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BREAKDOWN OF INSULATORS:
Literature Search

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11 August 1977

Scientific Report No. 1

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Breakdown of Insulators: Literature Search

The irradiation of dielectric coated metal surfaces by incident magnetospheric fluxes generates problems related to the charging, breakdown and discharging of the dielectric insulator. The overall search objective is to locate and organize reference materials that address significant aspects of the problem. The study divides into ten somewhat independent subjects.

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Emphasis is placed on the readily available literature during the period up to and including 1961. The experimental measurements during this period were conducted under idealized conditions to achieve reproductibility. That is, the breakdown E field is externally generated and surface breakdown and premature breakdown through voids are suppressed.

To unify material, certain basic references concerned with solid state, transport and kinetic theory are cited where appropriate. A few references investigating recent breakdown theory are cited and briefly discussed. The bulk of the theoretical breakdown references and all of the experimental references that are cited in this report are for the time period prior to 1961.

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INTRODUCTION

This literature search on the electrical breakdown of insulators is motivated by problems related to satellites in synchronous orbit. Of these, the presence of discharge currents through external plasma or through dielectric insulating materials mounted on satellite conducting surfaces represent a possible source of undesireable electromagnetic energy. The literature search is oriented to the insulator breakdown aspect of this problem.

The search is designed primarily as a road map pointing to references that address various aspects of the problem. Time constraints preclude the latter approach in any case.

The total area of investigation is diagrammed in Figure 1 where ten somewhat independent topics ranging from the incident magnetospheric fluxes to the discharge current flow, are identified. Other schemes to categorize the search are, of course, possible; the intent is to provide a reference format that directs the search to important and critical areas and hopefully covers all the important topics.

1. AN OVERVIEW OF THE SEARCH

Before embarking on the search, an overview of the problem and of certain aspects of solid state materials is presented. The purpose is to further clarify objectives by pointing out basic topics and appropriate references concerning carrier behavior.

Similarly, a brief qualitative review of solid state aspects of transport and breakdown theory is given to aid in clarifying and anticipating topics that are considered in more detail in references cited at a later point. This allows citing references of a more general and basic kind that address relevant topics in solid state theory.

It is first noted that the realistic insulator condition of interest is the following:

- a thin slab of insulating material,
- mounted on a metal plate,
- and irradiated by a spectrum of particle and photon fluxes.

Thin, in this case, is not a dimension measured in layers of atoms or Angstroms as in thin film theory, rather metal thickness is of the order of Satellite construction materials and insulator thickness is of the order of heat shroud materials.

The breakdown E field for this configuration is generated by the charge separation induced by particles injected into the insulator slab. The electrical breakdown is consequently more complex than that of a thin insulator irradiated only by an externally generated E field. The portion of the literature search indicated by item 6 of Figure 1 addresses the latter problem. This is a subject much investigated both theoretically and experimentally and is extensively reported in the open literature.

The relationships of the breakdown E field to parameters such as temperature, thickness of insulator, duration of E field, frequency--as derived from the idealized insulator condition in category 6 of Figure 1 references, are assumed to provide basic information useful to an investigation under more realistic conditions.

It is important to note that experimentally measured breakdown E fields as reported in Category 6 references are obtained by preventing other discharges from disrupting measurements, that is by preventing surface breakdown (flashover and tracking) and internal breakdown in voids. Thus reported measurements are usually maximum measured breakdown fields. The presence of other discharges can adversely affect the reproducibility of measurements or introduce unacceptable scatter into data.

These considerations are important since they imply that surface breakdown may be the important phenomenon in some situations. Criteria have been proposed that allow judgments in this matter. (See Whitehead 1951, pages 8 and 9.)

Here the "breakdown strength" conductivity and dielectric constants of the insulator and external medium are compared to determine which is more susceptible to breakdown. It is noted, however, that the external medium at synchronous orbit differs radically from the ambient conditions at the earth's surface where most testing and measuring of breakdown fields has been done.

Because of the considerable literature on idealized breakdown, the Category 6 [illegible] (See Figure 1) is emphasized. Other categories were investigated at a cursory level.

At this point, the items in Figure 1 are considered more fully, as they apply to the realistic insulator condition of interest. The phenomena leading to discharge currents occur as follows:

- Incident magnetospheric fluxes produce charge separation within the insulator (2);

  Injected primary and secondary electrons within the insulator;

  A potential barrier at the surface;

  Reflected and emitted particles exterior to the insulator;

  Possible interior radiation damage to the lattice with the production of traps (1).

- The E field produced by charge separation electrically breaks down the insulator (6).

- Discharge streamers or channels are produced within the volume or on the surface (9).

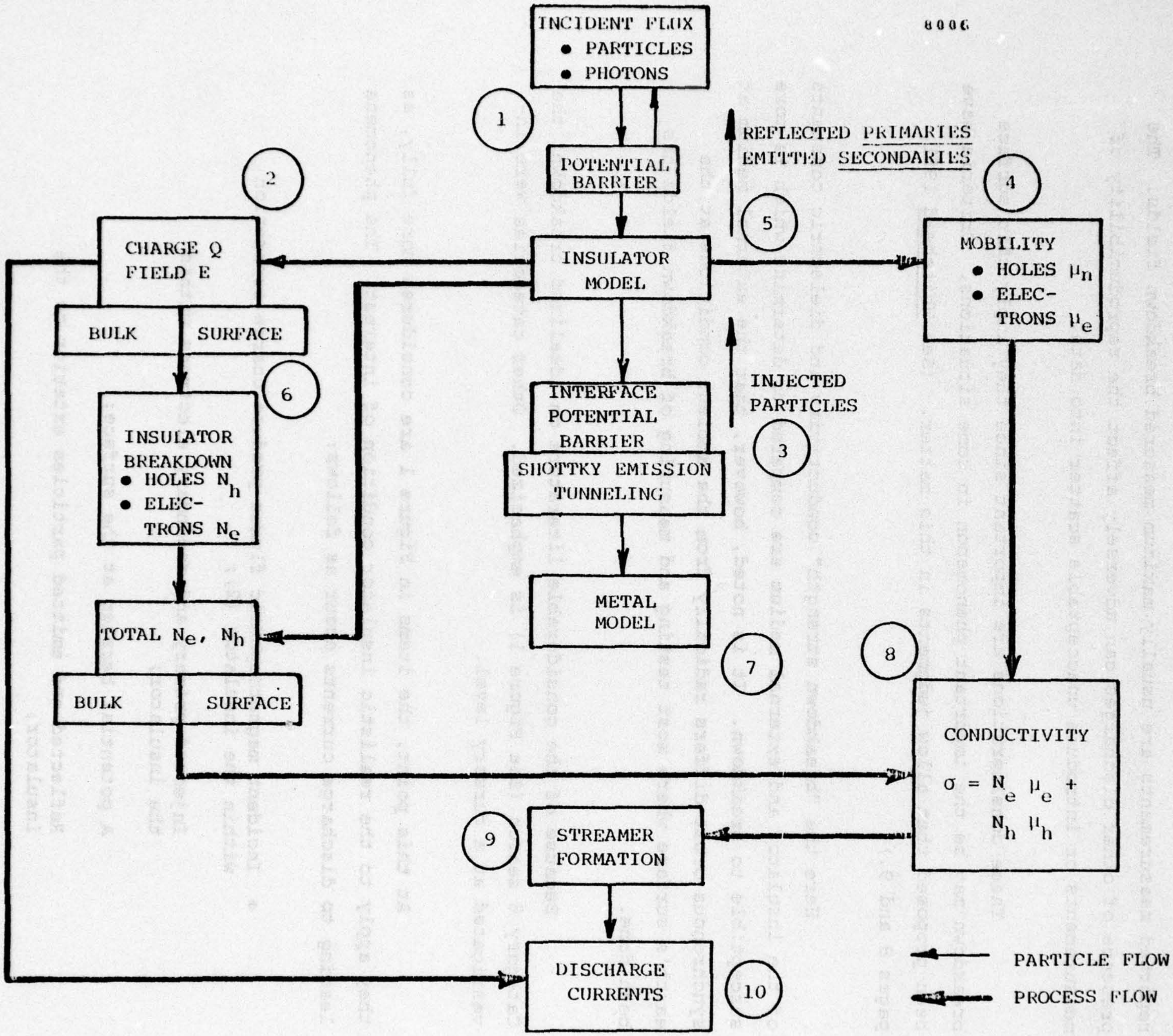


Figure 1 Flow Chart for Insulator Charge, Breakdown and Conduction

- The conductivity of channel or streamer is determined by (4), (6), and (8).

  When discharge channels grow to connect the regions of separated charge, discharge currents (2) flow until extinguished or a steady state is reached.

To estimate discharge current waveforms (10) requires that the time dependence of the above phenomena be predictable. Currents that flow prior to breakdown are of interest if they contribute significantly to radiation spectra.

To describe and predict much of the phenomena (1) -- (10) depends on the transport properties and equations for conduction carriers in the solid state activated by strong E fields. These are also basic to insulator breakdown mechanisms that include the absorption of E field energy by carriers in the conduction band and/or holes in the valence band and the subsequent transfer of energy to the lattice by collisions. Breakdown, as described more fully at a later point, is achieved either when lattice temperature exceeds a critical temperature T_c and/or the rate of lattice ionization becomes unstable. The transport equations make these predictions possible.

The differences in breakdown theories arise from variations in the insulator material and structure (crystalline or non-crystalline) and by variation of transport properties (heat and carrier conductivity, carrier mobility, diffusion coefficient, heat capacity), and also the photon and field environment, the initial density of conduction carriers, details of the transfer of carrier energy to the lattice, and the conduction mechanisms. There are currently believed to be five possible conduction mechanisms for non-crystalline insulators (see Lamb, 1967, Chapter 1 and associated references).

In a realistic situation, as has been noted, it may be necessary to predict where breakdown will be initiated: through the insulators bulk or in surface discharge through the external medium. This requires a comparison of breakdown strengths, conductivities and dielectric constants of the media as noted earlier.

Since these parameters, together with charge separation and discharge channel growth also determine discharge current waveforms, it appears the most relevant references are those concerned with the following properties and processes -- some of which must be known as functions of time:

- Charge separation and associated E field
- Conductivity
- Breakdown field strength
- Dielectric constant
- Discharge channel growth

All the above depend on the transport properties of solid state materials in a given temperature, E field, and injected particle environment.

2. TRANSPORT IN INSULATORS

A brief discussion of the transport equations allows an opportunity to observe where certain solid state reactions fit into the predictions of particle (carrier) behavior in insulators. The transport equations provide a math-physical model to describe the average behavior of an initial swarm of conducting carriers activated by E and H fields while interacting statistically with other particles and the insulator lattice.

There are three areas relative to the transport equations where solid state processes and mechanisms are considered. These are:

A. Processes that determine initial conditions and density of carriers under environmental conditions of E, H irradiation, temperature, externally injected particles and/or photons, and the boundary materials;

B. the transport equations which describe carrier dynamics after time t=0, or an equilibrium steady state condition; (the expressions apply to the conducting particles, which are usually electrons in the conduction band and/or holes in the valence bond); and

C. Mechanisms that determine the statistical interaction of carriers with other particles and the lattice.

In the classical kinetic theory Item C reactions appear in the collision integral of the Boltzmann Equation. The collision "cross section" or probability of a reaction together with the distribution function of the carrier (Fermi-Dirac in equilibrium) contain the statistical information that determines the time rate of change of the distribution function, f, due to the reaction.

The Items A, B, and C are now discussed and references made to appropriate literature sources.

2.1 Processes Determing Initial Conditions

The "initial" density of carriers in the conduction band of insulators can be strongly influenced (increased) by E fields as compared to the relatively small effect of thermally raising electrons in the valence band to the conduction band. The latter effect is small because of the large energy gap separating the two energy bands in insulators.

The above "field emission" mechanism has two simultaneous effects:

- A reduction of the potential barrier confining an electron to the valence band, a trap site, or to another medium at a boundary;
- an increase of the thermal energy of the bound carriers.

The mechanism is labelled Schottky emission when applied to emission through potential barriers at metal-insulator boundaries or emission from valence to conducting carrier states. It is labelled Poole-Frenkel when carriers are released from trapped states.

For details concerning these mechanisms, see Lamb, 1967, Chapter 6 and associated references.

A somewhat similar mechanism is the "tunneling" that can occur through "thin" potential barriers of the order of tens or hundreds of Angstroms. However, this mechanism is perhaps not applicable (except possibly at metal-insulator boundaries) to the relatively thick insulators of interest. Tunneling is also treated in Lamb, 1967, Chapter 5 and associated references are listed there. It is noted in Stratton, 1961, Page 236 that tunneling from valence to conduction band can occur for high E fields.

The basic mechanism of these phenomena requires first the determination of a local potential energy function (a "barrier" or a containing well) and its appropriate use in the single electron Schroedinger equation of quantum mechanics. The object is to find the probability of transmission through the potential barrier (in the case of "tunneling") or above the reduced barrier in the case of field emission. In similar fashion, the much-used energy band structure defines the bound valence band energies, the forbidden gap with embedded traps, and the energies and densities of nearly free conduction electrons. Here the potential function used in the Schroedinger equation is tailored to the particular solid state medium of interest, and the potential of trapped states is determined by field perturbations near defects.

For the treatment of energy band structure in crystalline media and elementary treatments of non-crystalline insulators, many basic tests on solid state theory are available (see Van der Ziel, 1957; Seitz, 1940; Slater, 1951; Kittel, 1968; and, Harrison, 1970). The references are listed in roughly ascending order of completeness and sophistication.

A modified energy band structure is expected to apply to non-crystalline insulators. For discussions of this subject, see Lamb, 1967, Chapter 2 and accompanying references and LeComber and Mort, 1973, Chapter 1, with accompanying references. Note also, a comment from a "state of the art" reference J. DeVreese, 1976, Page 438 regarding amorphous insulators:

"At present there appears to be wide-spread agreement that, if short range order in an amorphous state is the same as the crystalline, some basic features of electronic structure of the crystal are preserved. In particular, it is generally accepted that the energy distribution of the density of states remains essentially the same. Theoretical support to this idea has been put forward by Klima and McGill."

The possibility of photon absorption that allows carriers to climb a barrier potential or become released from traps into the conduction band is determined by the energy required of the photon and the mechanism for its absorption. This subject is basic to studies of the optical properties of insulators and of photoconduction. For survey discussions and lists of references on these subjects, current to about 1972, see LeComber and Mort, 1973, Chapter 13 (by E. A. Davis) and Chapter 15 (by J. Mort).

2.2 The Transport Equations

The five transport equations describe the time dependence or conservation of carrier density, the vector momentum (or current density) and the energy of carriers in solid state materials. The expressions apply usually to electrons in the conduction band and/or holes in the valence band, but may treat polarons or ions as carriers.

The "polaron" is a particle representation of an electron moving in a polar medium which characterizes some insulating materials. The electron distorts the polar structure which then reacts on the electron as though its mass had been increased. For a brief general discussion of polarons, see Kittel, 1968, Page 329. For a discussion of (small) polarons as they relate to non-crystalline disordered insulator materials see Lecomber and Mort, 1973, Page 261. These are the materials of most interest. An updated discussion of polarons is given in the reference J. Devreese, 1976, Page 409.

The carriers interact with fields and they interact statiscally with other particles and with the lattice. The Maxwell equations are also used to describe field interactions with the medium. The Poission equation is the equation most used in references encountered in this search. However, Wolk, 1973 uses the Maxwell equations in developing transport equations in generalized coordinates.

The transport equations formulate the conservation of carrier particle density, momenta and energy or their equilibria. In practice the expressions are generated at the simplest level by a single particle phenomenological theory. At the other extreme, use is made of the more complete and rigorous kinetic theory that deals, in principle, with swarms of particles.

In the latter approach, the dynamics of the swarm is determined by solving the Boltzmann equation for the distribution function f. Many simplifications are used and the carrier expected density, momenta and energy are determined by suitable integrations using f. (For a typical example of expansions in f used to facilitate solving the Boltzmann equation see Stratton, 1961, Page 255.)

An alternative, more approximate but simpler kinetic theory approach derives the transport equations directly by taking velocity (or momentum) moments of the Boltzmann equation. Here a form of f is needed to "evaluate" moments of the collision integral. The integral operations determine average carrier density, momenta, and energy.

The most complete transport equations are generated by using kinetic theory. Examples of this approach, as applied to solid state are given in considerable detail in the references:

- R. Stratton, 1961, Chapter 4
- W. Wolk, W, Granneman, 1973

The first reference considers kinetic theory applied to intrinsic breakdown of solid state insulators.

The second reference presents an extensive critical account of the use of kinetic theory applied to transport phenomena. It provides a summary example of the application of kinetic theory to determine certain transport coefficient terms appearing in transport equations which may be used and/or neglected in the single carrier phenomenological theories (e.g., electronic and heat conductivities, diffusion coefficient, thermoelectric coefficients, carrier mobility, heat capacity). Also developed here are the drift current and heat current densities (essentially first and second moment equations) to include thermoelectric properties and chemical potential as functions of carrier density. Also treated here are the transport processes of solids under electron bombardment.

Though dielectric breakdown is not discussed, the transport equations governing the absorption of E field energy by carriers and the subsequent transport of energy to the lattice by collisions are processes included in the general approach. These are basic mechanisms in breakdown theory.

The reference also develops in a concise and unified manner, the important solid state phenomena:

> Onsonger relation, Seeback effect, Peltier effect, Thompson effect, thermal conductivity, electrical conductivity and the Lorenz ratio. See Wolk, 1973, Pages 142-150.

The experimental measurement or sensing of these phenomena allow estimates of transport or solid state parameters.

At this point, in order to give some indication of the transport "mechanisms" involved, it is judged useful to present a simple form of the transport equations as derived by formally taking the zero, first and second velocity moments (or momentum (k vector) moments in quantum application). The form of the equations readily displays the coupling of the three equations:

- Carrier density continuity
- Carrier drift current or momentum balance
- Carrier energy balance

and the appearance of reaction terms (carrier collisions with lattice and other particles) that are modelled in the collision integral or its equivalent.

In the primitive form of interest, the equations are given. (See Spitzer, 1962, Allis, 1956) for the classical expressions). These require quantum modifications to describe initial conditions and the collision terms:

1. $\frac{\partial n}{\partial t} + \nabla \cdot n \vec{v}_d = X$, X= Reaction terms that increase or decrease the rate of change of n with time. Also source terms (secondary carriers) generated by absorption of other particles, (photons, primary electrons)

2. $\frac{\partial nm_* \vec{v}_d}{\partial t} + \nabla \cdot nm_* \overline{\vec{w}\vec{w}} - n\vec{F} = Y$, Y= Reaction terms that increase or decrease the rate of change of momentum with time

$= \bar{Y}$, $\bar{Y}$= $nm_* \nu_c \bar{v}_d$

is an approximate formulation where ν_c is the average collision frequency of carriers with "elastic" momentum exchanging particles (carriers with phonons and lattice imperfections)

3. $\frac{\partial}{\partial t} nm_* \overline{\vec{w}\vec{w}} + \nabla \cdot \underbrace{nm_* \overline{\vec{w}\vec{w}\vec{w}}}_{Q} - n\vec{F} \cdot \vec{v}_d = Z$, Z= Reaction terms that alter the rate of change of carrier energy with time

$\longrightarrow$ indicates vector

$\overline{}$ indicates average

See Wolk, 1973 for the transport equations expressed in generalized coordinates, and also the "hydrodynamic" version.

Although the expressions are written with carrier densities, momenta and energy in mind, they are formally applicable to the transport of any "particles" in the insulator medium.

The expressions apply to "classical" or quantum solid state particles but differ in the details of applying the required statistics. See Ziman, 1962 Page 264 for a discussion on this subject applied to the basic Boltzmann equation from which transport equations are derived.

The right hand side of the above expressions are derived from moments of the collision integrals (or the quantum equivalent). (See Ziman, 1962, Chapters III, IV, V, VI, VII.) Solid state theory is required here to define interactions among particles and the lattice.

In the equations n represents the carrier density (usually electrons in the conduction band and/or holes in the valence band), $\vec{v}_d$ is the drift velocity; hence, $nm_* \vec{v}_d$ is the reaction momenta of carriers, and the formally written term $nm_* \vec{w}\vec{w}$ of Equation 3 is related to carrier energy. Hence, 1 is a continuity equation of carrier density and 2 and 3 represent momentum and energy balance or conservation. m_* is the equivalent mass (quantum mechanically determined see Slater, 1951).

$\vec{F} = Q\,(\vec{E} + \vec{w} \times \vec{H})$ where Q is the charge.

$\vec{w}$ is the total velocity $= \vec{v}_d + \vec{U} \qquad |\vec{U}| >> |\vec{v}_d|$

and $\vec{U}$ is usually taken isotropic.

Carrier density $= n = \int f d^3 \vec{w}$, f is the distribution function.

$n\vec{v}_d = \int \vec{w} f d^3 \vec{w}$ and $\vec{v}_d$ is the average or drift velocity.

The term $nm_* \vec{w}\vec{w}$ relates to the energy of the carrier, hence 3 is seen to be an energy balance expression and can be converted to an approximate temperature balance under most conditions.

More specifically, the term $\nabla \cdot nm_* \vec{w}\vec{w}$ can be written approximately: $\nabla \cdot nm_* \vec{w}\vec{w} \simeq \frac{3}{2}\, kT\, \nabla n$ (where T is the carrier temperature) and $nm_* \vec{w}\vec{w} \simeq \frac{3}{2}\, kT$. Note in 3 that $\vec{F} \cdot \vec{v}_d$ represents energy absorbed from the E field by carriers. The energy lost to the lattice would be estimated by a term on the right hand side of Equation 3.

The heat tensor term $\bar{Q}$ is a complicating factor in Equation 3. ($\bar{Q}$ is the so-called heat flow tensor.) The term is discussed briefly in Spitzer, 1962. Buneman, 1961 applies a systematic analysis to Equation

3 with the heat flow tensor term equal to zero. M. Wolk, 1973 discusses certain weaknesses in the energy equation from other viewpoints.

The coupling of the transport expressions is readily noted: The "solution" of the energy expression in Equation 3 couples into 2 as a divergence term. Similarly, the solution of 2 for momentum couples into the continuity expression 1 as a divergence term. Hence, the "mechanism" for generating, for example, the various coefficients and approximate forms of the transport equations, and the coupling of thermal and electrical effects are derived from 1, 2, 3 by appropriate expansions conversions and/or simplifications. See M. Wolk, 1973 and Ziman, 1962 for details relevant to solid state applications.

The transport equations that are easier to use and understand are based on single carrier approximations. Here continuity, momentum or force or current equations and energy equations are used as derived by phenomenological considerations, and solved together with the Maxwell equations (the Poisson equation). Certain coefficient terms such as conductivity or diffusion coefficient are written in as required and evaluated by other means.

Some samples of this approach are given in:

- Franz's avalanche theory of intrinsic breakdown (see R. Stratton, 1961, Pages 248-251);
- Drudes classical theory of electrical conductivity (see Slater, 1951, Page 341);
- A theory of space charge limited currents in insulators (see Lamb, 1967 Chapter 4, and Tredgold, 1966).

In these references, relatively simple analyses provide a useful tool to investigate several important aspects of solid state transport phenomena.

There are obvious advantages to using simpler single electron theories. However, the subject of when it is valid to use them is not addressed here because no sources discussing this topic were found in the literature search.

2.3 Interaction of Carriers with Other Particles and the Lattice

The last item relevant to the transport equations considers the right hand side of the expressions 1, 2, and 3. Phenomenologically, these terms represent the collisional interaction of the carrier particle,

- in scattering collisions at sites of lattice imperfections. It is noted that imperfections generally scatter electrons more effectively than thermal phonons (see Ziman, 1962, Page 223,
- with lattice vibrations (phonons); that "scatter" the carrier (elastically);
- with excitons (bound electron hole pairs), this "particle does not contribute to conductivity until ionized by carrier impact or by photon absorption. It does transport energy in its unionized form; an interesting account of diffusion of excitons in molecular crystals is given in Kalman, 1961, Page 127;
- with lattice and traps in ionizing collisions;
- with other carriers of the same kind; this allows the carrier temperature to increase above the lattice temperature (see Stratton, 1961, Page 242);
- with recombining collisions of carriers with traps and holes (electrons) (see Johnson, 1973).

All the above processes require quantum mechanics to define the collisional mechanisms and probabilities.

The above interactions have been described as a "gas of excitations" relative to the carrier (see Ziman, 1962, Pages 2, 3, 257). The idea, supported by the particle-like modelling of reactions in solid state theory, provides a conceptual advantage with regard to transport processes because of the similarities with classical kinetic theory applied to transport processes in gases.

Not all the above (excitations) are relevant or important in a given material or application. Generally, the most important transport processes are those of the conduction carriers and of the thermal lattice vibrations and/or defects (see Ziman, 1962), and their interactions. Thus, transport expressions are characteristically generated using the relevant or important aspects of 1, 2, and 3 for a particular application.

Under the extreme conditions of carrier activation by high E fields, ionizing reactions and their statistics becomes important, particularly for breakdown theories. For a treatment of ionizing collisions by impact, see Stratton, 1961, Section 4.7.

Ideally, kinetic theory requires the solution of the Boltzmann equation for the distribution function f with the ionizing and recombining processes included in the collision integral. Apparently such analysis has not been successfully achieved to date. Consequently, breakdown theories are approximate and inaccurate to a somewhat unknown degree.

For elementary discussions of phonons, excitons, polarons, thermal transport of phonons and lattice imperfections, see Kittel, 1966. For discussions and formulations regarding phonon-phonon, electron-phonon, electron-lattice imperfection scattering, and electron-electron interactions, see Ziman, 1962. This reference also includes a treatment of thermal phonon transport in Chapter VII on "Lattice Conduction" that is more complete than Kittel.

For up-to-date discussions of transport processes in insulators, see J. DeVreese, 1976, particularly the first chapter on General Theory.

For more complete treatment of polarons, see Chapter 7 of LeComber, 1973.

A discussion of considerable practical importance relevant to transport processes is given in Ziman, 1962, Chapter XI on size and surface effects.

For an experimental and theoretical treatment of electron trapping and transport, see W. Johnson, 1973.

For a "state of the art" discussion of electronic properties of amorphous semi-conductors, with a list of references spanning 1960 - 1972 period, see DeVreese, 1976, pp. 435 - pp. 465.

3. DIELECTRIC BREAKDOWN

3.1 Introduction

This section addresses in more detail the Category 6 items of Figure 1 which were briefly discussed in the previous section. There are two main objectives. The first is to present references to breakdown theories in current use, together with brief descriptions. The second objective is to present references to experimental results.

There is a wide range of insulator materials; the main classification is the state of crystallinity. Most materials used for heat shroud uses are non-crystalline insulators (teflon, kapton, mylar, and polymeric films and coatings). Silica fabrics and silvered dielectrics have also been proposed. For descriptions of experimental investigations of these materials in simulated satellite environments, see K. G. Balman, 1976; W. Saylor, 1976; V. Robinson, 1976; and others in USAF/NASA, 1976. Though silica and silvered insulators have been cited as possible materials, it nonetheless appears that references that investigate non-crystalline insulators are the most relevant.

The goal of breakdown theories is to determine the magnitude of the E field at which the insulator breaks down, and there are various criteria used or proposed to define the breakdown conditions. The transport equations, describing the conservation of carrier density and of momentum and energy in the solid state environment, are a unifying element in all breakdown theories. It is usually an instability in the number density of the carrier or of carrier energy that is used as the breakdown criterion.

As has been noted earlier, the E field causing breakdown is produced by charge separation within the insulator as generated by particle and/or photon irradiation of the insulator. Photons, depending on their energy and the quantum energies of trapping sites, can fill or release carriers from traps thereby storing or releasing charge. See Johnson et al., 1973, for examples of theoretical and experimental investigations using 1) soft X-ray charging and thermal discharging to locate the energy of shallow traps, and 2) internal photoemission charging and optical discharging to locate the energy of deeper traps (3.5 ev below conduction band).

Injected particles (electrons) may be trapped up to a saturation point (see Lamb, 1967, Pages 23-29), thus, providing a charge separation mechanism that varies with time up to the saturation level.

The number and kinds of traps generally are much greater in non-crystalline insulators than in crystalline insulators, and have a pronounced effect on the charge storage potential. Consequently, the charge separation mechanism is a particularly important part of the breakdown process for irradiated non-crystalline insulators.

The charge separation is dependent on the energy of incident particles and on the highly variable surface structure of the insulator (i.e., the large and variable number of trap states that exist at surfaces). For theoretical and experimental investigation of charge storage due to trapping see W. Johnson, M. Lampert, August, 1973. Also, see A. Epstein, 1975, Chapter 2 on charge relations in MOS Systems, and see Leadon et al., 1976, Chapter 4 on charge storage in polymers. For effects of charge separation on conductivity see Lamb, 1967 and Tredgold, 1965. For a study (mostly experimental) of charge injection, storage and release in mylar and teflon insulators see J. Azariwicz, 1973. For a theoretical study with parallel experimental investigation of the polymer naphthalene, see J. Azariwicz, 1972.

The most relevant experimental references, in view of the above statements about materials and the E field, are those directly investigating breakdown for the specific materials of interest and under the proper simulated conditions to produce charge separation and the resulting breakdown E field (i.e., irradiation by simulated magnetospheric fluxes). One reference (USAF/NASA, 1976) provides abstracts concerning experimental measurements of this kind, but little actual data is presented. It is expected that quantitative experimental data will be forthcoming on the experimental studies reported in this reference.

Other available references located by the search concerning breakdown of irradiated insulators do not use the materials and irradiating fluxes of most interest. However, some examples of references of this kind are cited below.

As an approximation to the irradiated conductor-insulator configuration of interest, a typical irradiated MOS structure might yield useful quantitative information, or identification of trends or of appropriate mechanisms. A reference that considers such structures is A. Epstein et al., 1975. Although breakdown is not specifically discussed here, the radiation effects on phenomena related to the overall mechanism of breakdown are investigated (induced space charge, conductivity, the physics of solid-solid interfaces and of charge relationships). This reference surveys and cites about 137 references on these and related topics.

For a reference that investigates the modelling of ionization and recombination effects on irradiated MOS structures see R. Leadon, 1976. These are important processes in the breakdown mechanism.

Finally, as an example of recent experimental and theoretical studies of irradiated non-crystalline insulators see W. Johnson, 1974, 1975 and 1976. This work includes breakdown investigation of SiO_2 insulator mounted on Si semiconductor.

The following conclusions were reached regarding the search for experimental investigations of breakdown in insulators:

- Little data was located regarding breakdown measurements using the specific materials (insulators) and irradiating fluxes of interest. Though the report NASA, 1976 describes ongoing experimental programs to investigate breakdown under the required simulated conditions, little data was available at the time of this writing from these sources.

- The experimental data that is reported on breakdown of insulators covers experimental measuring programs up to about 1960, which are extensively covered in the literature. These data are obtained under idealized breakdown conditions, the most important being an externally generated E field and the suppression of flash-over, tracking and internal discharge. The purpose of these early measurements was to obtain basic data and also to test theory which dealt with somewhat idealized conditions. The insulator materials investigated and that are reported upon are both crystalline and non-crystalline; although they are not the materials of specific interest. However, it is expected that the insulator materials of interest will have properties within the range of those reported.

The material to follow is organized in two parts:

- Breakdown Predictive Theories
- Breakdown Comparative Measurements

3.2 Breakdown Predictive Theories

It is convenient to report breakdown theories in two groups: those prior to 1961 and those later. Two important surveys regarding theoretical breakdown in insulators (dielectrics) cover the period previous to 1961 (see Whitehead, 1951, and Stratton, 1961). These surveys cite 260 references in the open literature. Though many breakdown theories for various applications were generated after 1961, only four are reported here. They differ to some degree from the earlier theories. The later theories will first be described. See Budenstein, 1975; W. Johnson, 1974; Kidley, 1975; Hayes, 1973; and, Nekrashevich, 1971.

3.2.1 Some Recently Proposed Breakdown Theories

Of the later theories, Budenstein, 1975 is perhaps the most "revolutionary". The motivation here is described as an attempt to develop theory consistent with experimental evidence. This theory assumes breakdown is initiated when a localized charge density reaches a critical value. Chemical bonds are then disrupted, which frees lattice particles to form a high temperature, high pressure gas of electrons, ions, atoms and/or molecules. Hence, the critical breakdown criterion is the breaking of the chemical bonds. A mechanism for channel or streamer growth is part of the theory, and breakdown proceeds as for a high T, high P gas. This work is presently ongoing in two phases: study of the channel growth process, and fundamental theoretical study involving the bond breaking process. Some modification of tradition energy band theory is involved. Several references by the same author that are related to his breakdown theory are given in this report. Time did not permit acquiring and examining them.

The reference Hayes, 1973 investigates breakdown in a gaseous plasma immersed in a strong E field, but doubtless the theory can also be applied, in modified form, to solid-state plasmas. This theory defines breakdown using criteria dependent of the zero moment continuity equation of carrier density, formulated as a boundary value problem. The equation of continuity is solved by a variational numerical technique and the minimum eigen value defines breakdown. Similar variational techniques to solve the Boltzmann equation are discussed in Ziman, 1962, Page 275. The mathematical treatment allows the estimate of the minimum breakdown field as well as the maximum. A maximum estimate is the usual result of variational formulations. However, it is more important in practical usage to be able to predict the minimum breakdown field, hence, the special value of this analysis.

In Johnson, 1974, a breakdown model is developed to describe the insulator SiO_2 breakdown in a SiO_2, Si slab configuration. The theory proposes Fowler-Nordheim tunneling at irregularaties of SiO_2-Si interfaces. (For a basic treatment of this tunneling mechanism, see Fowler, 1928. The theory has undergone considerable extensions since the original formulation). The tunneling produces local high current and heating. Positive ions from SiO_2 drift to irregularities and increase the E field. Positive feedback ensues with consequent thermal runaway. Hence, the breakdown condition is defined from a form of energy balance equation. The reference Ridley, 1975 is a more complete development of this theory by one of the investigators. This pattern of breakdown has some resemblance to "internal field emission breakdown" discussed in Stratton, 1961.

The reference Nekrashevich, 1971 proposes and develops a simple one dimensional breakdown theory based on a macroscopic single particle representation of the energy transport equation (second moment) that includes an energy term representative of non-electrical processes. The equation is solved for total current density, allowing for appropriate boundary conditions at boundary interfaces. The breakdown criterion uses an instability of the total current.

An interesting consequence of this approach is the possibility of predicting reduction or increase of the E field required for breakdown caused by non-electrical contributations to the energy equation.

Realistic applications of the theory may require extending the analysis to two or three demensions. The weaknesses in the use of the energy equation should be considered as discussed in M. Wolk, 1973. The overall simplicity of the approach should not obscure the fact that heat capacity and the conduction and ionization coefficient terms, whose use is implied, are functions of the temperature, the solid-state parameters, and implicitly of the E field. The calculation of currents at boundaries, where tunneling or field emission may occur, requires separate investigation. However, boundary currents should be consistent, at least approximately, with a first moment transport equation in the interface boundary region where much trapping can occur in insulators.

3.2.2 Breakdown Theories Before 1961

As has been noted earlier, two references are available that critically survey the literature of the theoretical breakdown of dielectrics. These are S. Whitehead, 1951 and R. Stratton, 1961. These two reports, and the 260 references they cite covering the period up to 1961 are the sources of the brief description that follow. Another survey report in this time period (see Mason, 1959) contains most of the summary experimental material referenced in section 3.3. This survey work contains 115 references of a theoretical and experimental character as applied to the breakdown of solids.

As will be discussed more fully, all the breakdown criteria use a version of the energy transport equation (3) of page 12. Using the equation, the breakdown criteria postulates an equilibrium or instability in the energy

$$\frac{\partial E}{\partial f} \geq 0$$

where E is the carrier energy. E is represented formally in equation (3) by the term

$$E = nm_* \overline{\vec{w}\vec{w}}$$

If the latter quantity is reduced to a scalar $\frac{1}{2}nm_* w^2$, E can be related to T. Then:

$$\frac{\partial T}{\partial t} \geq 0$$

becomes a breakdown criterion.

The solution of the breakdown equation then provides a critical field F_c such that breakdown occurs when $F \geq F_c$.

In view of certain difficulties inherent in the heat or energy equation (see Wolk, 1973; Spitzer, 1962; and Buneman, 1961), its use to define a breakdown condition could be too restrictive or inaccurate in some situations. However, references discussing these limitations and their possible role in preventing a match between theory and experiment were not located in the search. Rather, the scatter in experimental measurements and deviations from theory of experimental results are generally assumed to originate from variability in materials, boundary, surface conditions and other experimental parameters. The difficulties in acquiring reliable measured data are surveyed in Mason, 1959, and O'Dwyer, 1958.

Two general categories of breakdown theories are identified:

- Thermal Breakdown (see Stratton, 1961 and Franz, 1958)
- Intrinsic Breakdown

Intrinsic breakdown is further subdivided into:

- Collective Breakdown
- Avalanche Breakdown
- Internal field emission breakdown

These are discussed in Stratton, 1961, Pages 235-236.

In general, breakdown is said to occur when enough energy has been transferred to the lattice that the lattice temperature T_o exceeds a critical temperature T'_o. This usually required an unstable increase of carrier energy E, and consequently the breakdown condition is not sensitive to the precise value at T'_o.

As has been noted, the energy balance equation is a unifying feature of all the breakdown theories discussed and referenced in this section, and as they appear in the referenced surveys (see Stratton, 1961). The equation is a form of equations (3) (see page 12) and is conveniently written:

4. $$\frac{dE}{dt} = A(F,E,T_o) - B(E,T_o)$$

where

E is the carrier energy (formally represented by $nm_* \overline{\vec{w}\,\vec{w}}$ of equation (3))

$A(F,E,T_o)$ is the rate energy is absorbed from the $\vec{E}$ field. It is represented by $\vec{F} \cdot \vec{v}_d$ in equation (3) and represents a gain of carrier energy since $\vec{v}_d$ is in the direction of $\vec{F}$.

$B(E,T_o)$ is the rate energy is transferred to the lattice. It is represented by appropriate energy moments of the collision integral (or its solid state equivalent) on the right side of equation (3). Collisions of carriers with the lattice (phonons) is the chief reaction (see Stratton, 1961, Pages 240, 254).

F if the applied E field intensity.

T_o is the lattice temperature.

The various theories use different means of estimating A and B in equation (4). Since breakdown is characterized by

$$\frac{dE}{dt} \geq 0,$$

the above equation becomes the breakdown equation by asserting:

$$(A - B) \geq 0,$$

and usually:

$$(A - B) = 0$$

is taken as the breakdown criterion. The equation is then solved for the breakdown field F.

3.2.2.1 Thermal Breakdown

Thermal breakdown uses the same form of energy balance as eq (4). However, when this equation is applied to a macroscopic heat balance of a volume of insulator, the form $\frac{dE}{dT}$ becomes $VC_v \frac{dT_o}{dt}$ and applies to the lattice energy, not the carrier energy (C_v is the lattice heat capacity, T_o the lattice temperature, and V the volume of insulator).

The heat loss term A now becomes the heat lost at the insulator surfaces to the ambient medium $D(T_o, T_a)S$ where S is the area, T_o is lattice temperature, T_a is ambient temperature.

The heat gained (or absorbed) is expressed

$$B = \frac{\sigma F F}{J}$$

where σ is the conductivity (a transport property). σ depends theoretically on the number of density of carriers and the mobility.

$$\sigma \simeq N\mu$$

The mobility depends primarily on the collision reaction of carriers with the lattice imperfections and phonons. See Kittel, Page 215, and Lamb, 1967, LeComber, 1973 and Mott, 1971 for more extensive treatment of conductivity applied to non-crystalline materials, which are the type of most interest.

The heat equation can be solved to estimate t_F , the formative time lag:

$$t_F \simeq C_v \int_{T_a}^{T'_o} \frac{dT_o}{\sigma(T_o,F)F^2 - D(T_o,T_a)\frac{S}{V}}$$

This time lag is characteristic of thermal breakdown. Note also that the term S/V indicates that size is a factor in thermal breakdown.

Thermal impulse breakdown is defined when F is large enough in equation (5) so that the last term D S/V may be neglected.

A transport term K (the heat conductivity) is needed in the evaluation of D. Thus, the three transport terms C_v, σ and K are needed to evaluate the breakdown equation. Discussion of these important terms at a rather basic level are available in Kittel, 1968. For more complete and unified discussion, see Wolk, 1973: For more complete discussion of thermal breakdown see Stratton, 1961 and Franz, 1958.

3.2.2.2 Collective Breakdown

The mechanism of collective breakdown operates when the density of carriers n is large enough so that inter-carrier collisions exceeds collisions with the lattice phonons and imperfections. The energy absorbed by carriers from the E field (which is designated F to distinguish it from energy E), then is distributed among carriers in a Maxwellian distribution that allows the carrier temperature T to rise above the lattice temperature To. The criterion that determines when collective breakdown operates is $n > n_c$, where n_c is a critical electron density. For discussion of n_c . see Stratton, 1961, Pages 243, 263 and 264.

Since the distribution function f is Maxwellian under collective breakdown conditions, the average rate terms in the energy equation which provide the breakdown equation can be evaluated using the Maxwellian distribution function. See Stratton, 1961, Page 242 and Shockley, 1951).

The energy balance expression for collective breakdown becomes approximately

$$\frac{d}{dt}\left(\frac{3}{2}\,nkT\right) = \overline{A}(F,T,T_o) - \overline{B}(T,T_o)$$

where T is the carrier temperature

T_o is the lattice temperature.

The breakdown $F = F_B$ is determined from

$$(\overline{A} - \overline{B}) = 0$$

and $\overline{A}$ and $\overline{B}$ are averages of A, B obtained by using the Maxwellian distribution function f.

For more detail in solving for the breakdown field $F = F_B$, see Stratton, 1961, Page 242. It is noted that a characteristic of collective breakdown is that when $F > F_B$, the breakdown is very rapid. (Temperature of the lattice T_o reaches T_o' rapidly.) This differentiates collective breakdown from avalanche breakdown and thermal breakdown, which proceed more slowly.

It is noted that the survey reference Stratton, 1961 includes collective breakdown criteria for crystalline materials that contain a significant number of trapped carriers (see Stratton, 1961, Page 243).

For details of these analyses using single carrier theories, see Stratton, 1961, Pages 242-244. For details of collective breakdown analyses using the kinetic theory techniques, see Stratton, 1961, Pages 263-268 and Pages 268-269. Also, see Fröhlich, 1947 and O'Dwyer, 1957.

3.2.2.3 Avalanche Breakdown

When the initial carrier density $n < n_c$, then breakdown proceeds by ionization of the lattice. Those carriers having ionizing energy or greater, ultimately produce cumulative avalanching of the electron density. It is possible that when $n > n_c$ that collective breakdown then takes over.

The distribution function f is difficult to determine in this case because of the ionizing and recombination processes that must then be accounted for in the Boltzmann equation. This impinges on the accuracy with which collisional reactions of the carrier with the lattice and other particles can be known theoretically.

Approximate estimates of breakdown fields when $n < n_c$ are based on interelectronic collisions being negligible compared to electron-lattice collisions, and the requirement that enough carriers of the swarm have energy $E > I$, where I is the ionizing energy. This criterion has made possible a formulation for high energy and low energy breakdown criteria. The reference Stratton, 1961 discusses an approximate formulation of the low energy breakdown of Von Hippel (see Stratton, 1961, Page 239-242) and the high energy criterion of Fröhlich (see Stratton, 1961, Pages 244).

For details of the high and low energy criteria and breakdown fields using the refinements of kinetic theory, see Stratton, 1961, pages 269-273. For details of a single carrier avalanche multiplication breakdown. see Stratton, 1961, Pages 244-248. For avalanche multiplication breakdown including holes, see Stratton, 1961, Pages 248-252. These are relatively simple average carrier theories. For details of avalanche multiplication breakdown using many of the refinements of Kinetic theory, see Stratton, 1961 and Franz, 1956.

It is noted that the thickness of insulator material is a factor in avalanche breakdown (see equation 185, Stratton, 1961) whereas collective breakdown is not influenced by material size. Furthermore, the breakdown field F_B is expected to increase rapidly as the thickness L decreases, up to some limiting $L = L'$. The time influence (a formative time lag in avalanch breakdown similar to thermal breakdown) is indicated in the avalanche breakdown equation (3a) in Stratton, 1961, Page 250.

It is noted that avalanche breakdown theories require many simplifications; the most severe resulting from the influence of ionizing and recombining processes. It is remarked in Stratton, 1961, Page 284, that improvements in existing theory require investigation of non-homogeneous electron distributions and the effect of recombinations (neglected in existing theory) on the impact ionization rate.

3.2.2.4 Internal Field Breakdown

The density of free carriers can be increased by the action of an external E field causing tunneling or field emission from the valence band. For a discussion of this mechanism, see Stratton, 1961, Page 252-253 and Franz, 1956, and Zener, 1934.

Again, the energy balance equation is used to define breakdown by equating the heat required to increase the lattice temperature to the breakdown $T_o = T_o'$, to the heat absorbed by carriers in the conduction band from an E field of intensity F:

$$\int_0^{t_F} JFdt = e\mu F_B^{\ 2} \int_0^{t_F} ndt = C_V\,(T_o - T_o')$$

The carrier density n is a function of time as determined by the tunneling rate (a quantum determination). The dependence of mobility μ on carrier collisions has been briefly referred to elsewhere. However, to repeat these references relating to non-crystalline materials, see Lamb, 1967, LeComber, 1973 and Mott, 1971.

3.3 Breakdown Comparative Measurements

The breakdown prediction theories referred to in the previous section demonstrate that the breakdown field varies significantly with temperature, insulator thickness, and the time to breakdown in the case of thermal and avalanche breakdown. These theories also predict a variation of breakdown strength with the frequency of AC fields.

However, as noted in Mason, 1959, because of the very intense fields required for breakdown (on the order of 1 to 15 M Volts/cm), strong electrostatic compressive forces are present (plus mechanical stress heating) which can cause failure before the electrical breakdown is realized. Consequently, breakdown measurements often must be made at relatively low temperatures and in short times. Hence, use is frequently made of impulse testing (pulses of short duration) for measuring intrinsic breakdown field strengths.

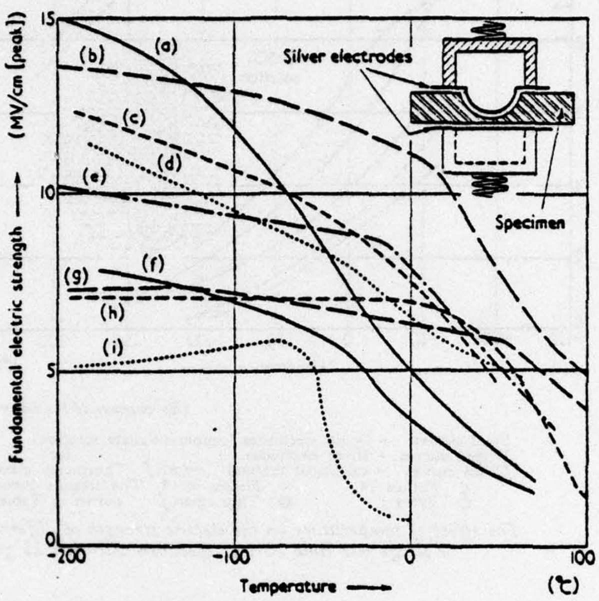
The phenomona of surface breakdown and internal breakdown within insulator voids also limit the ability to measure the intrinsic breakdown field predicted by theory.

The references Mason, 1959 and Whitehead, 1951 present representative breakdown data as a function of the variables cited above for a limited number of insulator materials, both crystalline and amorphous. The latter class of material is more relevant to the objectives of this survey

The comparative data reproduced here originates in the above reports. Time has not permitted an extensive examination of the original sources listed in their bibliographies.

3.3.1 Breakdown Field Strengths VS Temperature

The variations of breakdown field strength of amorphous substances as a function of temperature has been most successfully predicted by Fröhlich See Fröhlich, 1939 and Whitehead, 1951, Pages 37-48. In this theory a critical temperature T_c is defined above which intercarrier collision rates exceed collisions with the lattice. This is the definition of collective breakdown as discussed earlier (see Stratton, 1961). Below T_c, the dielectric strength (breakdown field) increases with temperature, but decreases with temperature when $T > T_c$. The trends in breakdown strengths of the polymers in Figure 1 bear out these predictions. It is expected that the following data should provide ballpark estimates for similar materials.



(*a*) Polyvinyl alcohol
(*b*) Polymethyl methacrylate
(*c*) Polyvinyl chloride-acetate
(*d*) Chlorinated polythene (55 per cent chlorine)
(*e*) Chlorinated polythene (8 per cent chlorine)
(*f*) Clear baking oil-varnish
} Polar

(*g*) Polystyrene
(*h*) Polythene
(*i*) Polyisobutylene
} Non-polar

(*By courtesy of the Institution of Electrical Engineers*

Electric strength/temperature characteristics of long-chain polymers (*Ball and Oakes*[1])

Figure 2 (See Mason, 1959, Page 4)

The trend of higher breakdown fields for polar polymers is consistent with a "polaron" carrier of relatively high effective mass.

It is instructive to compare the above amorphous insulator breakdown strengths with those produced in another kind of amorphous insulator, glass, shown in Figure 3.

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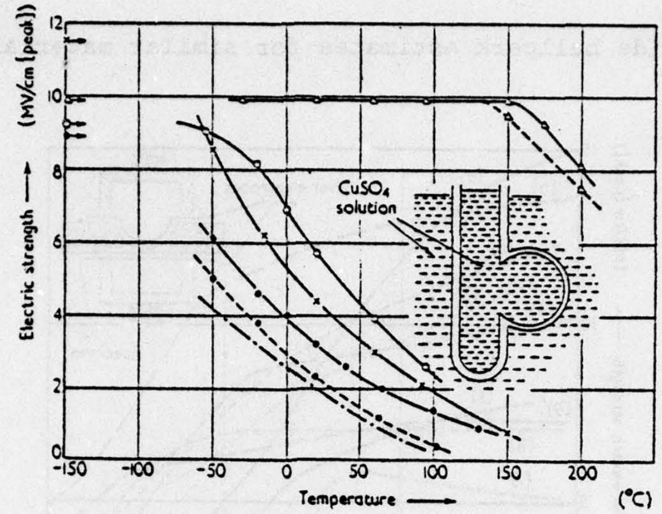


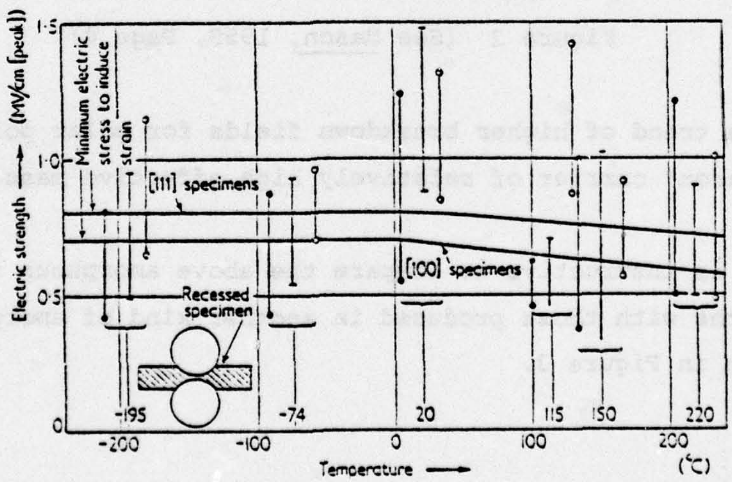
(By courtesy of the editor, 'Physica'

Solid curves - liquid electrodes (copper-sulphate solution)
Dotted curves - silver electrodes } for
Chain curves - calculated thermal strength } Thuringian glass
△ Philips 18 × Philips 08 } The alkaline content is
○ Pyrex ● Thuringian } shown in Table 2

The effect of temperature on the electric strength of different glasses
Voltage rise time 30 sec; specimen thickness 25 microns

Figure 3 (See Mason, 1959, Page 8)
(See Vermeer, 1956)

Finally, the variation of breakdown strength with temperature of a familiar crystalline insulator material is shown in Figure 4.



(By courtesy of the Physical Society

Temperature dependence of electric strength of potassium-chloride crystals, showing variation with the direction of the applied field

Figure 4 (See Mason, 1959, Page 14)
(See Cooper, 1953, 1957)

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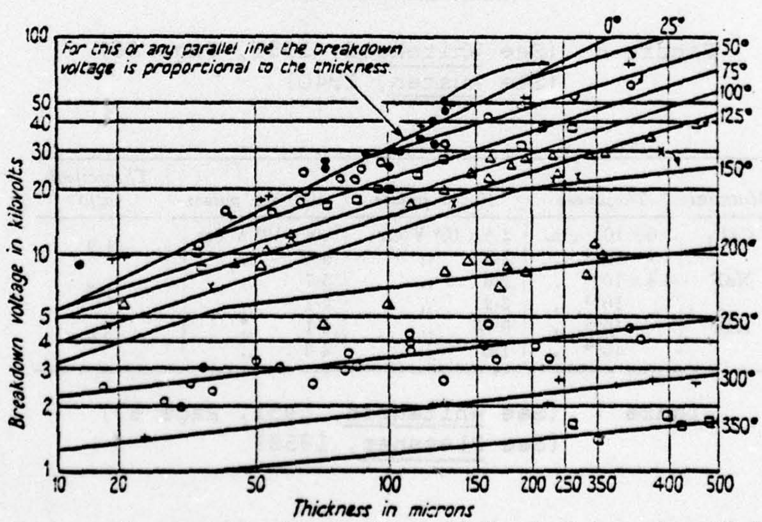
A tentative conclusion here is that crystalline material has intrinsic breakdown strengths about 1/10 that of polymer insulators, and amorphous glass insulator resembles nonpolar polymer substances most in breakdown characteristics. It would be unwise to generalize on these estimates.

3.3.2 Breakdown Strength VS Thickness

As noted in the section on predictive theories, both thermal breakdown and avalanche intrinsic breakdown depend to some degree on insulator size (thickness). For a discussion of thickness effects, see Whitehead, 1951, Pages 83-89, and Fröhlich, 1947. Some sample measured values of breakdown strength for glass, mica and the highly crystalline salts C_aF_2 , N_aF KB_r are given below. It is noted that amorphous insulators show less dependence on thickness, probably due to the smaller mean free path (see Whitehead, 1951, Page 87).



Variation of breakdown voltage of hollow lead glass spheres (G-I glass) with temperature and thickness.

Figure 5 (See Whitehead, 1951, Page 83)
(See Moon, 1933)

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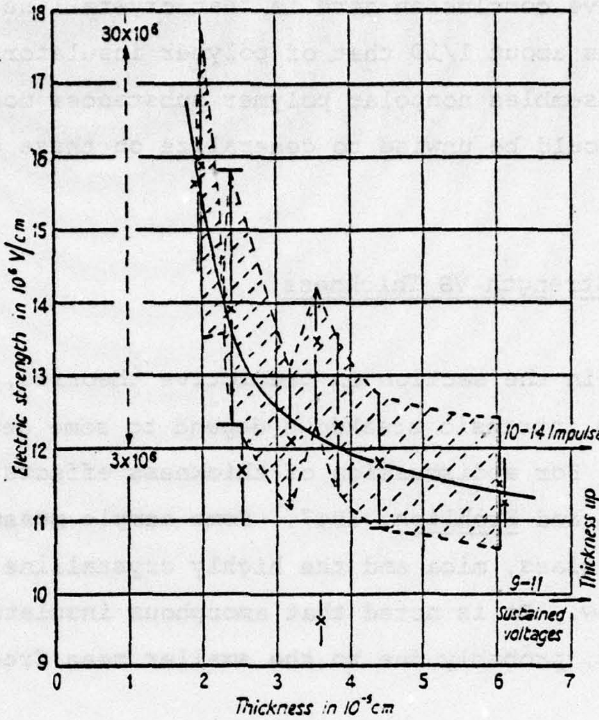

Electric strength of clear ruby muscovite mica.
× indicates mean value.
Vertical lines indicate range of dispersion.
(Austen and Whitehead.)

Figure 6 (See Whitehead, 1951, Page 86)
(See Austen, 1940)

Material	*Thickness*	*10-sec. pulses*	*10^{-5}-sec. pulses*	*Theoretical ratio*
CaF_2	6×10^{-5} cm.	$2{\cdot}8\times10^6$ V/cm.	$4{\cdot}6\times10^6$ V/cm.	1·9
	10^{-5} ,,	2·8 ,,	6·4 ,,	
NaF	$4{\cdot}4\times10^{-5}$,,	2·6 ,,	5·7 ,,	1·7
	10^{-5} ,,	3·2 ,,	7·1 ,,	
KBr	10^{-4} ,,	0·75 ,,	2·1 ,,	2·6
	10^{-5} ,,	1·6 ,,	4·8 ,,	

Figure 7 (See Whitehead, 1951, Page 87)
(See Plessner, 1958)

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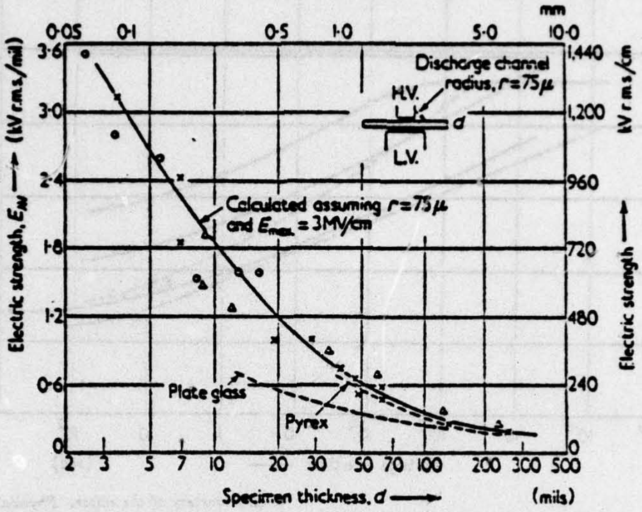

(By courtesy of the Institution of Electrical Engineers

Variation with thickness of the 1 min electric strength of sheet insulation tested in clean oil at 20° C. The solid curve is calculated; the dotted curves and points are experimental values

Figure 8 (See Mason, 1959, Page 44)

3.3.3 Breakdown Strength VS Time

References to analyses of breakdown strengths using the energy balance equation indicate that thermal and avalanche breakdown involve time lags and breakdown fields reduced in strength as the duration of the E field is increased. For a discussion of time effects and impulse breakdown see Whitehead, 1951, Pages 89-96.

The time lag calculated (the so called formative time lag) is, theoretically, the time for the electron (carrier) temperature to become very large (see Whitehead, 1951, Page 93). The calculation does not include the time for a discharge channel to be formed, a process much longer to accomplish. The measured time lags are usually larger than the formative time lags that are calculated. Data reported in Mason, 1959 for time lag effects are given to indicate the magnitude of these effects on the breakdown field. These include a comparison of the breakdown of glass for an E field having various rise times, see Figure 9, and includes data relevant to the operation of longer processes (the failure of polyethelene with the number of cycles of E field), see Figure 10. Discussion of the longer time processes is given in Mason, Pages 43-48.

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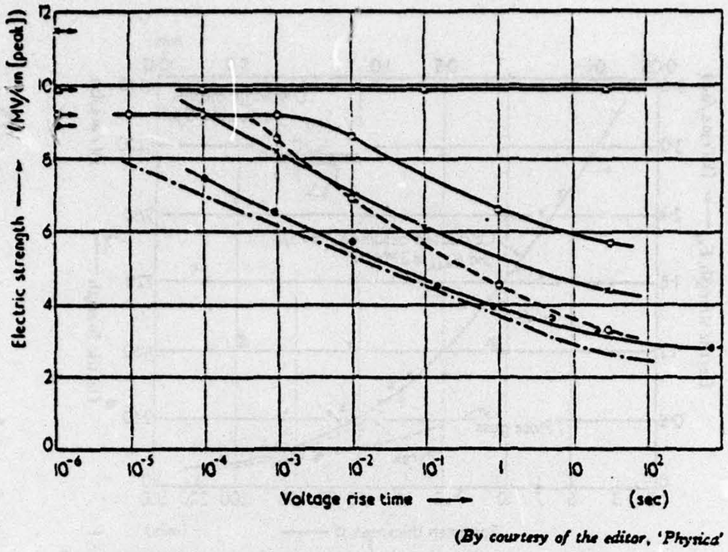
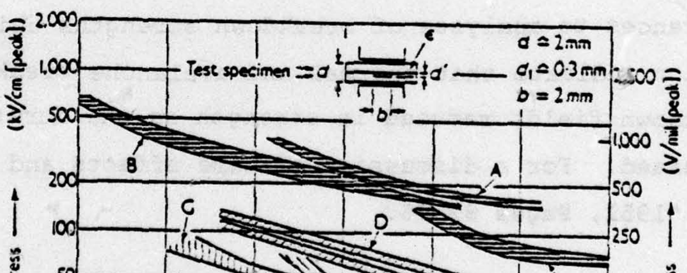


(By courtesy of the editor, 'Physica'

Solid curves – liquid electrodes (calcium-sulphate solution)
Dotted curve – silver electrodes
Chain curve – calculated thermal electric strength } for Pyrex glass
△ Philips 18 × Philips 08
○ Pyrex ● Thuringian

The effect of voltage rise time on the electric strength of different glasses at 20° C; specimens 25 microns thick (Vermeer[14, 15])

Figure 9 (See <u>Mason</u>, 1959, Page 10)
(See <u>Vermeer</u>, 1956)



(By courtesy of the Institution of Electrical Engineers

A, B; polythene cables (Howard[44]). C; disk specimen of polythene. D; plasticized polystyrene. E; non-plasticized polystyrene. F, H; phenolformaldehyde with nylon and cellulose filler (F, with moulded cavity; H, with machined cavity). G; nylon

The life of insulation in the presence of internal discharges

	A	B	C	D and E	F and H	G
Permittivity ε	2·3	2·3	2·3	2·6	5·6	4·0
Discharge inception stress: kV cm⁻¹(peak).. ..	137	100	35–50	28	18	20

Figure 10 (See <u>Mason</u>, 1959, Page 28)

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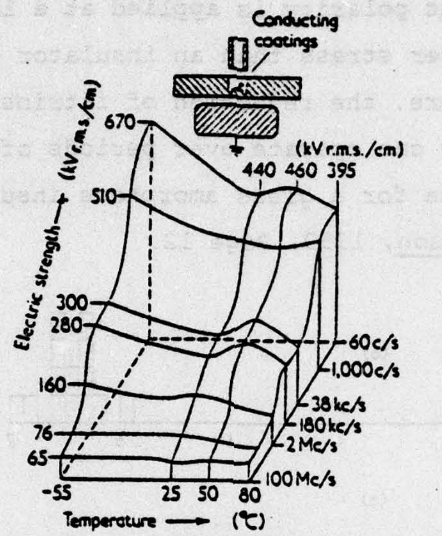
3.3.4 Breakdown Field VS Frequency

An interesting display of the effect of frequency and temperature on the breakdown of polyethylene are given in Figure 11, which is taken from Mason, 1959, Page 7.



(By courtesy, American Institute of Electrical Engineers

The effect of frequency and temperature on the electric strength of polythene

Figure 11

A comparison of AC and DC behavior of the polymers polythene and polystyrene are displayed in Figure 12 which is taken from Mason, 1959.

Comparison of a.c. and d.c. Electric Strength Values for Polythene and Polystyrene, in the Absence of Discharges[10]

Temperature (°C)	Electric strength (MV cm⁻¹ (peak)) ± Standard Deviation			
	Polythene		Polystyrene	
	a.c.	d.c.	a.c.	d.c.
−196	7·7 ± 3 per cent	8·0 ± 4 per cent	6·7 ± 3 per cent	7·0 ± 8 per cent
−95	7·1 ± 8 per cent	7·4 ± 4 per cent	7·1 ± 4 per cent	6·7 ± 7 per cent
17	3·8 ± 26 per cent	7·2 ± 7 per cent	6·3 ± 13 per cent	6·8 ± 5 per cent
70	—	—	5·5 ± 12 per cent	6·6 ± 5 per cent

The test specimens were between 10 and 60 microns thick.

In these tests the stress was increased at a steady rate such that the breakdown voltage of about 30 kV was attained in about 30 sec. With polythene the a.c. electric strength at 20° C was some 30 per cent lower than the value shown above, if the stress was increased in 2·5 kV steps at 30 sec intervals.

Figure 12 (See Mason, 1959, Page 7)

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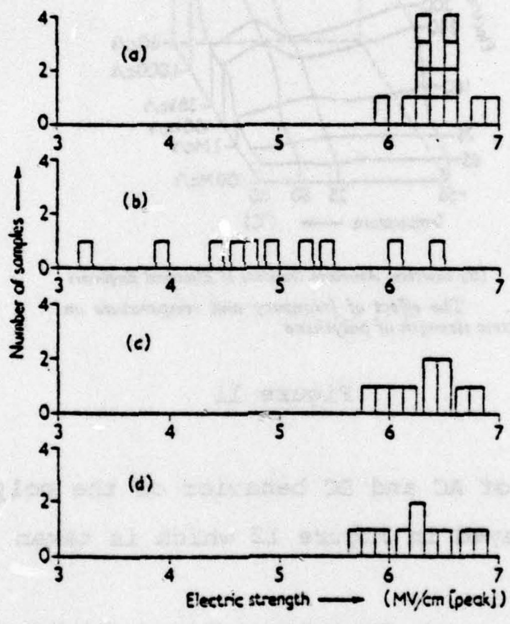
3.3.5 Breakdown Strength VS Prestressing

Insulators can build up a space charge to oppose the applied electrical E field stress. Hence, when external stress is removed, the remaining space charge can continue to electrically stress the insulator. If an external field of the right polarity is applied at a later time, the insulator may break down at a lesser stress than an insulator that has not undergone prestressing. Furthermore, the reduction of intrinsic breakdown strength of prestressed insulator can operate over periods of several hours. An example of this phenomena for a glass amorphous insulator is displayed in Figure 13, taken from Mason, 1959, Page 12.



(By courtesy of the editor, 'Physical Review'

(a) No prestressing. No annealing
(b) Prestressed at 1·3 MV cm^{-1}. No annealing
(c) Prestressed at 1·3 MV cm^{-1}. Annealed afterwards for 3 hr at 150°C
(d) No prestressing. Annealed for 3 hr at 150°C

Decrease of electric strength of glass at 20° C due to space charges formed during prestressing

Figure 13 (See Mason, 1959, Page 12)

3.3.6 Flashover and Tracking

Breakdown by surface discharges is discussed in Whitehead, 1951, Pages 223-233 and in Mason, 1959, Pages 31-48. Surface breakdown is roughly divided into two phenomena: flashover and tracking. Flashover is a gaseous discharge external to the surface and causes no permanent impairment of the surface insulating properties. Tracking discharges take place wholly or partially within the insulator and on its surface. Permanent impairment can occur. For more detail on these processes, see the above references. Measured data on a few insulating materials are given in Mason, 1959 where, certain empirical expressions in use are presented with critical comment. Whitehead, 1951, provides mainly a discussion with tentative conclusions provided by investigators working in the field.

For examples of more recent work in this area, see M. Mulcahy, 1971 and K. Bouchard, 1968. The latter reference is concerned with surface discharges on metal surfaces. A more recent reference is M. Akahane, 1974, which reportedly contains 17 additional references, but has not been reviewed for this survey.

3.3.7 Internal and Partial Breakdown

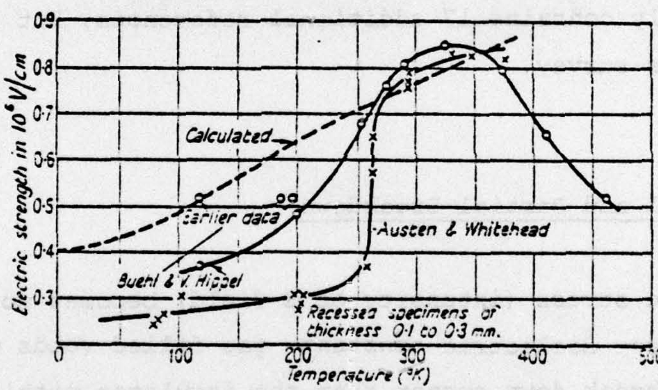
Because stress (intensity of E field) becomes more intense in regions of lesser dielectric constant, gas filled voids within insulator materials can break down sooner than the insulator within which they are embedded. Mason, 1959 discusses this phenomenon and presents: empirical formulae in use; some equivalent circuit representations; photographs of breakdown channels; and some representative data for breakdown occurring for direct voltages, surges, and alternating voltage, each for a limited number of materials, some of which are non-crystalline substances. In addition, a section on mechanisms of deterioration by internal discharges is qualtatively summarized for a number of non-crystalline materials with a number of references to sources in the open literature.

Whitehead, 1951 discusses similar material and includes external gas discharges and the detection of discharges. Since this work is a survey, as is Mason, 1959, the material is well referenced to sources in the open literature.

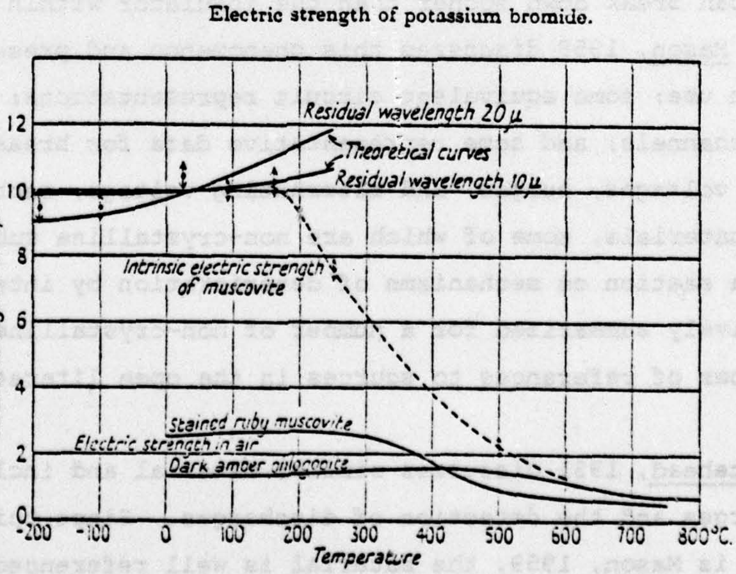
3.3.8 Comparison of Predictions and Breakdown Measurements

Samples of comparisons between measured and predicted breakdown fields are not extensively reported in the survey literature encountered on this search. However, a fair amount of representative experimental data is reported and also, a few empirical laws are discussed in Mason, 1959 and Whitehead, 1956. By using the theoretical prediction theories referred to elsewhere, and the reported experimental data, comparisons could be made by using appropriate theoretical calculations. Since time did not permit this exercise, the predictions reported here are derived from the limited amount available in the reference surveys Mason, 1959, Stratton, 1961, and

EFFECT OF TEMPERATURE



Electric strength of potassium bromide.



Electric strength of mica.

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Figure 14 (See Whitehead, Page 77)

Whitehead, 1951. Though limited, it is felt these comparisons are representative because of the survey nature of the three references. No doubt an examination of the numerous original references cited in these reports would reveal many more comparisons between theoretical and experimental data.

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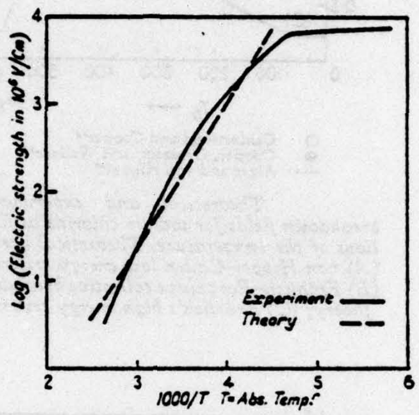
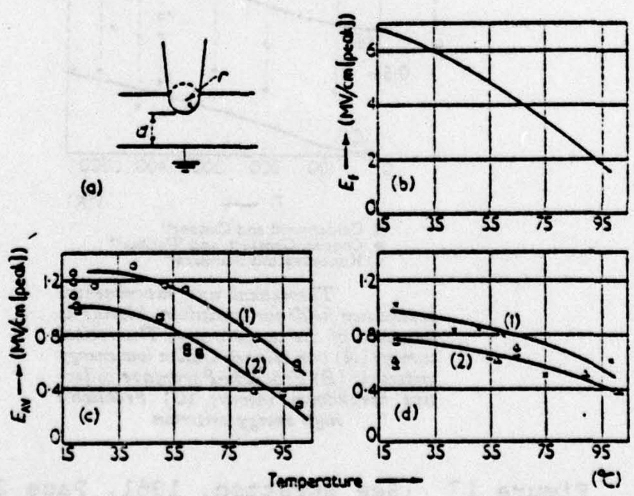


Comparison of Fröhlich's theory with von Hippel and Maurer's experiments on glass.

Figure 15 (See Whitehead, 1951, Page 81)

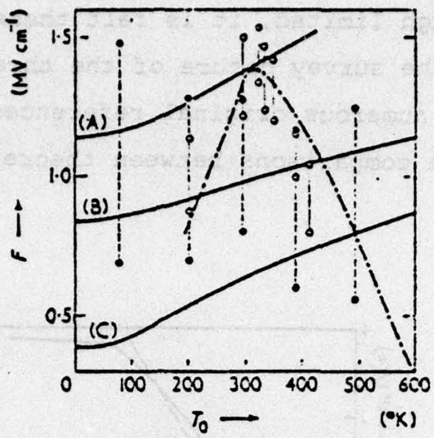


(By courtesy of the Institution of Electrical Engineers

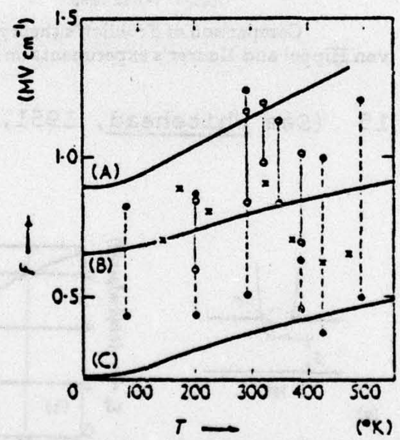
(*a*) Point-plane electrode system.
(*b*) Fundamental electric strength.
(*c*) Tests with a negative point.
(*d*) Tests with a positive point.
(Electrode separation ~ 300 microns in curves (1) and ~ 550 microns in curves (2)

Variation of the fundamental and divergent field electric strengths of polythene with temperature

Figure 16 (See Mason, 1959, Page 17)



Theoretical and experimental breakdown fields for sodium chloride as functions of the temperature. Theoretical curves: (A) von Hippel–Callen low energy criterion; (B) Fröhlich–Paranjape collective breakdown theory; (C) Fröhlich's high energy criterion



Theoretical and experimental breakdown fields for potassium chloride as functions of the temperature. Theoretical curves: (A) von Hippel–Callen low energy criterion; (B) Fröhlich–Paranjape collective breakdown theory; (C) Fröhlich's high energy criterion

Figure 17 (See <u>Stratton</u>, 1961, Page 279)

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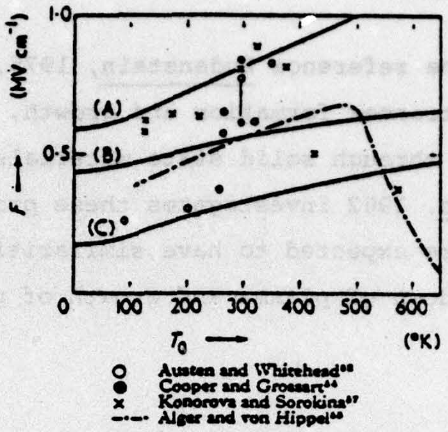
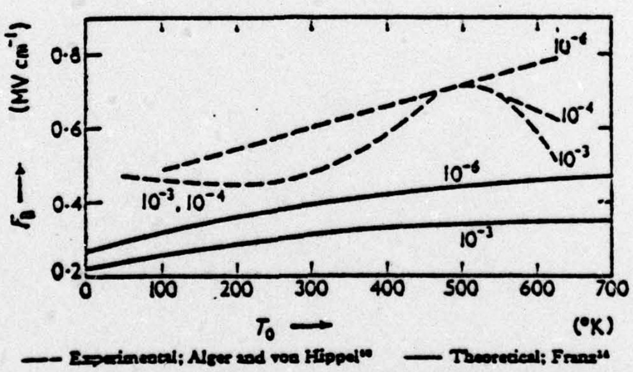


Theoretical and experimental breakdown fields for potassium bromide as functions of the temperature. Theoretical curves: (A) von Hippel–Callen low energy criterion; (B) Fröhlich–Paranjape collective breakdown theory; (C) Fröhlich's high energy criterion

Figure 18 (See Stratton, 1961, Page 280)



Experimental and theoretical avalanche breakdown fields for potassium bromide at various temperatures. The numbers next to each curve refer to the formative time lag (in seconds) for the theoretical curves and the time of application of the saw tooth pulse for the experimental curves, respectively

Figure 19 (See Stratton, 1961, Page 283)

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3.3.9 Discharge Channels

Except for the reference Budenstein, 1975, which cites on-going theoretical work on streamer formation and growth, no sources investigating streamers or channels through solid state materials were located. However, the reference T. Dakin, 1962 investigates these processes for gaseous media. The mechanisms here are expected to have similarities to the solid state case, since the breakdown of plasma and growth of plasma columns is involved in each case.

SUMMARY

The literature search on dielectric breakdown identifies references that contribute to a relevant and realistic overview and that are consistent with the objectives and applications of the search. A preliminary investigation served to categorize the search into ten somewhat independent topics.

Since not all topics could be reviewed, the search emphasizes the literature most extensively reported and that investigates parameters of dielectric breakdown chosen to be fundamental in nature. Most of this type of work was performed prior to 1961. Much of the theoretical work of this period is in current use, but a need to revise and expand it is recognized. The accompanying experimental investigations are performed under carefully controlled external conditions that differ from the magnetospheric environment. Nevertheless, the measured breakdown data that examines the variation of breakdown strength with basic parameters is intended to be useful for general conditions.

Some of the reference sources cited examine breakdown of insulators irradiated by particle fluxes. However, the materials, their configuration and the characteristics of the incident flux do not match those of specific interest. Investigations of the specific materials and similated magnetospheric environment are in progress (USAF/NASA, 1976).

Because the breakdown of the insulator lattice depends on the transport properties of carrier particles in their solid state environment, certain topics in solid state, transport and kinetic theories are cited where relevant. These topics are a unifying element in breakdown theory and are referenced for that reason.

The important breakdown work prior to 1961 is reported and referenced in three existing survey reports of the period. These have been much used in this report. Breakdown theory of more recent vintage is reported to a lesser degree. All experimental data reported is from the pre-1961 period.

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