
**ELECTRICAL PROPERTIES
OF
CABLE INSULATION MATERIALS**

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Paper-Insulated Lead Covered Cables

PILC-Fundamentals

INSULATION MATERIALS

- MEDIUM VOLTAGE
 - Polyethylene[PE]
 - Crosslinked PE [XLPE]
 - Tree Retardant Crosslinked PE [TR-XLPE]
 - Ethylene-Propylene Elastomers [EPR]
 - PILC
- HIGH VOLTAGE
 - Crosslinked Polyethylene
 - PAPER/OIL
 - Paper/Polypropylene [PPP]
 - SF6 Gas

PILC

- Cable is comprised of Paper strips wound over conductor with construction impregnated with dielectric fluid (oil)
- Long Service History
- Reliable/used since late 1800s
- Gradually being replaced by Extruded Cables

PILC

- Paper derived from wood
- Wood
 - Cellulose 40%
 - Hemicellulose 30% Poor Electrical Properties
 - Lignin 30% Serves as adhesive
- Cellulose must be separated from others
- Separation by bleaching
 - sulfate/sulfite process

PILC

- CELLULOSE-Insulation Material
- HEMICELULOSE-Non-fibrous
 - more polar
 - losses higher vs. cellulose
- LIGNIN-Amorphous
 - binds other components in the wood

Paper/Oil

- Cellulose chemical structure more complex vs. PE or XLPE
- Oil impregnates the cellulose/superior dielectric properties
- Different cable constructions for Medium vs. High Voltage

Paper/Oil

- LEAD SHEATH over cable construction
- Protects cable core
- Benefit: Superior barrier to outside environment

COMPARISON OF CABLE INSULATION MATERIALS

PE / XLPE / TR-XLPE /EPR / PILC

Polyethylene

- Low Permittivity: limits capacitive currents
- Low Tan Delta: Low Losses
- Very High dielectric strength (prior to aging)
- Easy to process/extrude

Crosslinked Polyethylene

- All of the above PLUS
- Improved mechanical properties at elevated temperature
 - does not melt at 105°C and above
 - thermal expansion
- Improved water tree resistance vs. PE

Tree-retardant XLPE

- All of the above PLUS
- Superior Water tree resistance to XLPE
- TR-XLPE properties brought about by
 - Additives to XLPE
 - Modifying the PE structure before crosslinking
 - Both

Paper/Oil PILC

- Long history of reliability
 - some cables installed 60 or more years !
- More tolerant of some common diagnostic tests to ascertain degree of aging
 - DC testing

EPR

- Compromise of extruded cable properties
 - Permittivity, Tan Delta > XLPE's
 - Dielectric strength slightly lower
- High temperature properties :
 - Equal to or > XLPE's

Advantages of Extruded Cables

- Reduced Weight vs. Paper/Oil
- Accessories more easily applied
- Easier to repair faults
- No hydraulic pressure/pumping requirements
- Reduced risk of flammability/propagation
- Economics
 - Initial and lifetime costs

Extruded Cables at High Temperatures

- PE/XLPE/TR-XLPE
 - At elevated temperatures, crystalline regions start to melt
 - Thermal expansion
 - Physical/mechanical strength reduced
 - At 105°C crystallinity gone:
 - PE flows
 - XLPE and TR-XLPE crosslinking allows for maintenance of FORM stability
 - At high temperatures, crosslinks substitute for the crystallinity at low temperature

Extruded Cables at High Temperature

- PE/XLPE/TR-XLPE
 - Although Crosslinks serve as Crystallinity substitute, they do NOT provide same degree of
 - toughness
 - moisture resistance
 - Impact resistance
 - Crosslinking assists in maintaining form stability, but not mechanical properties
 - Physical/electrical properties change as temperature increases

Extruded Cables at High Temperature

- EPR
 - Little to no crystallinity initially
 - Form stability maintained due to presence of inorganic mineral filler (clay)
 - Physical and electrical properties change to some extent as temperature is increased
 - Present day issue: operating reliability at higher temperatures vs. semicrystalline polymer insulation

Paper/Oil at High Temperature

- Cellulose: No significant thermal expansion
 - compare with extruded cables
- Oil: Some thermal expansion
- Degradation mechanisms differ at elevated temperature

Thermal Degradation

- Paper/Oil
 - Cellulose degradation consistent from batch to batch
 - Starts to degrade immediately under thermal stress
 - Moisture evolves
 - Follows Arrhenius model
 - Oil may form wax over time(Polymerization)
- Extruded
 - Degradation is polymer structure related
 - Degradation related to antioxidant efficiency
 - Does not start until stabilization system affected
 - No water evolution
 - No proven model exists

Summary: Paper/Oil

- Natural Polymer
- Carbon/Hydrogen/Oxygen
- More polar
- Not Crosslinked
- Linear Fibrils/no thermal Expansion
- Oil expands thermally
- Thermal degradation of cellulose at weak link (C-O)
- DC : No harmful Effect on Aged cable-does remove weak link

Summary: Extruded Materials

- Synthetic Polymer
- Carbon/Hydrogen
- Less Polar
- Branched chains
- Non-fibril
- Partly crystalline: much less for EPR
- Mineral fillers (EPR)
- Thermal expansion on heating
- Crosslinked
- Degrades at weakened regions/crosslinks 'hold together' form stability
- DC: Latent problem -effect depends on age (XLPE)

Electrical Properties

**Determined By Physical and Chemical
Structure**

Polyolefin Properties

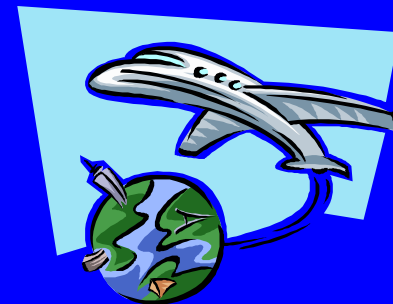
□ Electrical properties/General

- Dielectric constant
- Dissipation factor
- Volume resistivity
- Dielectric strength

❖ Polyolefin properties

- Structure/property relationships
- Dielectric strength
- Partial Discharge

❖ Measurement Methods



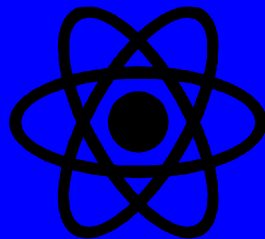
Electrical Properties of Polyolefins

- The Electrical Properties of Polyolefins may be separated into two categories:
 - Those observed at low electric field strengths
 - Those at very high field strengths
- LOW FIELD
 - Dielectric constant/dissipation factor
 - Conductivity
 - *Determines how good a dielectric is the insulation*
 -
- HIGH FIELD
- -Partial discharges (corona)
 - *Controls functioning and reliability*

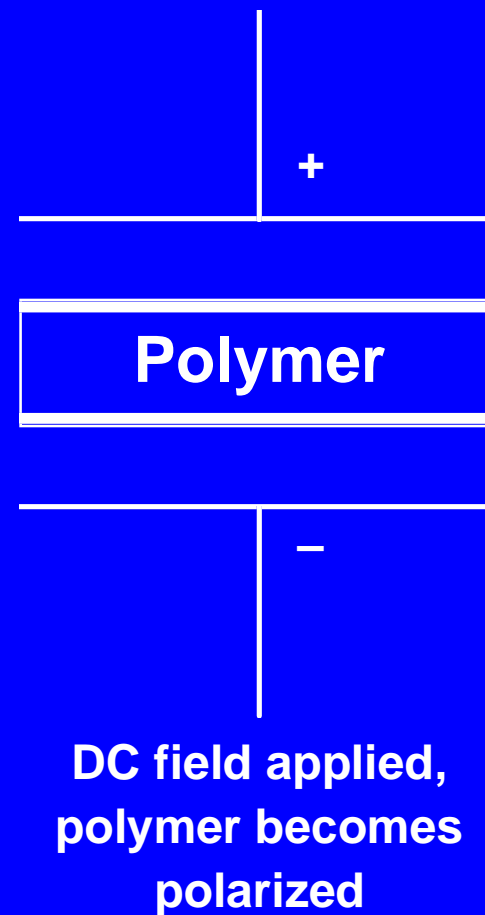
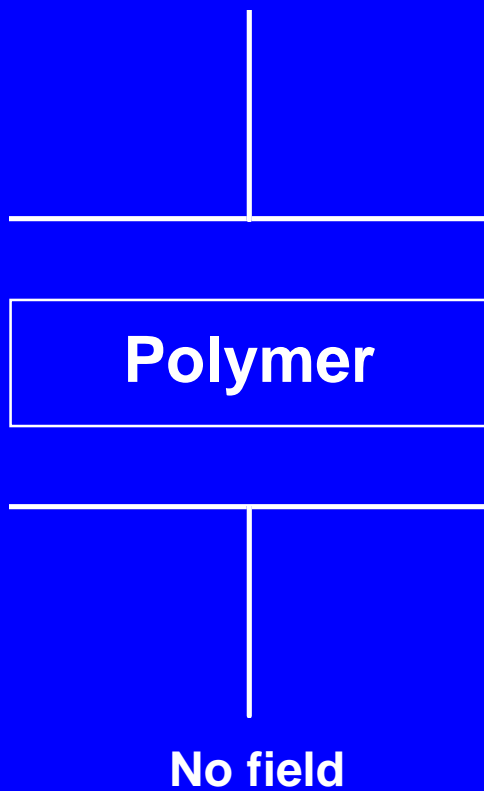


How does Polymer Insulation Respond to Voltage Stress

- Polar Regions tend to migrate toward electrodes
- Motion Limited
- Insulation becomes slightly 'mechanically stressed'
- Charge is stored
- Properties change
- Next few slides seek to picture events in idealized terms

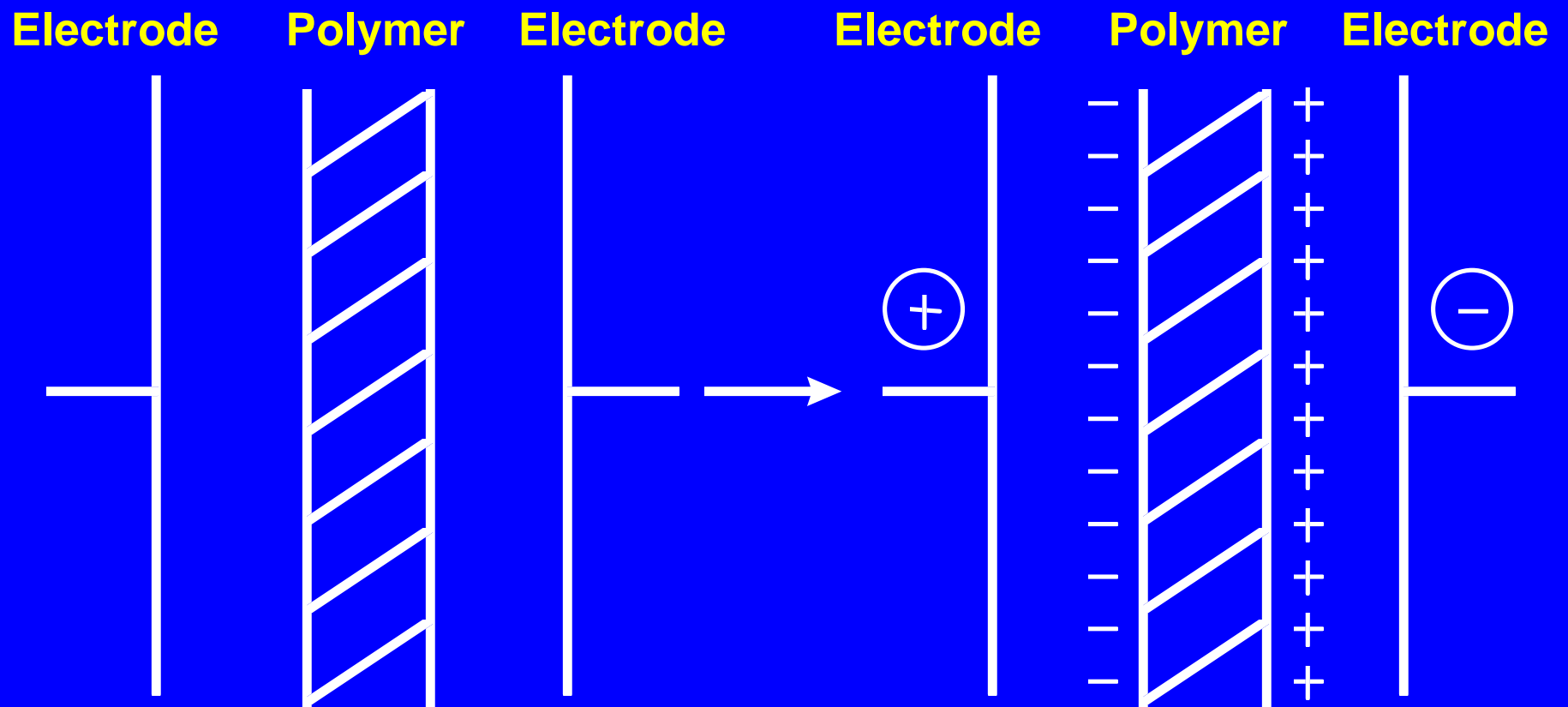


POLARIZATION OF A POLYMER THAT CONTAINS MOBILE CHARGE CARRIERS



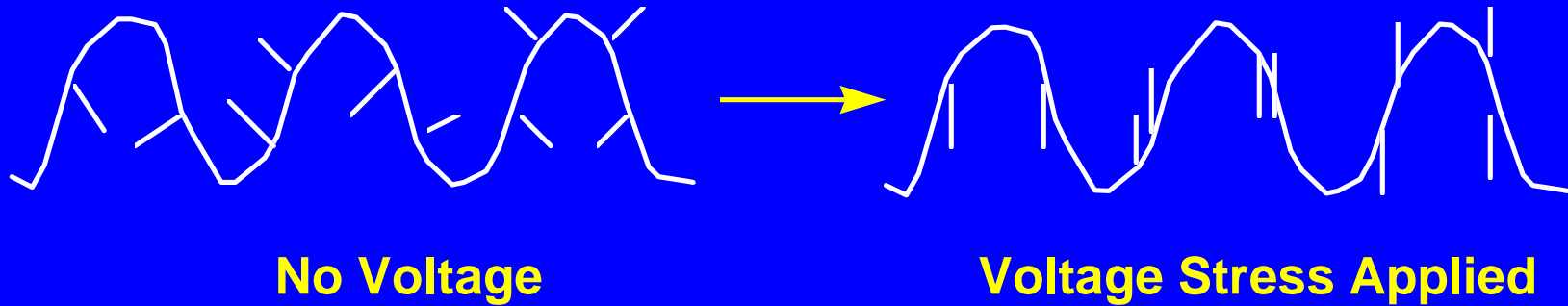
ORIENTATION OF POLYMER UPON APPLICATION OF VOLTAGE STRESS

Alignment of Charge Carriers



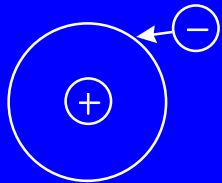
IDEALIZED DESCRIPTION

orientation of polar functionality of polymer chains under voltage stress

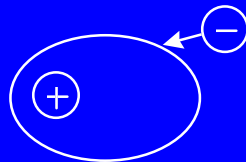


What happens to Dielectric when Field Applied?

NO FIELD



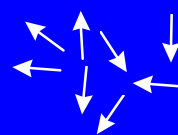
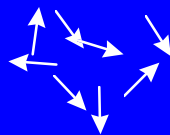
FIELD APPLIED



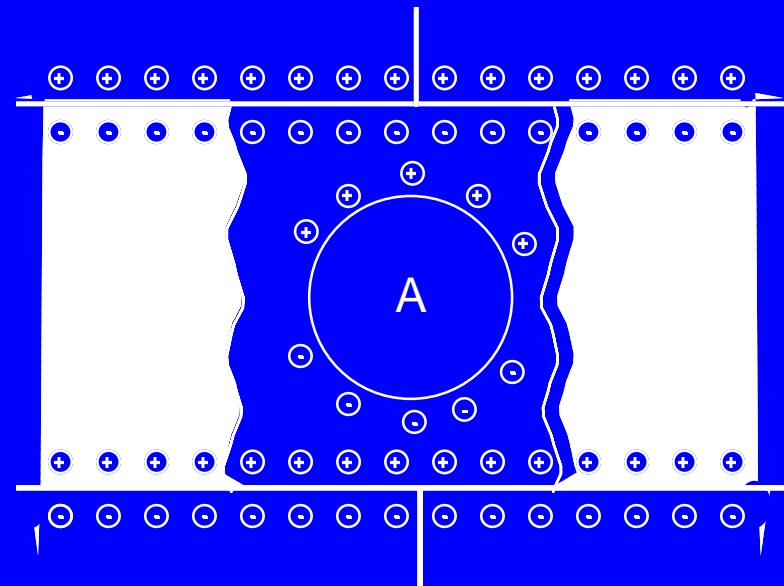
ELECTRONIC POLARIZATION



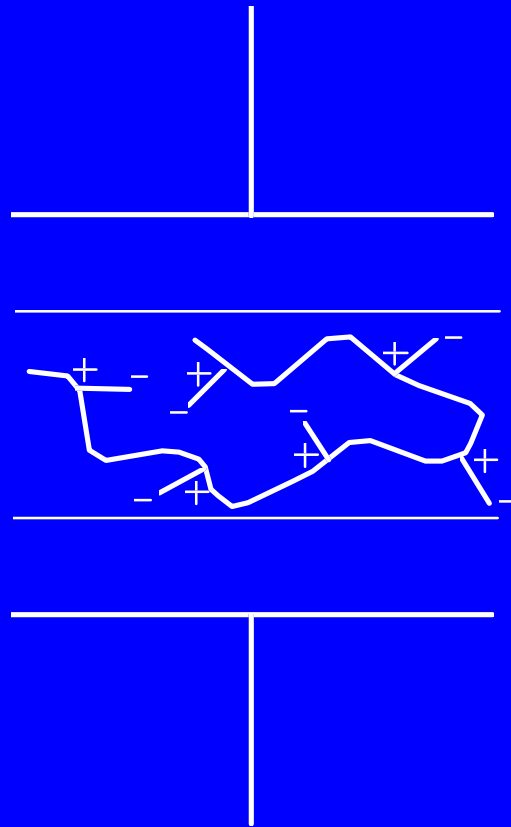
ATOMIC POLARIZATION



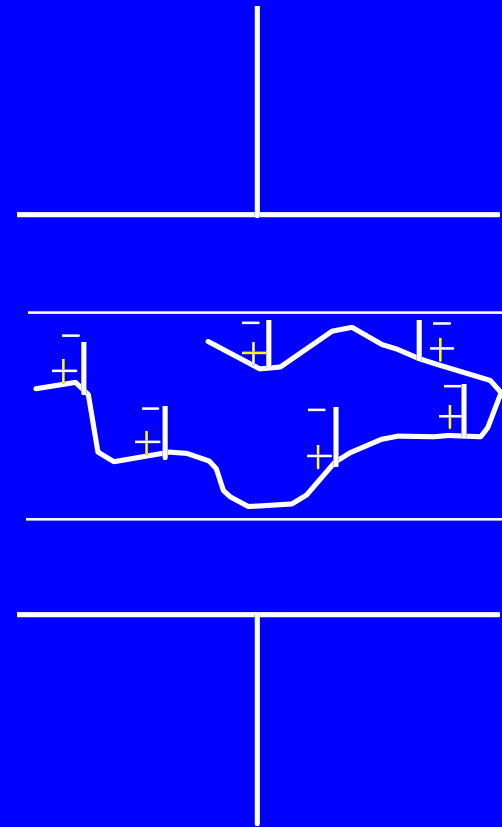
ORIENTATION POLARIZATION



POLARIZATION OF A POLYMER THAT CONTAINS SIDE GROUPS WITH PERMANENT DIPOLES

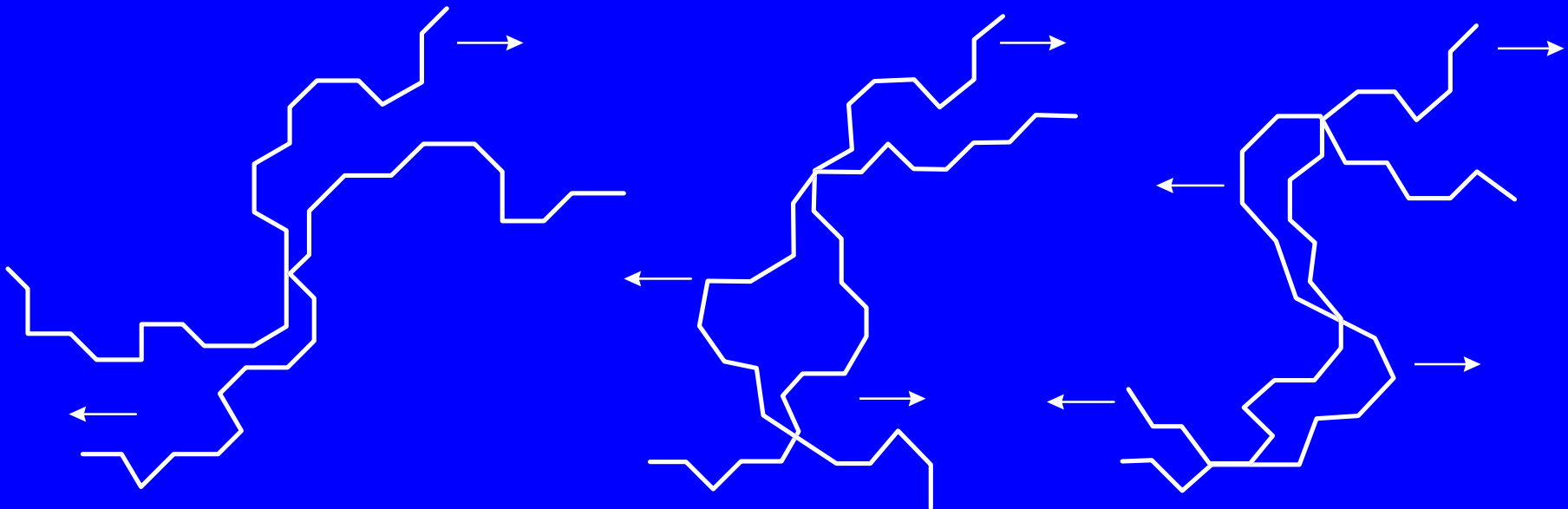


No field



field applied,
polymer becomes
polarized

SCHEMATIC OF SOME NORMAL MODES OF MOTION OF A POLYMER CHAIN



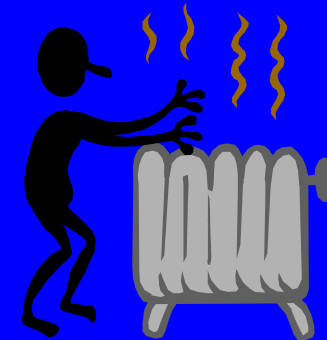
First Mode

Second Mode

Third Mode

Application of Low Voltage Stress

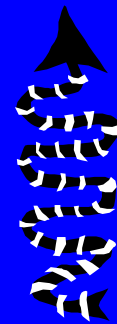
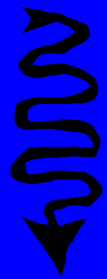
- Dielectric Constant: Ability to 'hold' charge
 - Lower Polarity -> Lower K
-
- Dissipation Factor: Losses that occur as a result of energy dissipated as heat, rather than electrical energy
 - > Polarity leads to > Losses



DC vs. AC

Under DC- Polarization persists

Under AC-Constant motion of the
polymer segments due to changing
polarity



Dielectric Constant

- TECHNICAL DEFINITION
- In a given medium (e.g. for our purposes, in a specific polymer insulation)—it is the Ratio of
 - (a) the quantity of energy that can be stored,
 - to
 - (b) the quantity that can be stored in a vacuum

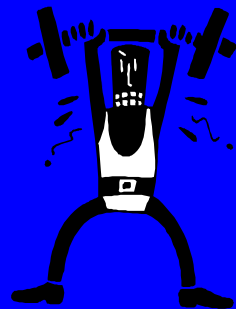


Dielectric Constant

- Relatively small if no permanent dipoles are present
- Approximately proportional to density
- Influenced by presence of permanent dipoles:
 - Dipoles orient in the electric field
 - inversely proportional to temperature
 - Orientation requires a finite time to take place
 - is dependent upon frequency
 - Relaxation time for orientation of a dipole is also temperature dependent

Dielectric Constant

- The dielectric constant of the electrical-insulating materials ranges from:
 - a low of about 2 or less for materials with lowest electrical-loss characteristics,
 - up to 10 or so for materials with highest electrical losses



Dielectric Constant of Common Polymers

- Polyethylene 2.28
- Polypropylene 2.25
- Butyl Rubber 2.45
- Poly MMA 2.7-3.2
- Nylon 66 3.34
- PPLP (Oil-Impregnated) 2.7
- Cellulose Acetate 3.2-7.0
- PVC 2.79
- Mylar (Polyester) 3.3
- Kapton (Polyimide) 3.6
- Nomex (Polyamide) 2.8
- Cyanoethylcellulose 13.3

Sources: M.L.Miller "Structure of Polymers",
Dupont and Tervakoski Literature

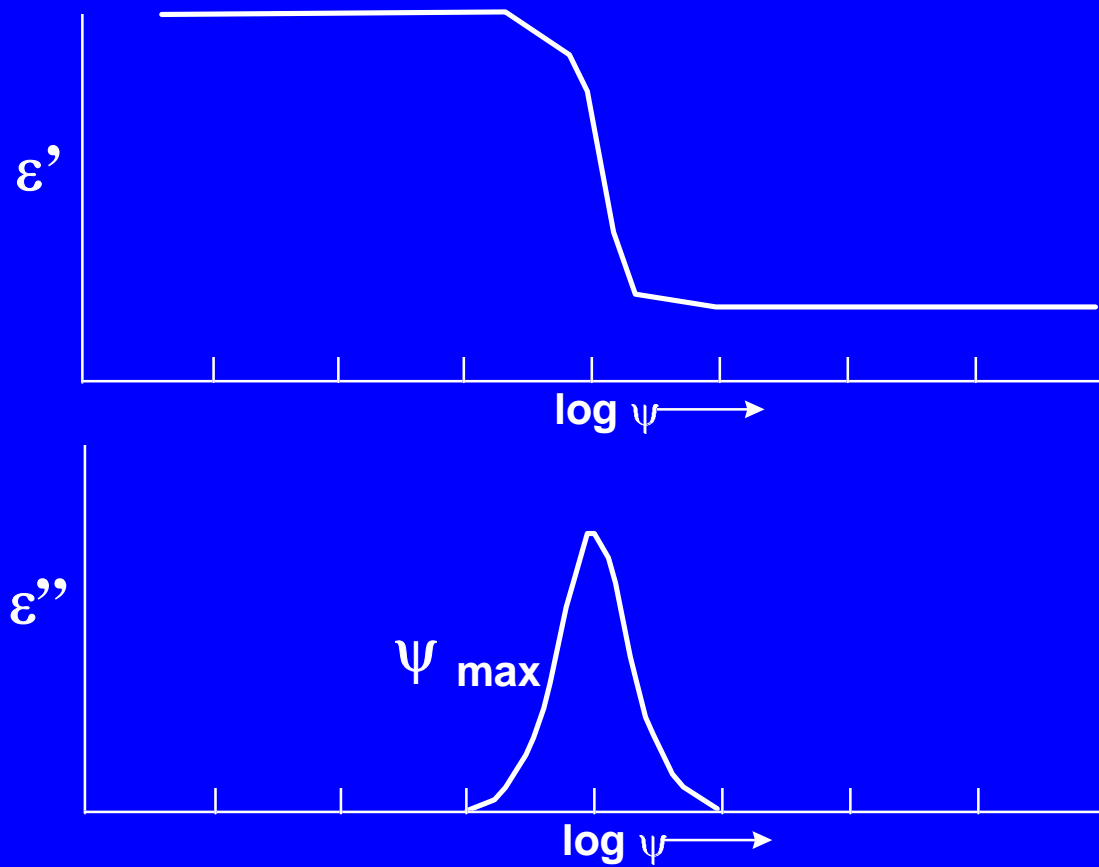


DIELECTRIC LOSSES

- From a materials perspective, losses result from polymer chain motion
- Leads to heat evolution
- Chain motion influence on electrical properties are depicted on next few slides



ϵ' AND ϵ'' AS A FUNCTION OF FREQUENCY



Dispersion

- Dipoles **RIGIDLY** attached - oriented by **MAIN** chain motion
- Dipoles **FLEXIBLY** attached - orientation of pendant dipoles
and/or
orientation by chain segmental motion
(shows **TWO** dispersion regions)
at different frequencies
- PE that has been **OXIDIZED**
- PE that is a copolymer with polar monomer, e.g., **SOME TR-XLPE**

Note: 60Hz is not necessarily where these phenomena show maxima

Dispersion

- At frequencies where dispersion occurs
 - some energy stored
 - some energy dissipated as heat

Complication:

- In the dispersion region, some dipoles are oriented while others are moving.
- Hence some dipoles move in a field that is **COMPOSITE** of applied field and local dipole induced field - called **INTERNAL FIELD** effect
- Leads to phenomena that are not sharply defined

Electrical Properties of Polyolefins

Poly Olefin Structure and Dielectric Behavior

- The electrical behavior of insulating materials is influenced by temperature, time, moisture and other contaminants, geometric relationships, mechanical stress and electrodes, and frequency and magnitude of applied voltage. These factors interact in a complex fashion.
 - Saturated hydrocarbons are non-polar
 - Dielectric constants are low
 - Dielectric constants essentially frequency-independent (if pure)
 - Dielectric constants change little with temperatureThe change that occurs is related to density changes

Electrical Properties of Polyolefins

Poly Olefin Structure and Dielectric Behavior

- Dielectric constant can be expressed for these nearly non-polar polymers by an expression of the form:

$$e = A + B(d - d_a)$$

Where,

B is a constant,

d is the density and

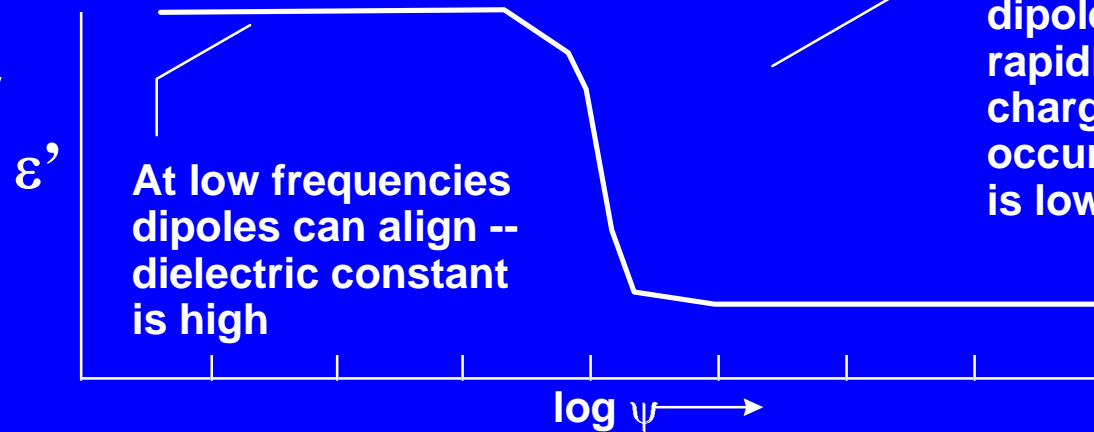
d_a is the density at which the dielectric constant is equal to A.

Dielectric constants for this equation fit a large number of data for polyethylene:

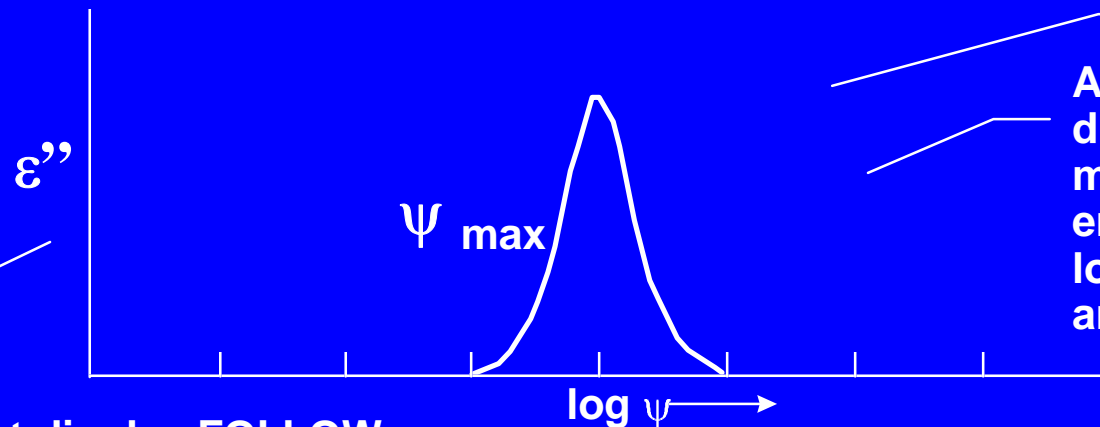
$$e = 2.276 + 2.01(d - 0.9200)$$

INSULATION POLYMERS AND DISPERSION

**Permittivity
or
Dielectric
Constant**



Losses



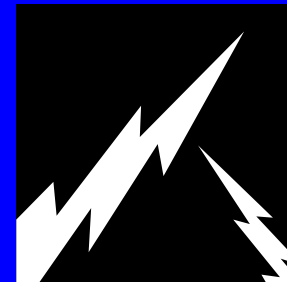
Permanent dipoles FOLLOW variations in the AC field - hence current and voltage out of phase - losses low

ϵ' and ϵ'' as a function of frequency - at constant temperature

Frequency at which permittivity drops and losses increase is where the polymer is said to show dispersion

ELECTRIC BREAKDOWN

- INABILITY OF INSULATION TO OPERATE or HOLD CHARGE UNDER STRESS
 - Insulation inherent properties
 - Thermal
- Stream of electrons released
- Discharge-
 - Preceded by Partial Discharge



Electric Breakdown

Types of Breakdown

- Failure of a material due to the application of a voltage stress
 - called the dielectric strength
 - expressed as kV/mm or V/mil
- Electric breakdown occurs when the applied voltage can no longer be maintained across the material in a stable fashion without excessive flow of current and physical disruption
- Theoretical understanding not clear even now
- What is clear is that there are several mechanisms of failure

Electric Breakdown

Types of Breakdown

Intrinsic Breakdown

- Defined by the characteristics of the material itself in pure and defect-free form under test conditions which produce breakdown at the highest possible voltage. Never achieved experimentally.

Thermal Breakdown

- Occurs when the rate of heating exceeds the rate of cooling by thermal transfer and thermal runaway occurs under voltage stress

Electric Breakdown

Types of Breakdown

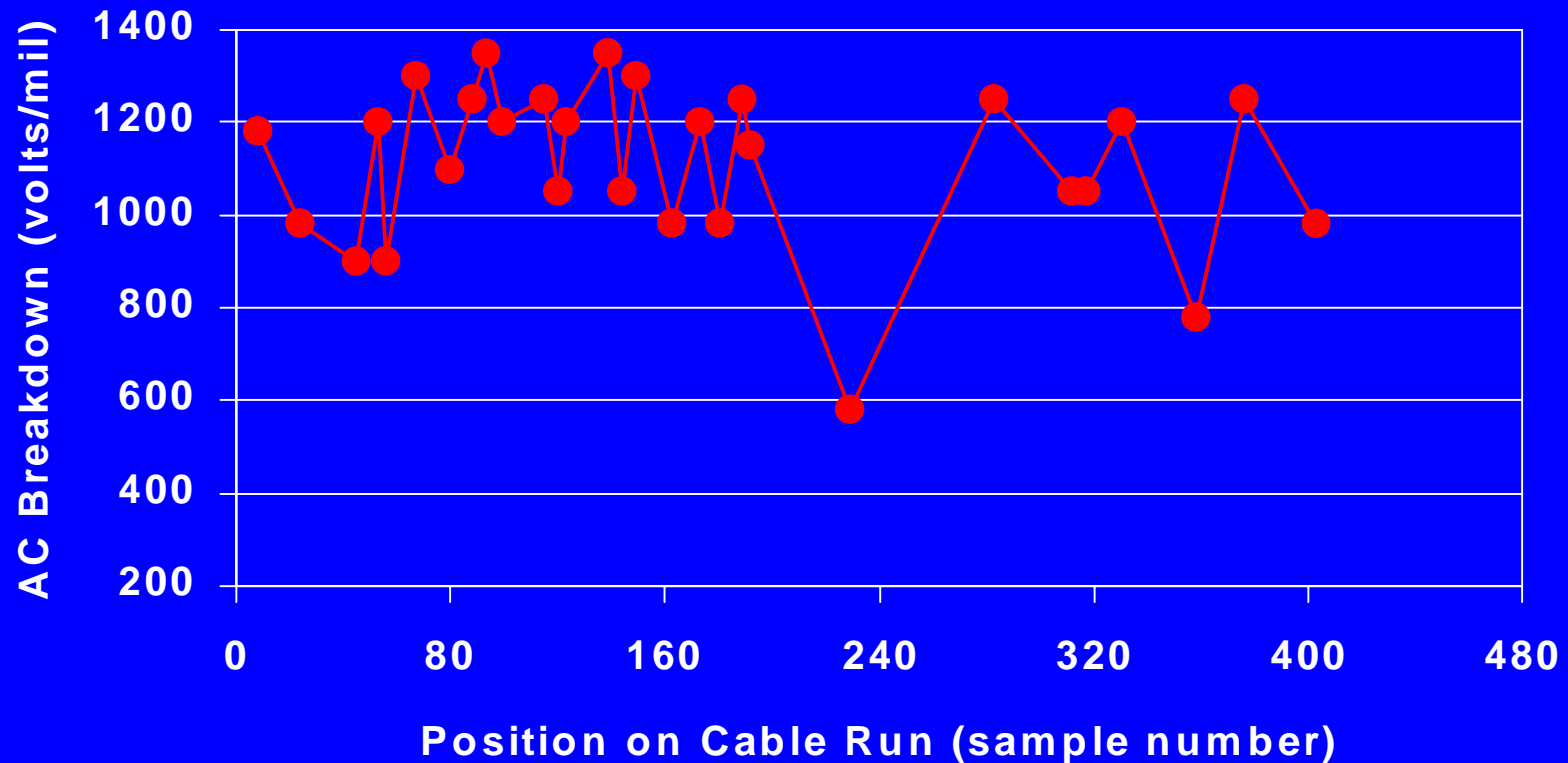
Discharge-Induced Breakdown

- Occurs when electrical discharges occur on the surface or in voids of electrical insulation. Ionization causes slow degradation. Corona, or partial discharge, is characterized by small, local electrical discharges

Treeing-Electrical

- Results from partial discharge

AC Breakdown Strength of 15 kV XLPE Cable Vs. Position on Cable Run For One 5000 Foot Reel of 50,000 Foot Run

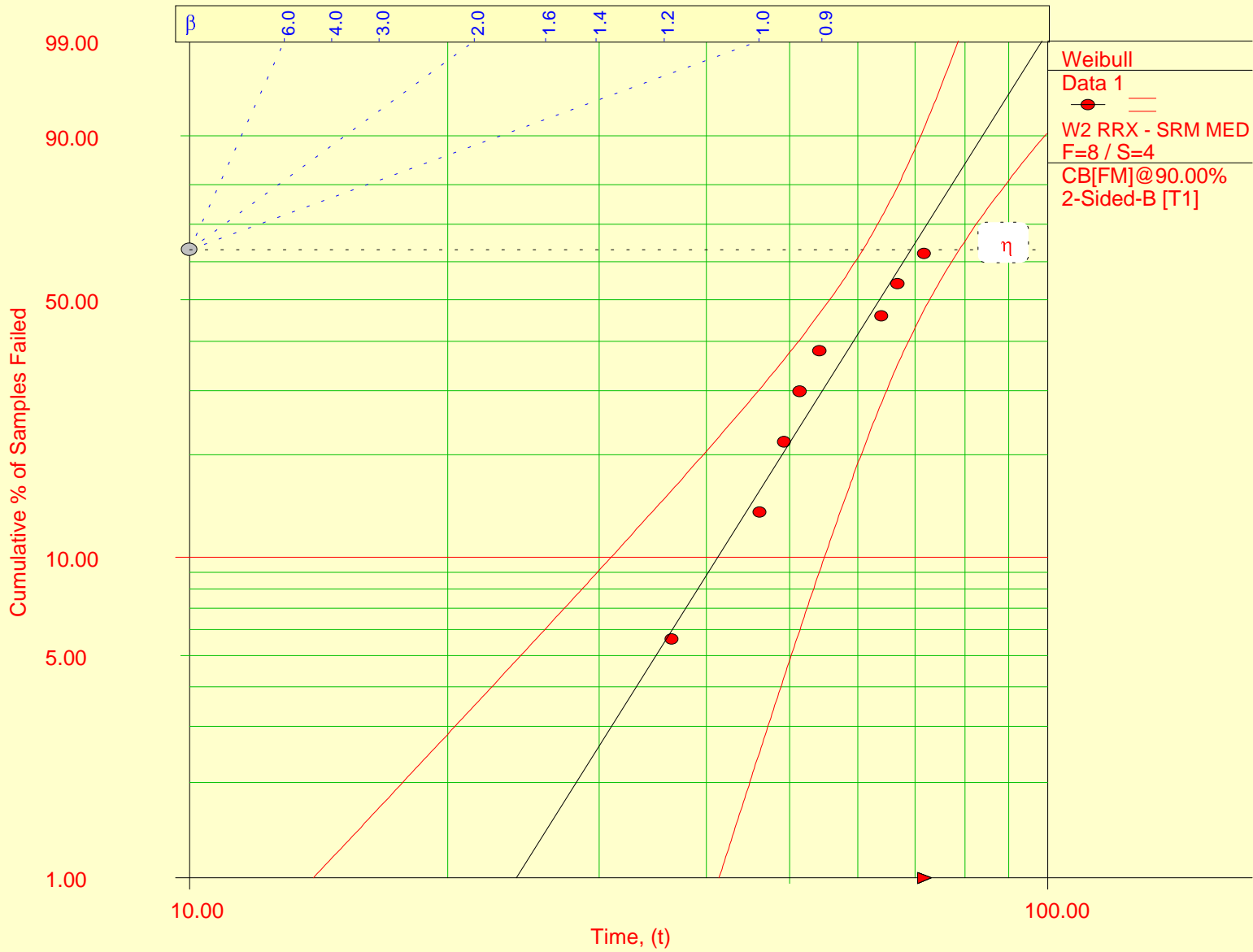


WEIBULL

- Commonly used to characterize time to failure information
- Defines
 - Characteristic Time to Failure
 - Scale Factor/ 63.2% probability of failure
 - Shape parameter/slope of failure times
- Called two parameter Weibull distribution
- **Controversial:** “Most physical models do predict this type of distribution for failure as a function of time (but not necessarily of voltage stress”)
Dissado and Fothergill, Page 323

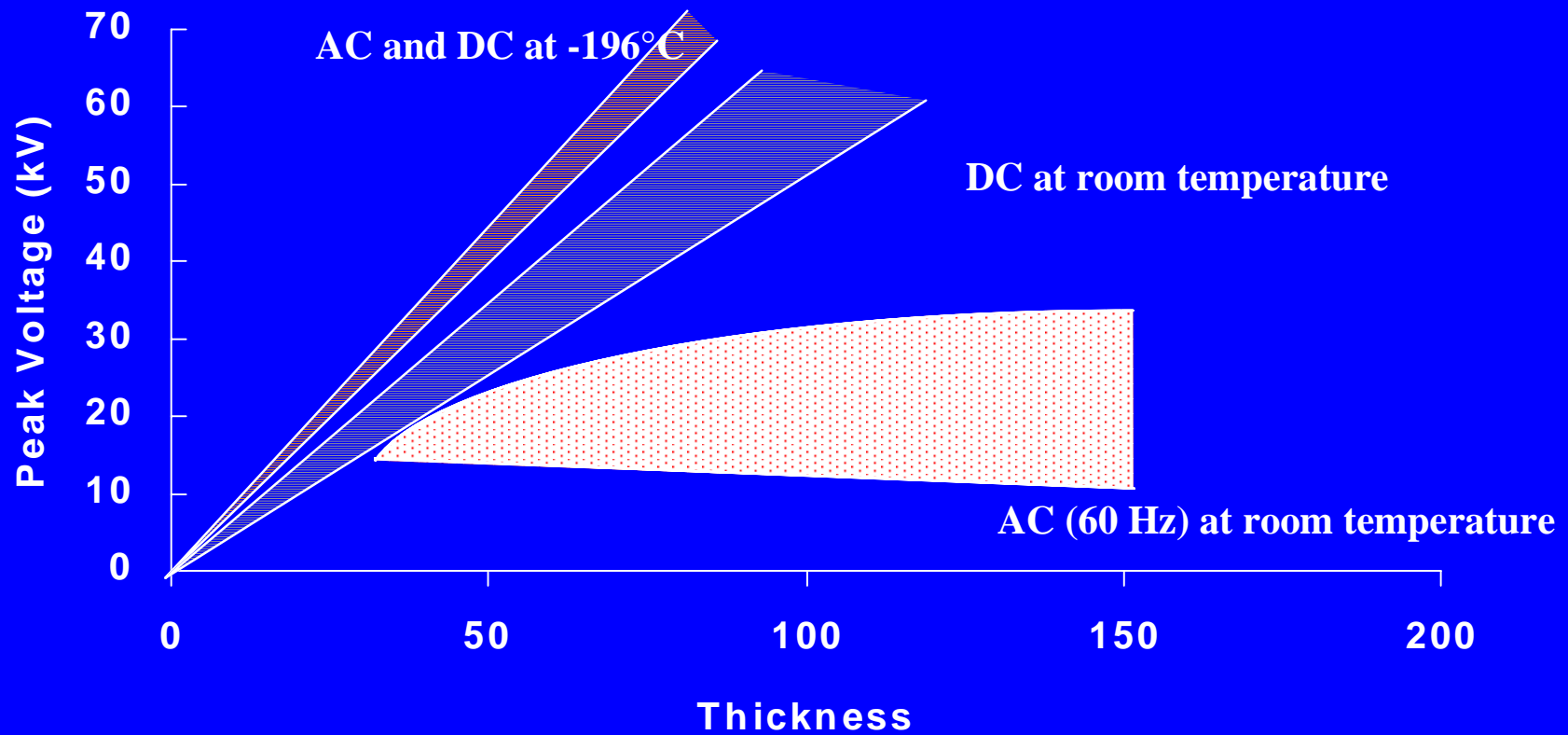


Probability - Weibull



$\beta=4.3432, \eta=69.2863, \rho=0.9791$

Short-Time Voltage Breakdown of Polyethylene



Dielectric Strength

Important Points to Remember !

- ❑ AC breakdown strength value NOT absolute
 - Related to rate of rise of the applied voltage stress
 - 5 minute step rise
 - 10 minute step rise
 - 30 minute step rise
 - Ramp
- ❑ Real world/stress is constant
 - Voltage endurance

Electric Breakdown

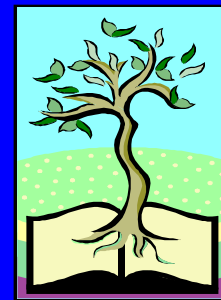
- Thickness, area, shape and nature of the conducting contaminants influence the breakdown voltage of plastics
- If the failure occurs at the periphery of the plastic instead of passing through, it is called a flashover
- Corona is not easily produced by a d-c voltage, even though the voltage across the air in a void is high, because initiation of corona also involves the rate of voltage change
- The localized voltage stress at a metal point (needle) is very high
- Dielectric strength depends on the thickness of sample

Electric Breakdown

Types of Breakdown

Treeing- Water

- Water tree growth induced by water in presence of voltage stress. Water trees generate at much lower stresses than electrical trees. Not a direct cause of breakdown



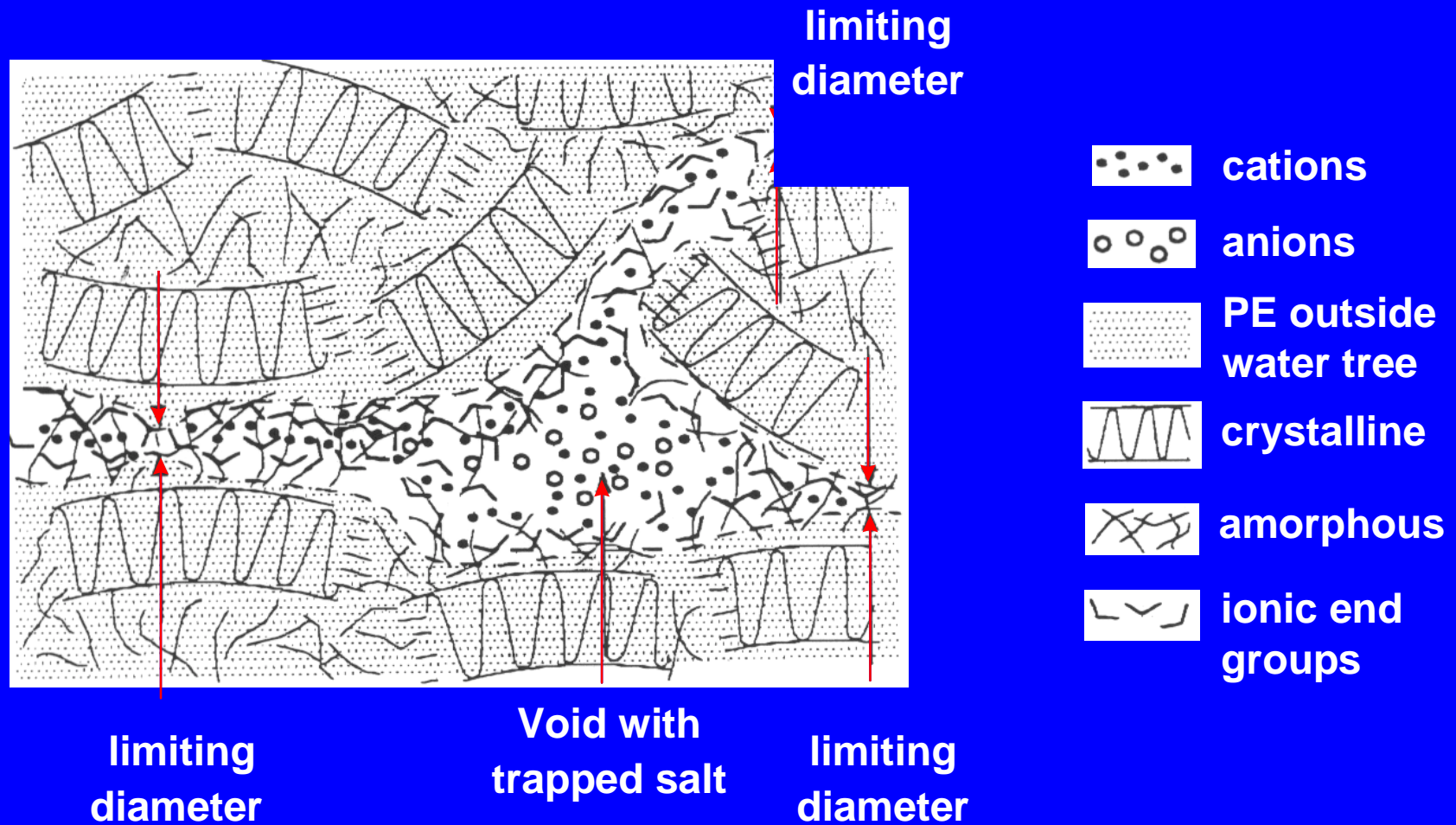
Water Treeing

- First reported in 1968
- Bahder, et al. 1972: First distinguished between water and electrical trees
 - Water trees/electrochemical trees
- Water and Voltage stress required
- Lead to reduced dielectric strength
- Cleanliness required
 - All known since mid-late 1970's
- Progress (?)
 - Ions influence
 - Jackets

Theories of Water Treeing

- *Mechanical*: fatigue of matrix
- *Chemical*: field brings about reactions
- *Thermodynamic*: migration of water into pre-oxidized areas
- *Electrical*: acceleration of electrons across voids damages matrix

A Model of Water Trees in PE



General Procedure For Performing Electric Breakdown Measurements

- The test specimen, (a sheet a few mils thick) is placed between disk-shaped electrodes having a diameter much smaller than the width of the specimen
- The edges of the electrodes must have a rounded edge
- Either a direct or alternating potential is applied across the electrodes and the potential is raised at some uniform rate until breakdown occurs
- Since the actual breakdown process generally involves non-uniformities in the insulating material, resulting in local concentration of the electric field, extreme care must be exercised in cleaning the electrodes and specimens

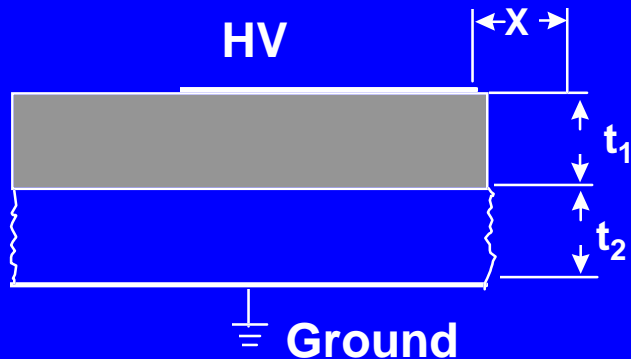
General Procedure For Performing Electric Breakdown Measurements

- A number of specimens are tested in order that the measurements may be a true reflection of the statistical distribution of inhomogeneities in the material under study
- The following variables must be strictly controlled and identical in a series of tests:
 - Specimen thickness
 - Electrode shape and size
 - Temperature
 - Frequency of applied field
 - Rate of increase of the field

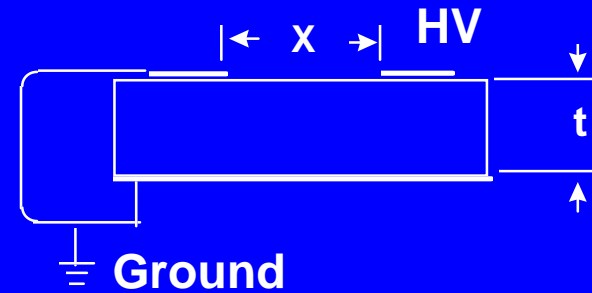
General Procedure For Performing Electric Breakdown Measurements

- In addition, care must be exercised in controlling the moisture content and other pretreatment variables of the specimen
- In general, such breakdown tests are associated with some particular conditions in which the insulation material will be used, and these conditions therefore become the dominant factors in designing the test procedures

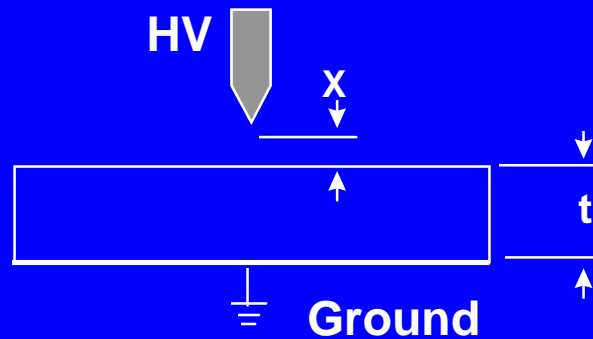
TYPICAL GEOMETRIC ARRANGEMENTS ILLUSTRATING THE USE OF PLASTICS AS AN INSULATOR



Two dielectrics in series



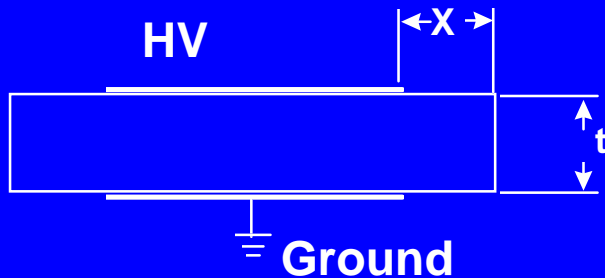
Configuration with nonuniform voltage gradient along the surface



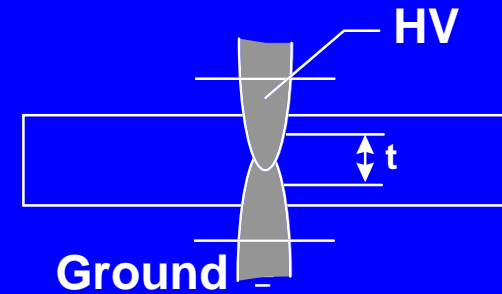
High voltage gradient at a sharp point



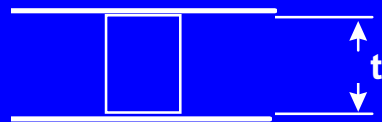
TYPICAL GEOMETRIC ARRANGEMENTS ILLUSTRATING THE USE OF PLASTICS AS AN INSULATOR



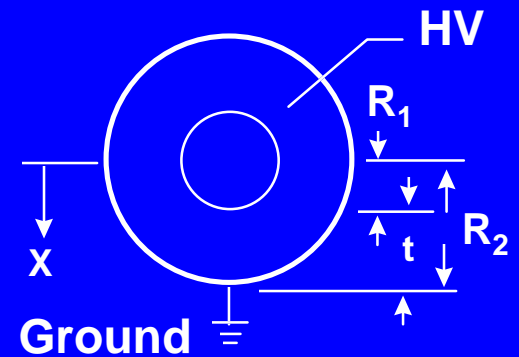
Uniform voltage gradient under electrode, nonuniform at edge of electrode and along creepage path on the surface



An inset Rogowski (curved) electrode provides uniform voltage gradient



Uniform voltage gradient along surface of plastic



Voltage gradient is not uniform across the diameter; is highest at the inner conductor



ELECTRICAL PROPERTIES

- Survey of topics reviewed
 - Dielectric constant
 - Dissipation factor
 - Dielectric strength
 - Water Treeing
 - Electrical Properties at low voltage stress are dependent upon Chemical structure of Insulation
-
- Reliability (Life) dependent upon other factors
 - Aging, local environment / beyond scope of this talk

THANK YOU

