set. The breakdown tests were started after about one hour which is the time required for the preparation of the cell and the electrodes.

6.1.2 Oil Volume:

At the outset it appears as though oil volume does not have an effect on conditioning process so long as the effective volume of the oil between the electrodes remain constant. But it may not be so. To explain the effect of oil volume on conditioning, we will have to consider the breakdown breakdown process in detail.

The solid particle in the oil take active part on the breakdown process. After a d.c. stress is applied to the gap, the solid particles in the oil become active[6] and start moving under the influence of the stress. They are drawn to the region of the greatest stress if the permittivity of the particles is greater than that of the oil. When some particles reach the anode, they acquire a positive charge and start moving towards the cathode. Thus particles oscillate in the gap. At the cathode, the positively charged particle enhance the local field causing a copious emission of electrons. As the stress increases, the number of particles in the region of maximum stress increases and the particle oscillation and electron emission also increases. Thus at a critical voltage particles will form a bridge to produce breakdown. This is the breakdown due to particle oscillation and bridge formation. After breakdown, the particles get ejected from the gap length and some of them get lost in the bulk of the oil or get settled on favourable sites, on the electrode, or on the walls of the cell. With repeated breakdowns the process of ejection of particles from the gap length progresses till only a few particles are left in the gap length. Therefore repeated breakdowns give improved breakdown strength. In this way the particle take part in conditioning.

When the total oil volume is very large the total number of solid particles present around the gap is larger than when the total volume is smaller. Therefore after a few breakdowns some solid particles that have been ejected from the gap length and have found suitable sites to rest upon, are eliminated from the gap length, but the volume has still a large number of solid particles to feed to the gap length and thus prolong conditioning. Then it is probable that the conditioning process lasts for a very long time if the volume of the oil is very large

In our experimental work we started with an oil volume of 400 c.c. and the conditioning region lasted about 200 readings So we reduced the volume to 300 c.cs and the conditioning region lasted about 40 - 50 readings. The volume could not be reduced below 300 ccs since it is the limit fixed by considerations of minimum oil above electrodes. With the largest gap length of 4 mm; we were only able to get observations in the initial portion of the conditioning region. In the later portion the breakdown voltage exceeded the 50 KV limit of the set.

6.1.3 Stirring of the Oil:

In the experiments with the large cell, the oil was stirred before every reading. At the outset, it appears that the stirring will prolong the conditioning effect because the solid particles will be continuously fed to the gap. On the other hand, stirring also helps to carry away the breakdown products from the gap so that the breakdown strength improves and thus the conditioning is faster. Therefore, both the effect of prolonging the conditioning and the effect of improving the breakdown strength may exist simultaneously.

Secondly in our experimental work because of non proper handling of the solid insulating materials by the suppliers additional impurities are introduced when we immersed these in oil. This will also create more problems in the variance. One more point is also there, there are certain insulating materials which absorb the oil so they will lose air bubbles which some time have found suitable site to rest upon the electrode itself. Both these points can reduce the breakdown voltage. So first point here is that we should directly contact the manufacturer, so that the proper handling of the solid insulating material can be done. Secondly we should have arrangement for proper stirring so that error may not come due to air bubbles.

6.2. Selection of Material for Combination With Transformer Oil:

After having obtained sets which represent random stationary process for oil, now it becomes necessary to select materials for combination with the transformer oil. Now we have taken measurments on solid insulating materials in air and transformer oil. The sets concerned were 6 to 11 and 16 to 21.

These results are shown in Fig. 6.2.~~1~~ a to f. The mean and variance is calculated for these materials (Appendix C). For Elephantoid, Empire cloth and Krempel the breakdown value in transformer oil is more than in air, table 6.2.1. The variance reduces for empire cloth and Krempel where as for elephantoid it increases.

6.3. Effect of Alignment of the Electrodes:

Bruce[7] has examined the various errors which may be introduced by faulty alignment of the electrodes, the electrodes which are fitted in Siemen's set does not have proper alignment. So we replaced another cell which has proper alignment. The breakdown behaviour for such an improper can be seen from Fig. 4.4.2 and 4.4.3.

6.4. Effect of Force Applied on the Material :

The Siemen set has no proper arrangement to fix an insulating material between the electrodes. In these circumstanc it is felt by the author that if force is applied more it can destroy~~m~~ the insulating material and it can reduce the thickness of the material resulting in a change of breakdown voltage. So it becomes necessary to introduce an arrangement for proper fixing which can be applied on the insulating materials. The arrangement is given in another cell which is replaced by the author.

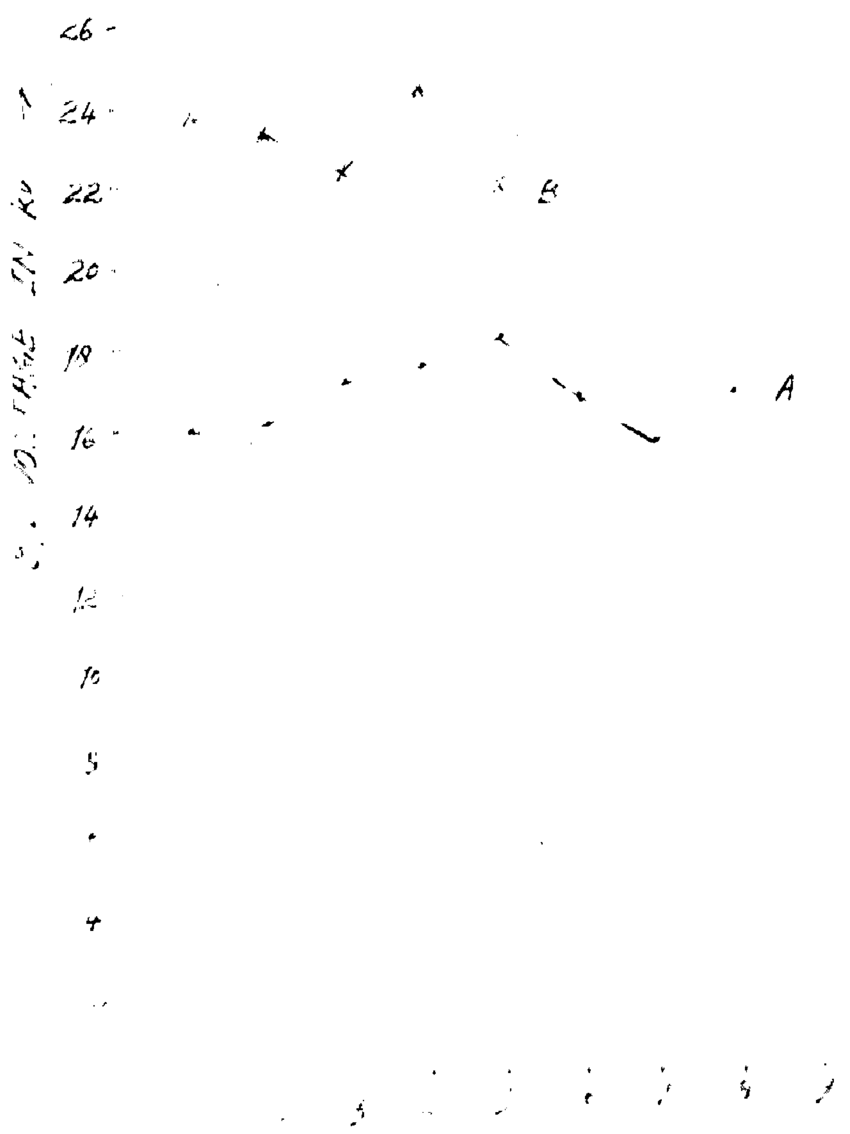
6.5. Effect of Improper Alignment of Sample:

As felt by author that some insulating materials are so flexible that they bend to ward either of the electrodes ; which

B/D VOLTAGE OF ELEPHANTIDE PAPER

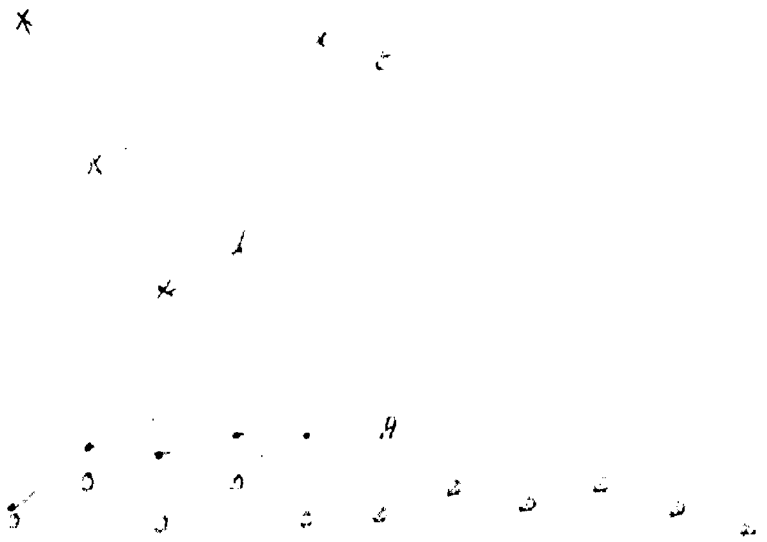
A IN AIR [illegible] 10

B IN TRANSFORMER OIL [illegible]



6.20

[illegible]



[illegible]

[illegible] 6.2C

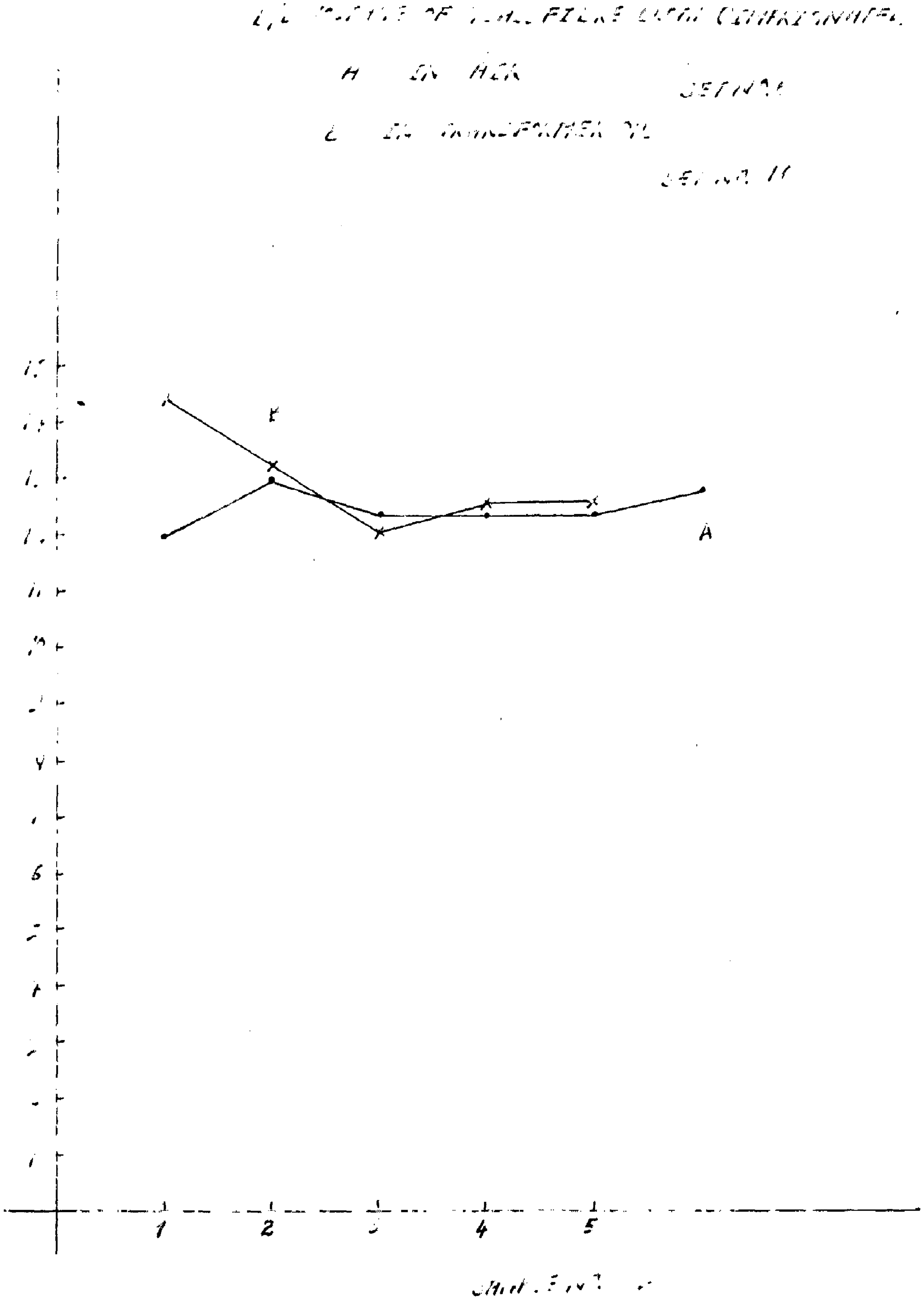


FIG. NO. 6.2.d

62d e

B/D VOLTAGE OF GLASS MICANITE FIBRE

A IN AIR Set No 11

B TRANSFORMER OIL Set No 21

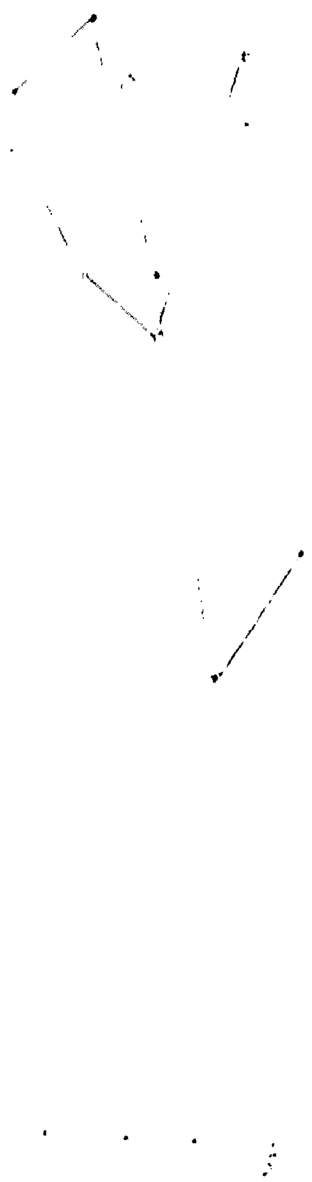


FIG. NO. 6.2.f

Table 5.2.1.

CALCULATIONS OF MEANS AND VARIANCES FOR IMPORTANT MATERIALS.

S.NO.	Name of the Solid Insulating Materials.	Media	Without fixer				With fixer			
			b/d strength KV/mm	Percentage change	Variance KV	Percentage change	b/d strength KV/mm	Percentage change	Variance KV	Perce tage chang
1	Elephantoid	AIR	13.54	37.85^{+}	0.74	13.51^{+}	-	-	-	-
		OIL	18.67		.85		19.50		1.29	
2	Empire cloth	AIR	40.40	31.60^{+}	0.64	14.06^{-}	44.07	10.93^{+}	0.41	2.4^{+}
		OIL	53.17		0.55		55.00		0.42	
3	Krempel	AIR	26.71	62.64^{+}	0.41	++	27.33	14.64^{+}	0.04	++
		OIL	43.44		2.3		42.00		1	

\+ Increase.

++ Increase significantly.

\- Decrease.

create non uniformity of the field around the solid insulating material. The effect can be seen if we compare the results for mean value and variance of sets 9,23 and 17,22 (Figs.6.2 a to f). The variance increases and the value of breakdown voltage increases by some value. So it is necessary to design a holder for proper alignment of the sample (solid insulating material). The dimension for this fixer is given in Appendix B. The Author has shown in Chapter 3, Fig.3.3.2 the dimension of the holder and replaced cell.

6.6 Effect of Time Interval :

We have taken three sets No.25,26,27 for different materials. Each set is designed for three different time intervals and results for breakdown value is plotted on the graph shown in Fig.6.6 a -c. The mean and variances for the about materials do change with change in the interval but the change does not follow a definite pattern. Actually when we use these materials in combination with transformer oil, the adsorption of oil between two readings could be significant and it might become necessary to get to the saturation point for oil absorption by the material after which we could expect the variances to become very low and readings will give a better results.

Discussing above points we can conclude that our main experimental results which are randomly stationary fulfill the requirements for further analysis by statistical methods.

6.7. Distribution of Breakdown Strength:

After having obtained sets which represent random

[illegible]

WHEN ELEMENT [illegible] IS IMMERSED IN

TRANSFORMER OIL

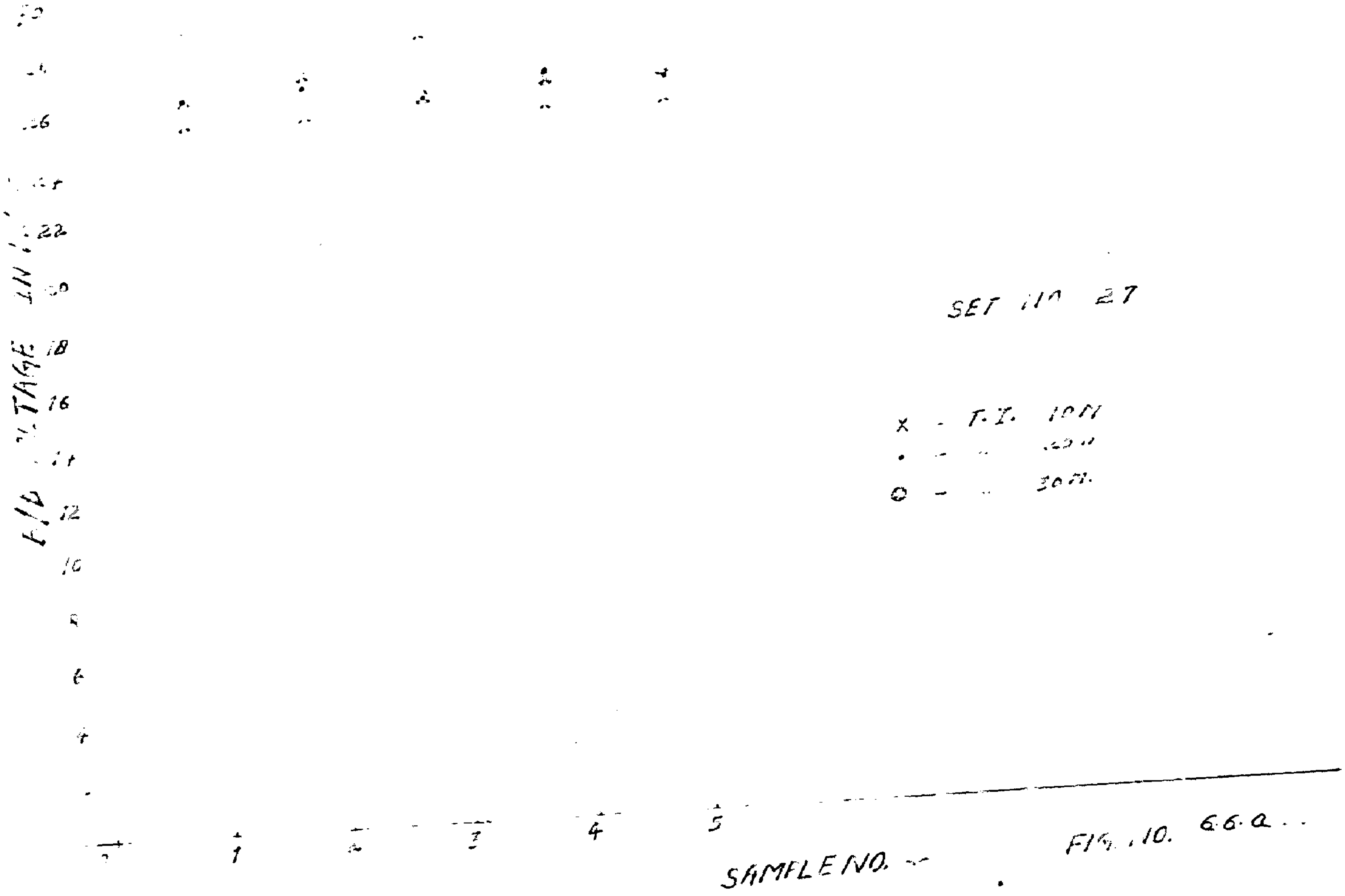


FIG. NO. 6.6 a

EFFECT OF TIME INTERVAL ON [illegible]

[illegible]

[illegible]

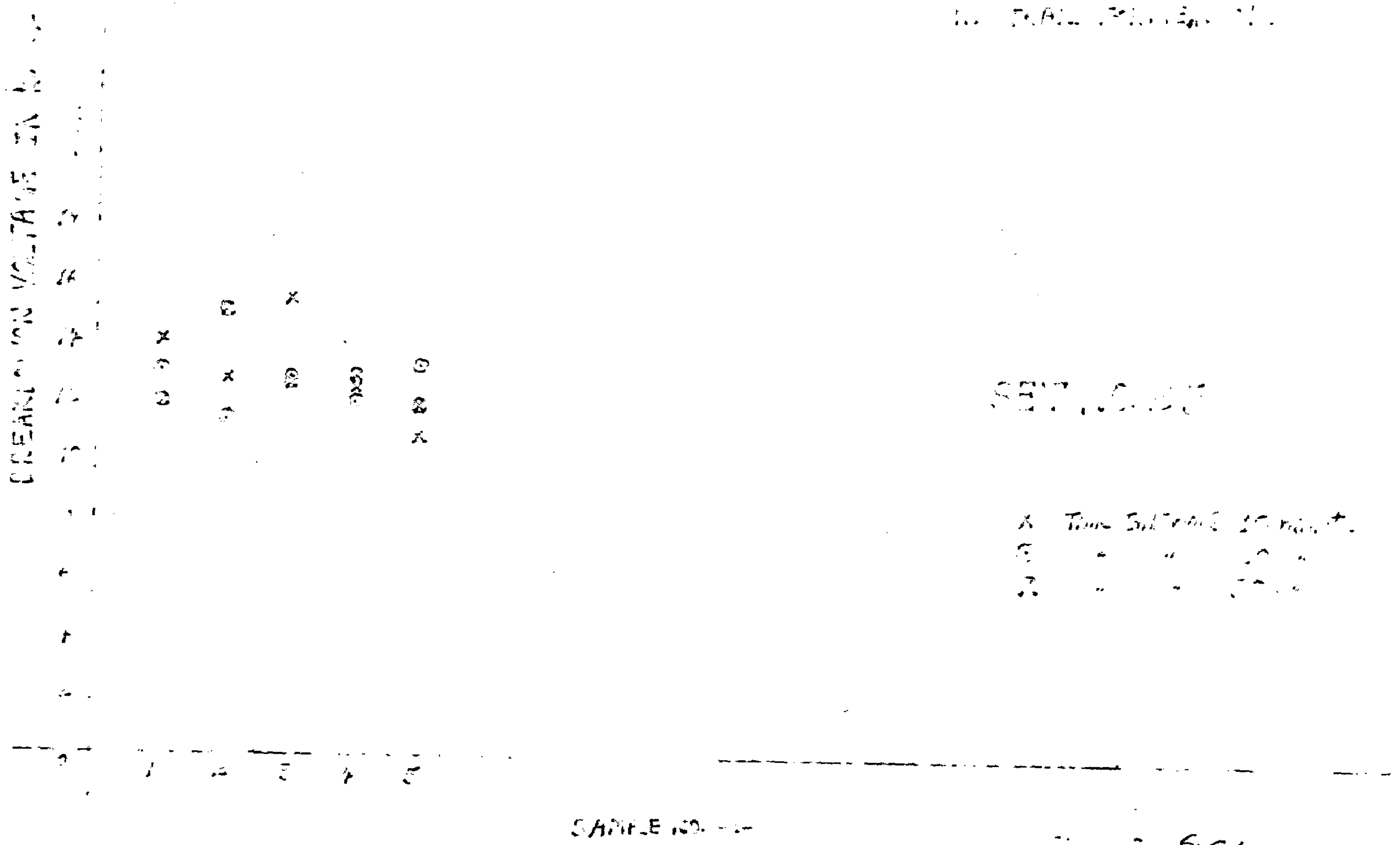


Fig. 6.6

66C

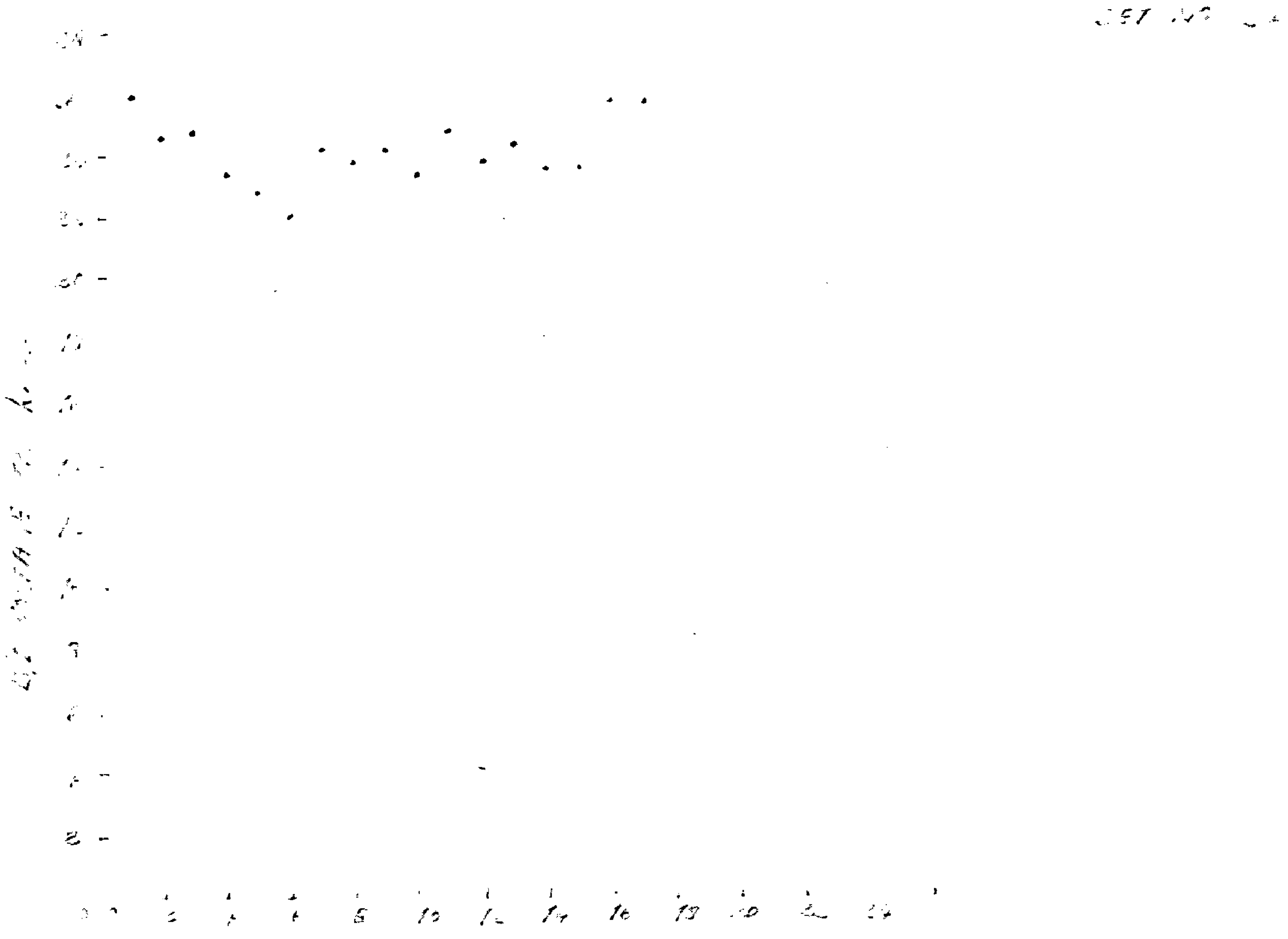
stationary process, the distribution of breakdown strengths could be determined.

The first step was to determine whether the distribution was normal X^2 goodness-of-fit test was used as a test for Normality Table 5.2.2 shows that only one set passes the test of normality. The histogram for all the sets i.e. set NO.24,28,29 had definite negative skewness. The histogram of sets that do not satisfy normality test were more negatively skewed than those which satisfied the normality test. Moreover, the cumulative plots on the normal probability paper of sets that satisfy normality test were curved as shown in Fig.5.2.2, whereas it should have been a straight line.

The breakdown in oil is not described properly by a normal distribution because the normal law does not satisfy the stability postulate[24]. The results of breakdown test on transformer oil have been successfully described by extremal distribution (based on initial exponential distribution) and an agreement between the theoritical function and the experimental results was markedly precise.

The exponential distribution of the type $\phi = \exp(\alpha E-\beta)$ was fitted to the experimental data. Table 5.4.2 gives the values of probabilities of X^2 for fitting a normal distribution and those X'^2 for fitting an exponential distribution function. We can find from this table that the exponential distribution is good-fit-to all the sets including those which did not pass the normality test. The exponential distribution functions are

[illegible] TRANSFORMER OIL [illegible]



F[illegible] N[illegible] 6.71

SET NO. 28

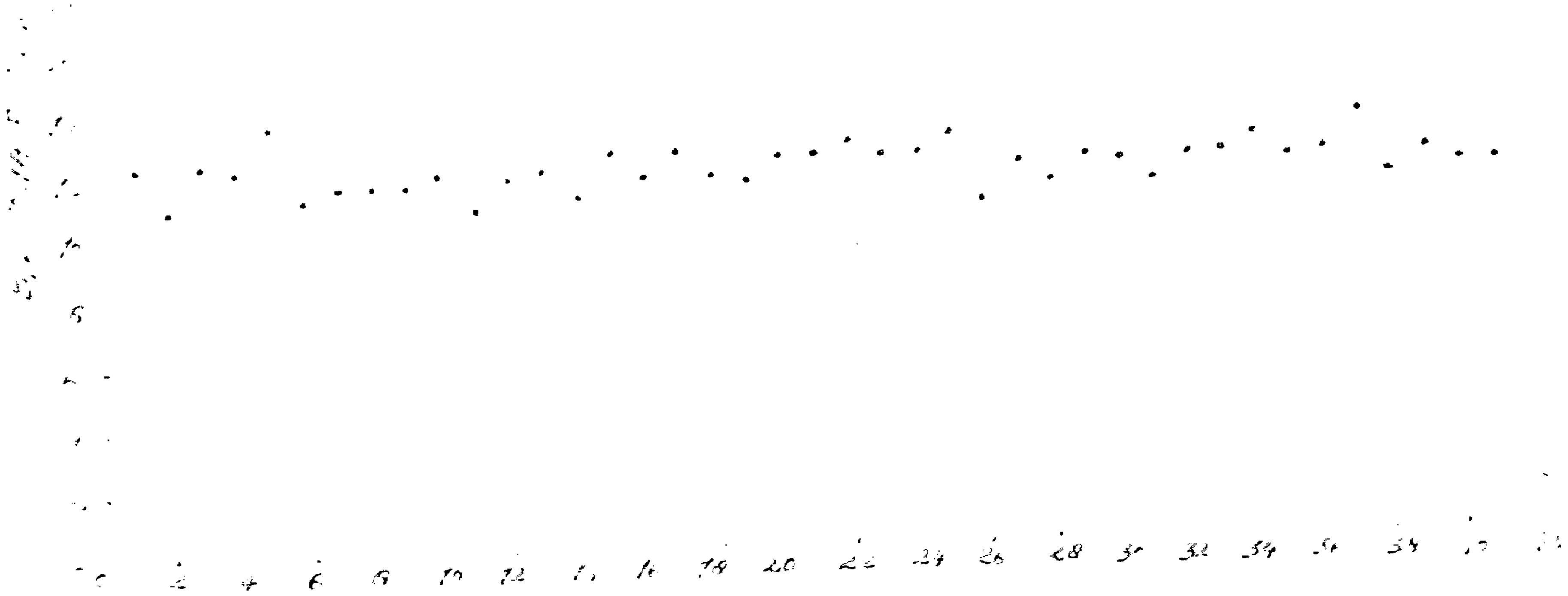
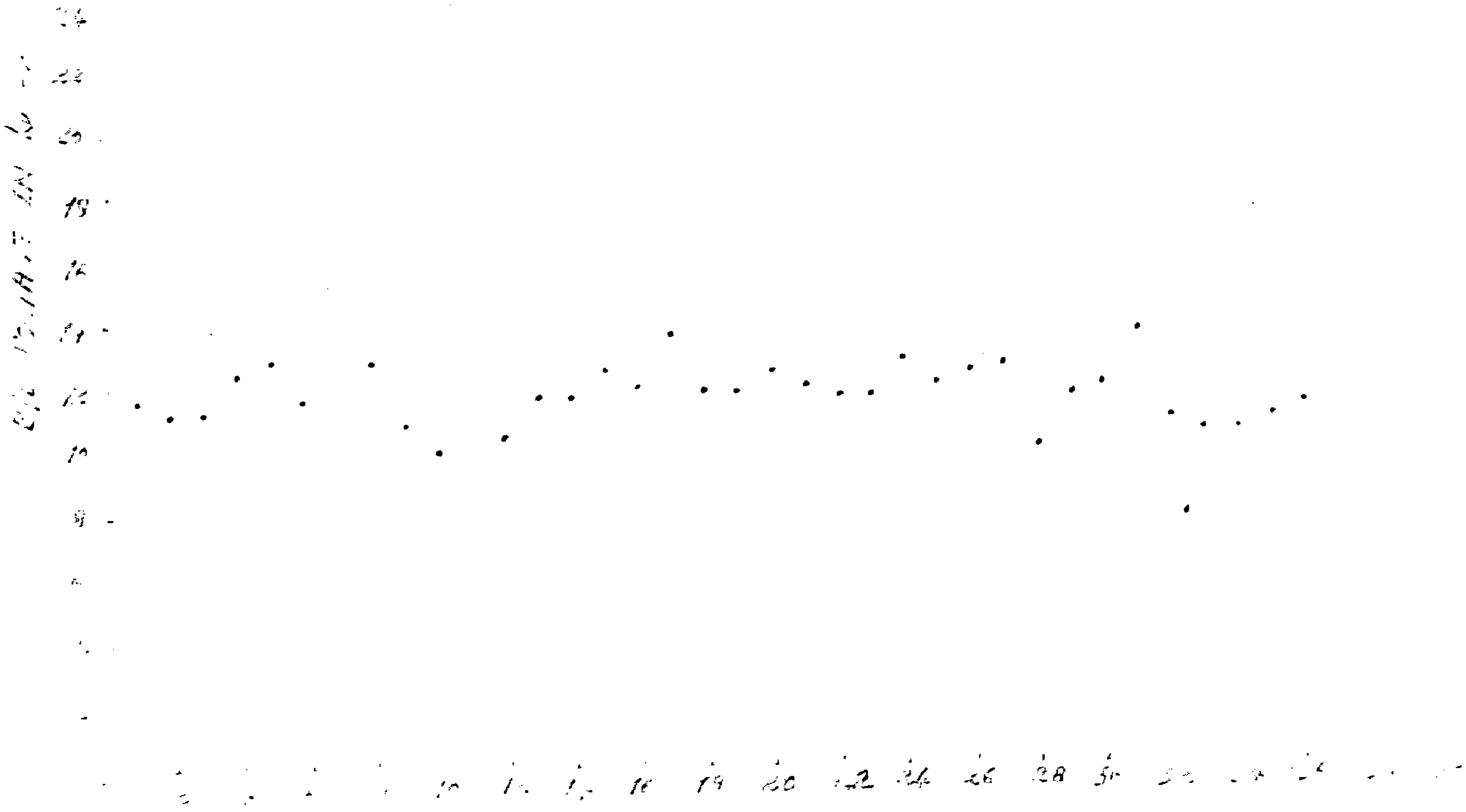


FIG. NO. 6·7 ii

[illegible]

[illegible]



[illegible] 67. iii

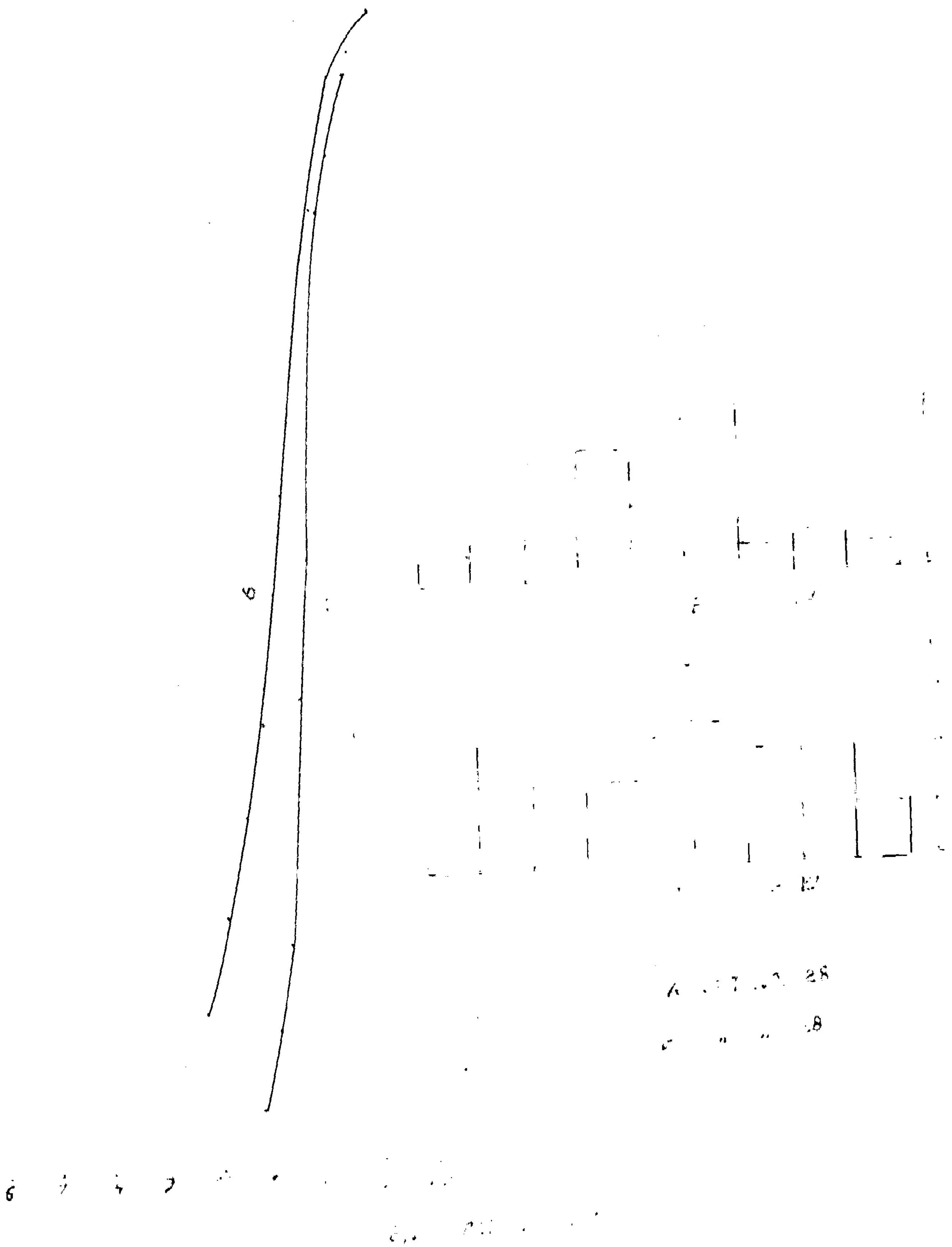
given in the same table. Graph is shown in Fig.6.7.b.

The extremal distribution of the smallest value based on initial exponential distribution is of practical importance since the design engineer would be interested of extreme low values and the corresponding probabilities of the breakdown strengths. The extreme distribution function described the experimental results of Weber and Endicott[24] and established the relation of breakdown strength with area accurately. The extreme value probability function of the type $\phi=\exp(-y-e^{-y})$ when $y = \alpha(E - Em)$ were fitted to the experimental results and the extreme value plots are shown in Fig.6.7C, table 5.6.2 gives the values of parameters $1/\alpha$ and Em.

6.8 Comparison of Results With Those of Others:

It is premise of this thesis that if the breakdown test results are to be fit for statistical analysis, the design of the breakdown test has to be evolved on the basis of statistics. After the design of the breakdown test is completed to yield results fit for statistical analysis, the evaluation of the results involves the determination of the form of distribution and the parameters of the distribution.

For a long time, the distribution of breakdown strengths of liquids was believed to be normal, arising out of the human errors and in accuracies in the testing procedure including the test equipment used. The observations were not subjected to rigorous statistical tests. Weber and Endicott[24] were the first to perform well controlled experiments on transformer oil



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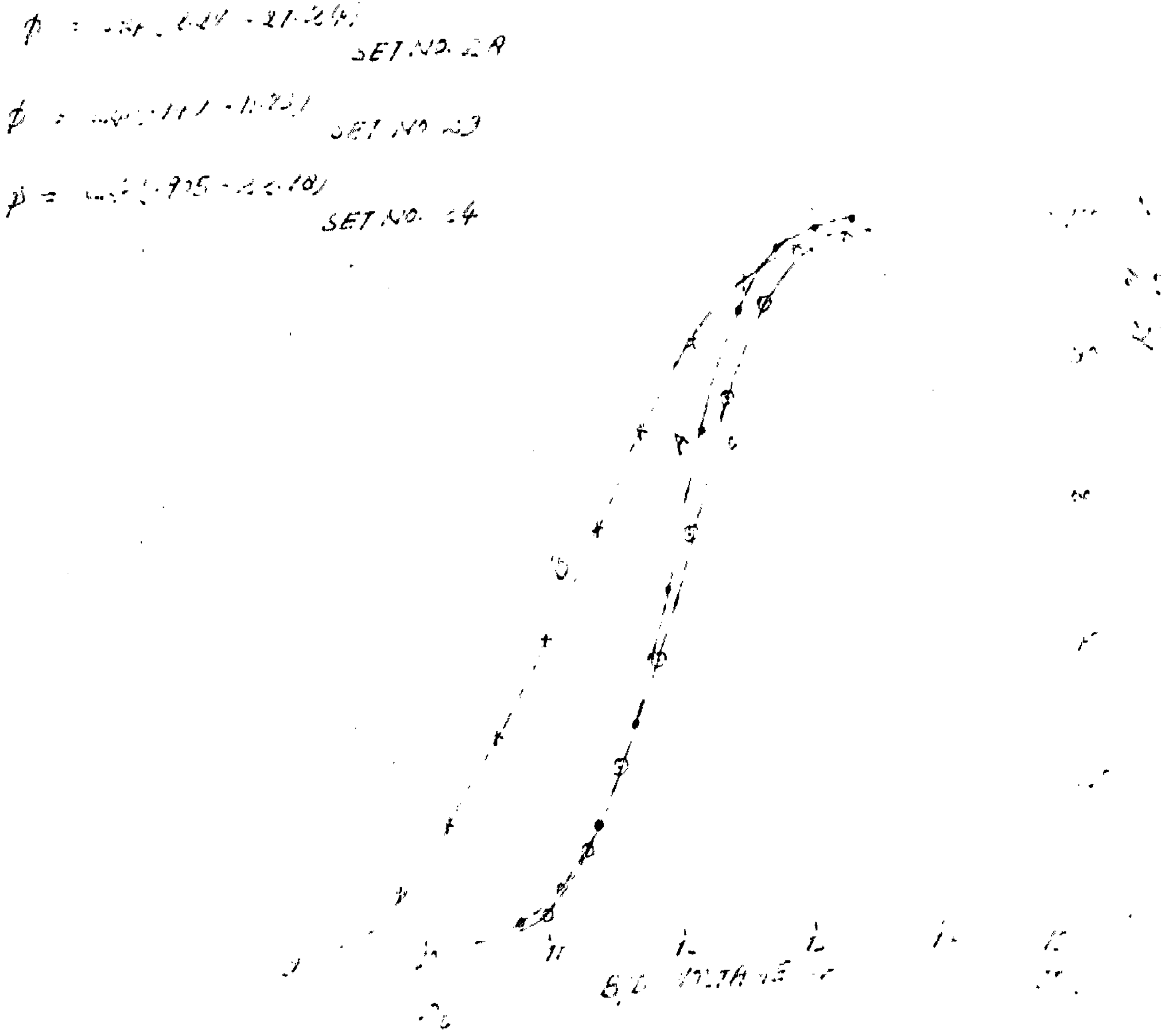
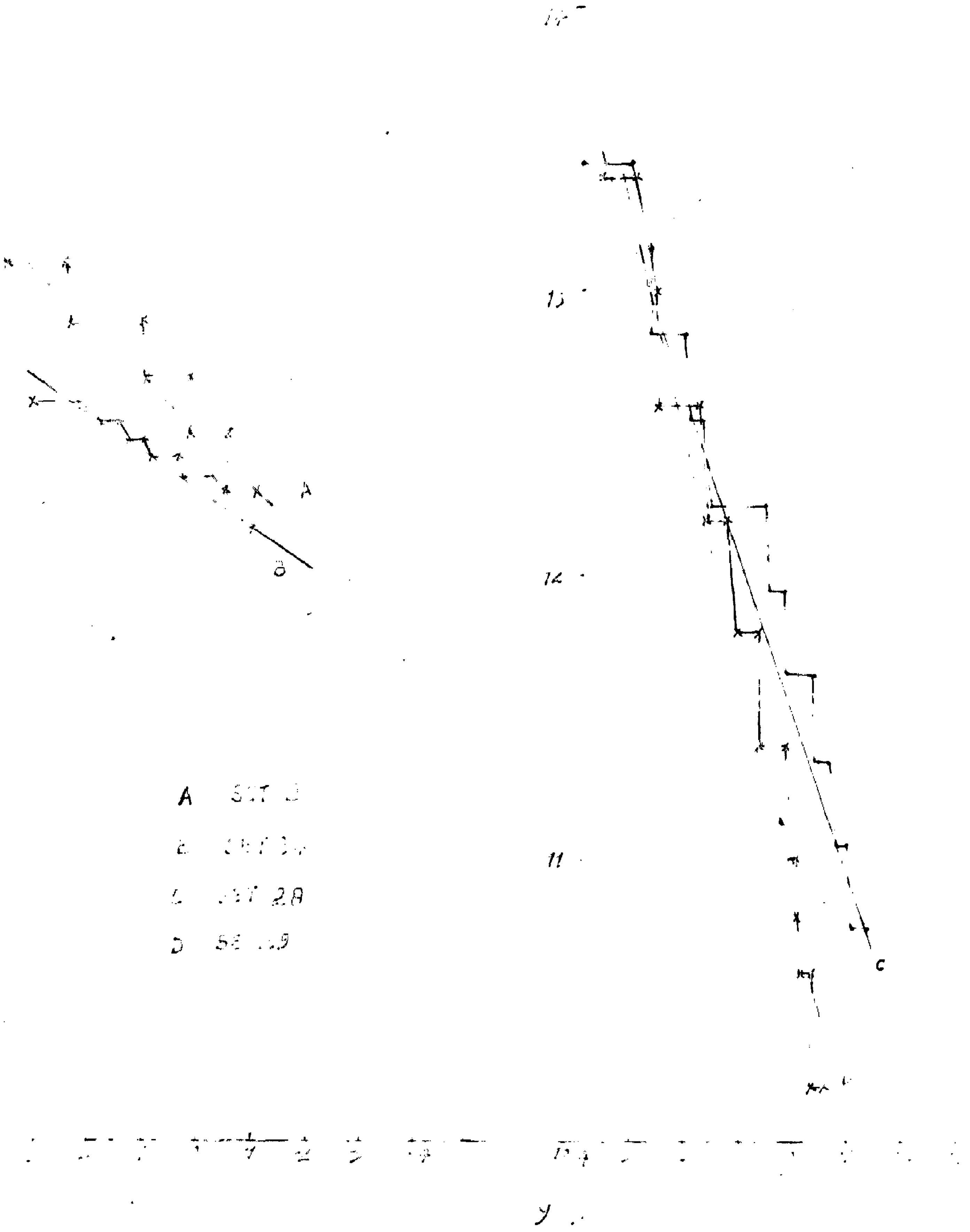


FIG. NO. 6.7b



6·7·C

using a.c. voltages and found that the extreme value distribution was a good fit to the breakdown test results and it satisfied the stability postulate. The extreme value distribution of the smallest value fits the results of the tests reported in this thesis.

CONCLUSIONS

The conclusions drawn in this thesis are given below:

(i) The results obtained from the experiments on Empire - cloth, Krempel in combination with transformer oil are encouraging.

(ii) The extreme value distribution of the smallest value (Gumbel Type I) fits the result of the above materials.

(iii) The improper alignment of the sample effect the variance. Getting proper alignment we got very low variance and good observations.

(iv) The time interval between the sets for a material effects the value of variances. This is due to oil absorbility condition for that material.

(v) When we are using empire cloth, Krempel, in combination with transformer oil, the permittivity will follow the ''logarithmic law of mixture'' accordingly permittivity change will give the change in breakdown voltage.

(vi) As viewed by Microscope, the structure of fibres show that the breakdown voltage in insulating materials reduced due to poor smoothness of compound on the material and air bubble entrapped in a solid dielectric leads to the breakdown at lower voltage.

(vii) Due to improper handling of the materials, damage in insulation are viewed and give poor breakdown voltage.

(viii) Conditioning period is low in solid insulating material because it is mainly effected by the temperature, humidity and pressure which can be assumed negligible.

Suggestions for Future Work :

There is much to be done yet to find out a suitable theory of breakdown strengths. With the help of proper use of statistics, we have only recently been able to remove some points of ambiguity in this field of breakdown in liquid and solid insulating materials. The work presented in this thesis could be continued in the following directions:-

(1) The test method could be improved by improved upon by employing a more accurate and improved methods of gap measurments, electrode and oil treatment.

(2) Reliability can be studied for these insulating material with the knowledge of reliability.

(3) If you can control, pressure, temperature, humidity, better result can be evaluated.

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APPENDIX - A

FUNCTIONAL TESTS

The recent concept is to discard the temperature classification of an individual material but to adopt new temperature classification to the insulation system as a whole. This has established a new approach to the problem of material evaluation by means of function tests.

These tests are based on operational conditions and service experience. Unfortunately both vary enormously. For machines, the common factors are heat, vibration, humidity and voltage. If the temperature is varied, the speed of chemical reaction of the first order and temperature is given by Arrheniou equation (1).

$$K = A\,e^{-E/RT} \tag{1}$$

where

K = Specific reaction rate.

E = Activation Energy.

A = Frequency factor of the molecular encounter.

R = Universal gas constant.

T = Absolute temperature.

The reaction which occur during the ageing of the insulating materials are not simple (some degradation products act as catalysts for other reactions), but if it is assumed that the rate of failure of system is largely determined by one specific reaction, the life temperature tests at three temperatures, if not more, are required. It is also necessary to fix a criterion of failure based on service experience. In the case of machines, it has been observed that most failures occur when they are restarted after a non-operational period.

APPENDIX - B

(i) **Calculations for Sample Size** : If we have sample of low dimension then the line of forces will be more at the edge of the sample so probability increase for the breakdown at the edge instead of occuring at the centre of the sample. So it becomes necessary to choose a sample of such a size that the electrical intensity at the edge reduces to a value to .1 Percent of the intensity at the surfaces of the electrode. For that referring reference 6 we choose a sample size of 5 x 5 cm^2 in which we have low value of intensity to some extent.

(ii) **Measurments for Thickness**: For thickness measurment we have used micrometer. Its least count is 0.01 out error may be on either side of ± .005 mm . We took 10 measurments for each material and calculated average values for them. The average values are given below:-

(i) Empire cloth - .2178 mm
(ii) Polyster Film - .1304 mm
(iii) Elephantoid - 1.2407 mm
(iv) Krempel - .2707 mm
(v) Glass micanite fibre - .2285 mm
(vi) Glass fibre cloth- .2184 mm

(iii) **Calculation for Dimensions of the Fixer**: When we have decided the sample size then it becomes very easy to select the dimensions of fixer, just by applying common sense, seeing the cell's dimensions and sample size we choose the following dimension for the fixer.

The length of the frame = 9 cm

The width of the frame = 9 cm

The cover plate size = 6 cm; 9.5 cm.

Screws are fitted as shown in Fig. 3.3.2.

S.NO.	Set NO.	Name of the Material	Room Temperature °F	Time Interval minute	Thickness of material. in m.m.	NO. of observations	Mean Value in KV	Variance/Standard Deviatio
1	10	Elephantoid in Air	87 °F	4	1.2407	8	16.8	0.74 / 0.86
2	20	in Transformer Oil	90 °F	4	1.2407	5	23.16	0.86 / 0.93
3	7	Empire cloth in Air	86 °F	1.5	.2178	5	8.8	.64 / 0.80
4	17	in Transformer Oil	89 °F	4	.2178	5	11.58	0.55 / 0.74
5	22	in Air with fixer	89 °F	4	.2178	14	9.6	0.41 / 0.64
6	9	Krempel in Air	87 °F	2	.2707	5	7.23	0.14 / 0.37
7	19	in Transformer Oil	89 °F	4	.2707	5	11.76	2.3 / 1.52
8	23	in Air with fixer	89 °F	4	.2707	9	7.4	0.04 / 0.21
9	6	Glass fibre cloth (IMP) in Air	88 °F	1.5	.2184	6	12.5	0.12 / 0.35
10	16	in Transformer Oil	90 °F	4	.2184	5	12.96	0.83 / 0.91

Contd.......

S.NO.	Set NO.	Name of the Material	Room Temperature °F	Time Interval minute	Thickness of material. in m.m.	NO. of observations	Mean Value in KV	Variance/Standard Deviation
11	8	Polyster film in Air	86 °F	1.5	.1304	5	13.94	.008 / 0.089
12	18	in Transformer Oil	88.5 °F	4	Do	5	11.76	2.3 / 1.5
13	11	Glass micanite fibre in Air	88 °F	1.5	.2285	5	9.078	10.3 / 3.2
14	21	in Transformer Oil	90 °F	4	.2285	4	11.7	2.6 / 1.6
15	27	Elephantoid in Transformer Oil	90 °F	10 20 30	1.2407	5 5 5	26.68 26.44 26.36	1.47 / 1.21 0.09 / 0.30 0.54 / 0.74
16	25	Empire cloth in Transformer Oil	89.6 °F	10 20 30	.2178	5 5 5	13.08 12.48 12.82	2.99 / 1.73 0.57 / 0.75 1.7 / 1.29
17	26	Krempel in Transformer Oil	91 °F	10 20 30	.2707	5 4 5	11.32 11.15 11.7	1.19 / 1.09 0.81 / 0.9 1.3 / 1.15
18	24	Elephantoid in Transformer Oil	89.5 300 CC	10	1.2407	18	24.2	1.29 / 1.14

S.NO.	Set NO.	Name of the Material	Room Tempera- ture °F	Time Inter- val minute	Thickness of mater- ial in m.m.	NO. of observa- tions	Mean Value in KV	Variance/Standard Deviatio
19	28	Empire cloth with fixer	89 300CC	5	.2178	41	11.98	0.42 / 0.65
20	29	Krempel	89 °F	10	.2707	36	11.37	1 / 1.00
21	5	Transformer Oil only	85 °F	1	1.06	74	26.54	7.9 / 2.82