ALMA MATER STUDIORUM
UNIVERSITA' DI BOLOGNA

HVDC Aging Modelling for Polymeric Cables: an Overview

Davide Fabiani, Gian Carlo Montanari

University of Bologna

Italy

Introduction

- Insulation aging is a multi-factor process
- Insulation performance evaluation → aging tests with several combinations of factors
- Different strategies:
  - Choice of candidate materials → short-term tests
  - Insulation qualification → long-term tests
- Which techniques?
  - Analytical techniques, space charge measurements
  - Life / aging tests… which models can we use?

Close and Return

Phenomenological aging theory

- **Aging can be quantified through a general equation:**

$$A(t) = f(p) = \int_0^t R(S_1, S_2, \dots, Sn)dt$$

where: $S_1, S_2, \dots, Sn$= stresses (e.g. electric field and temperature)
p = property, monotone behavior with time → diagnostic property
R=dA/dt → aging rate

$$A_L = f(p_L) = \int_0^L R(S_1, S_2, \dots, S_n)dt = R(S_1, S_2, \dots, S_n)L$$

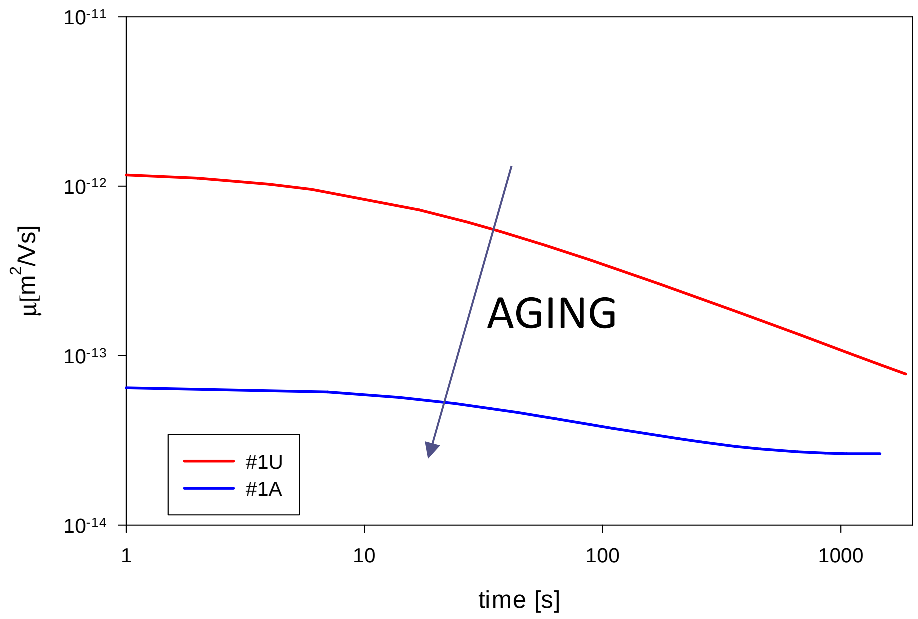
Hp: R=dA/dt = K
S_i constant with time

$$A(t) = f(p) = R(S_1, S_2, \dots, S_n)t$$

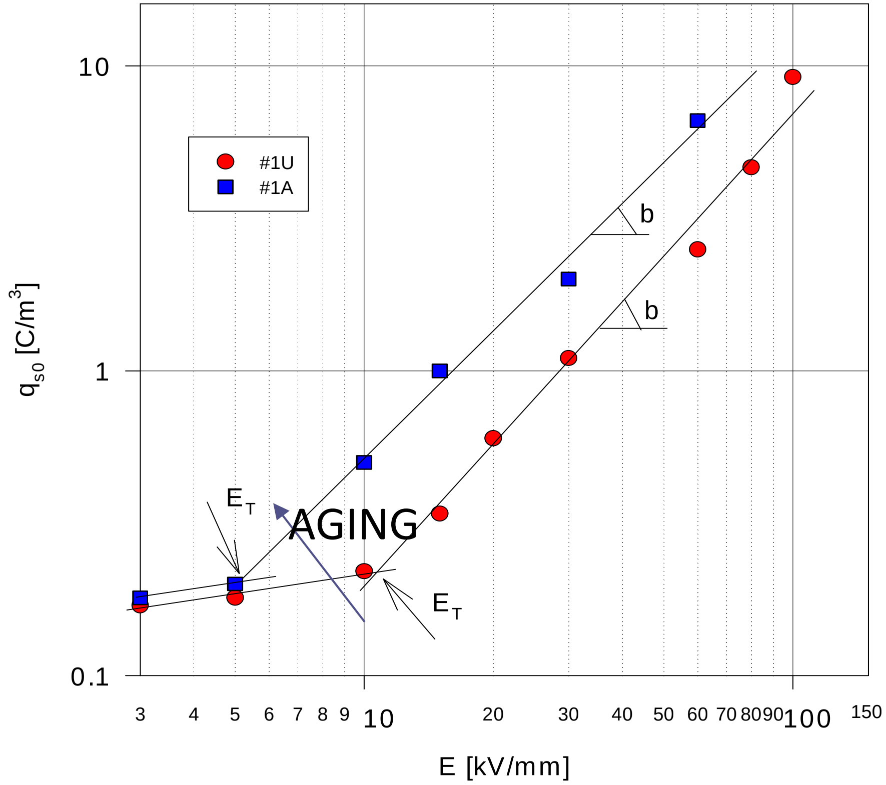
$$L = \frac{A_L}{R(S_1, S_2, \dots, S_n)} \qquad A(t) = A_L \frac{t}{L}$$

Aging theory

Property, p, correlated with aging….space charge



Apparent trap controlled mobility



Space charge vs. field

Tests on LDPE, unaged (#1U) and aged at 200 kV/mm for 103 h (#1A)

Space charge amount → DIAGNOSTIC PROPERTY

Degradation mechanisms AC/DC

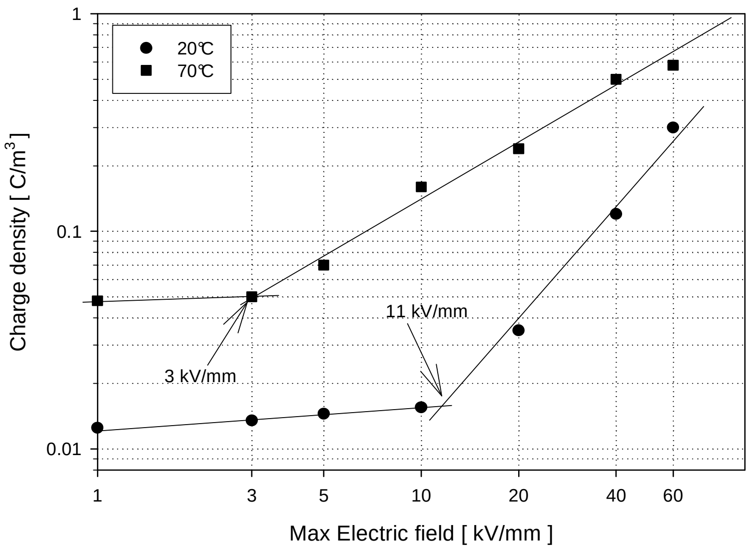
- We do not know precisely the degradation mechanisms in insulation under AC/DC
  - Multiple stress and factor of influence
  - Highly non-homogeneous materials
- We know that:
  - AC degradation → accelerated by partial discharges
  - DC degradation → space charge

The role of space charge

- Literature show relationship between space charge accumulation in polymeric insulation and dc aging.
- In particular:
  - increasing amount of SC accumulate with aging;
  - voltage polarity inversions accelerate dc insulation degradation;
  - large SC accumulation accelerates degradation and shorten insulation breakdown time.

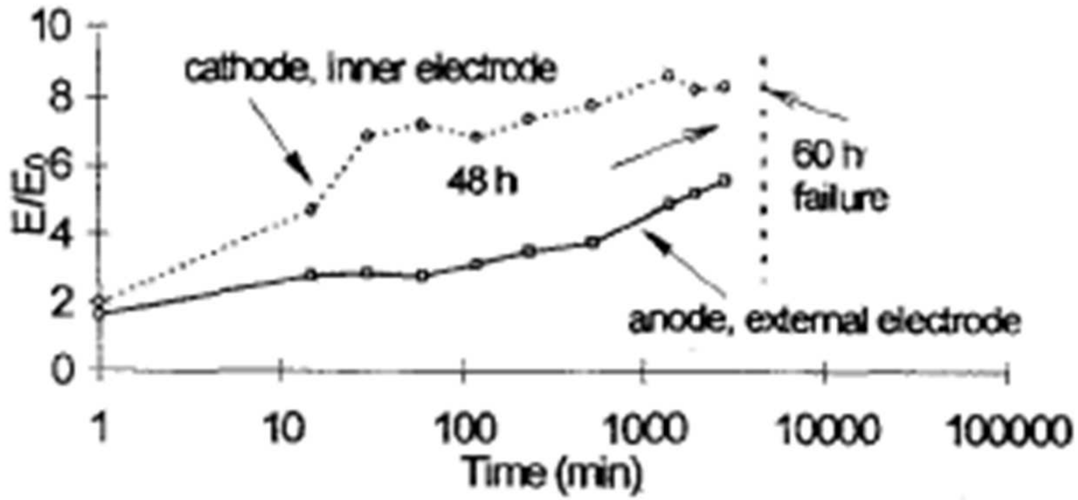
The role of space charge

- Space charge accumulation increases with field and, generally, with temperature
- Threshold field for space charge accumulation decreases with temperature



The role of space charge

XLPE used in HVAC… often not good under HVDC



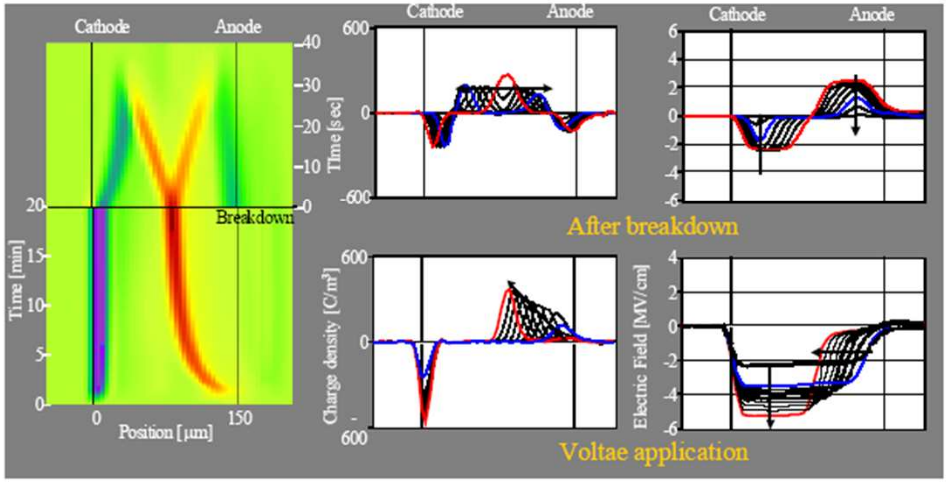
Electric field magnification as function of time, till breakdown, for XLPE minicables poled under DC field of about 10 kV/mm.

* Zhang et al, IEEE T DEI 1996

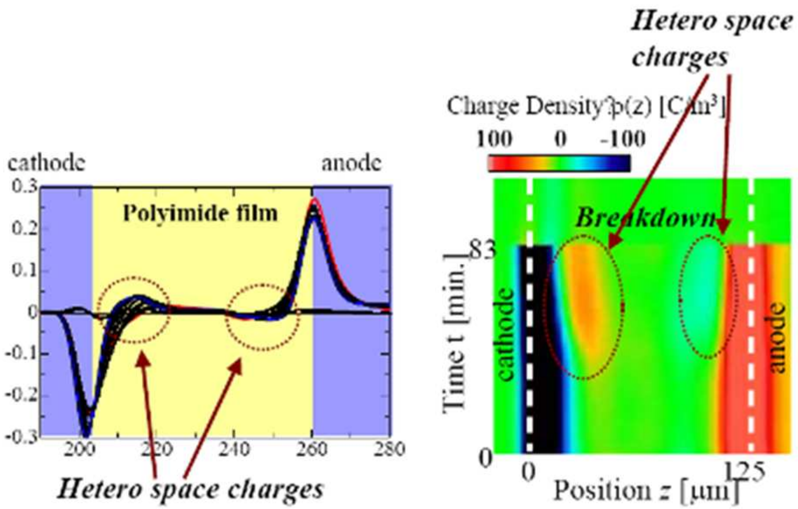
The role of space charge

- Evidence that Space charge is a cause of aging (direct or indirect cause of aging)

Direct effect on aging: breakdown



Typical slow packet-like charge behavior and breakdown in LDPE (low density polyethylene) under high DC stress *

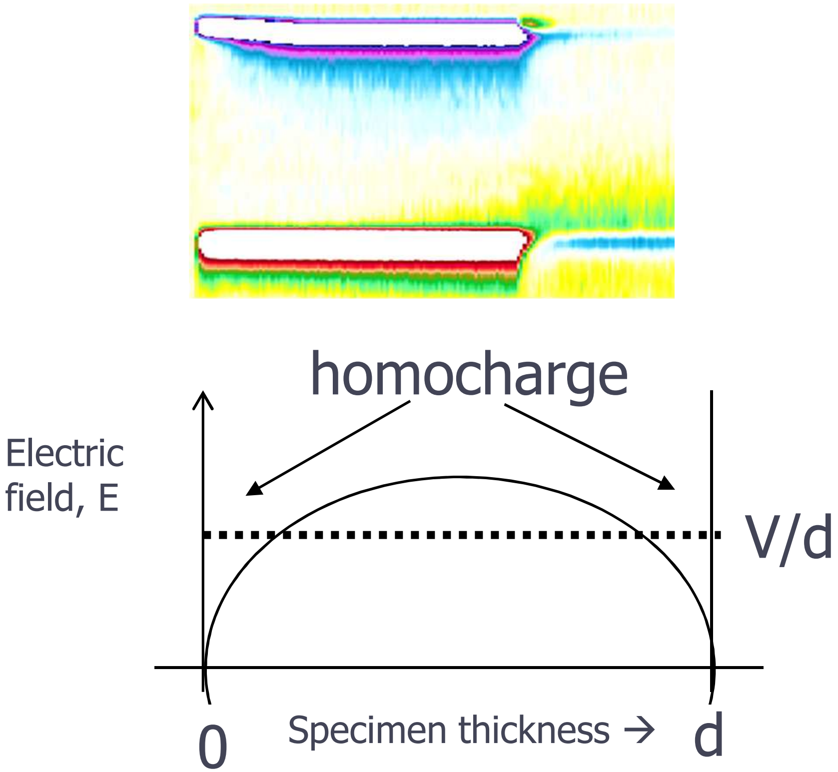


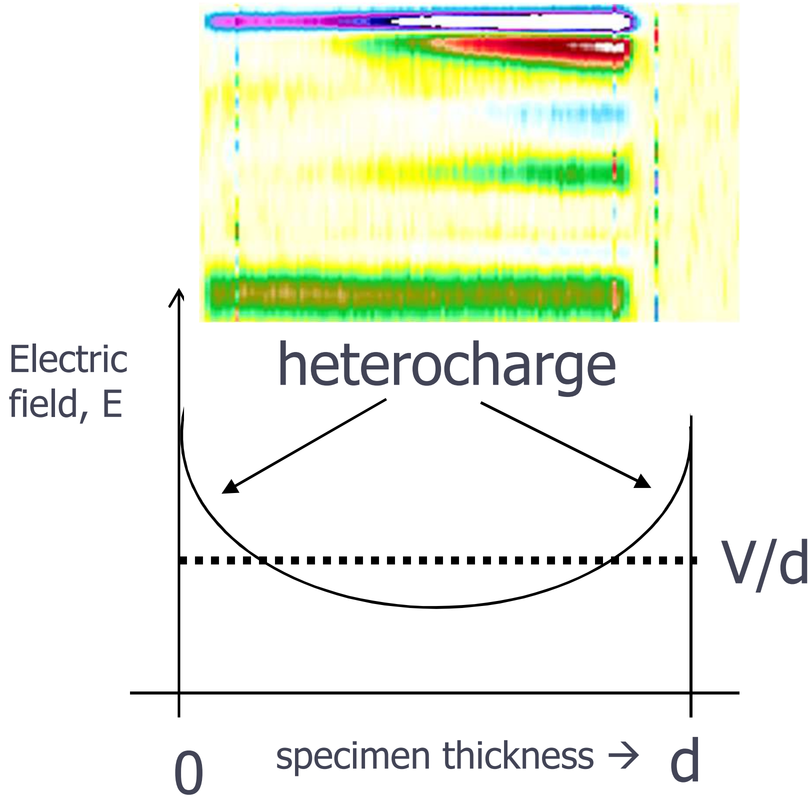
Time dependence of charge distribution under high dc stress till breakdown. *

* N. Hozumi et al – CIGRE Report WG D1.23, 2010

The role of space charge

…depends on the kind of space charge accumulation





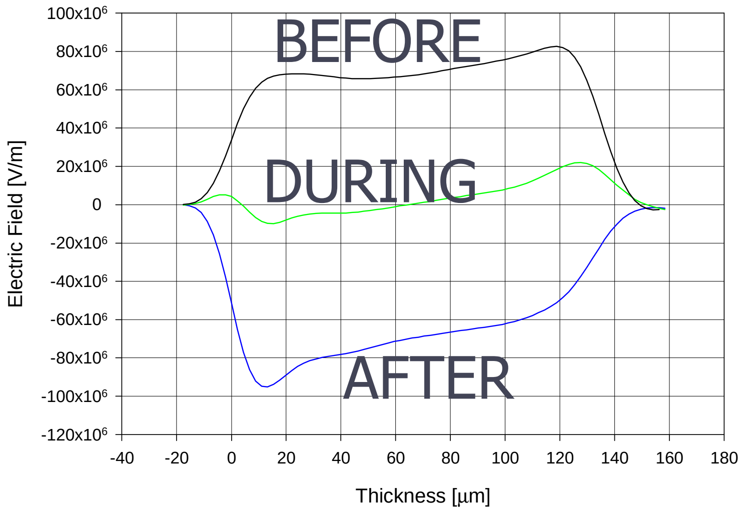
Homocharge → higher field in the bulk with respect to laplacian
Heterocharge → higher field at the electrodes with respect to laplacian

Consequences of space charge

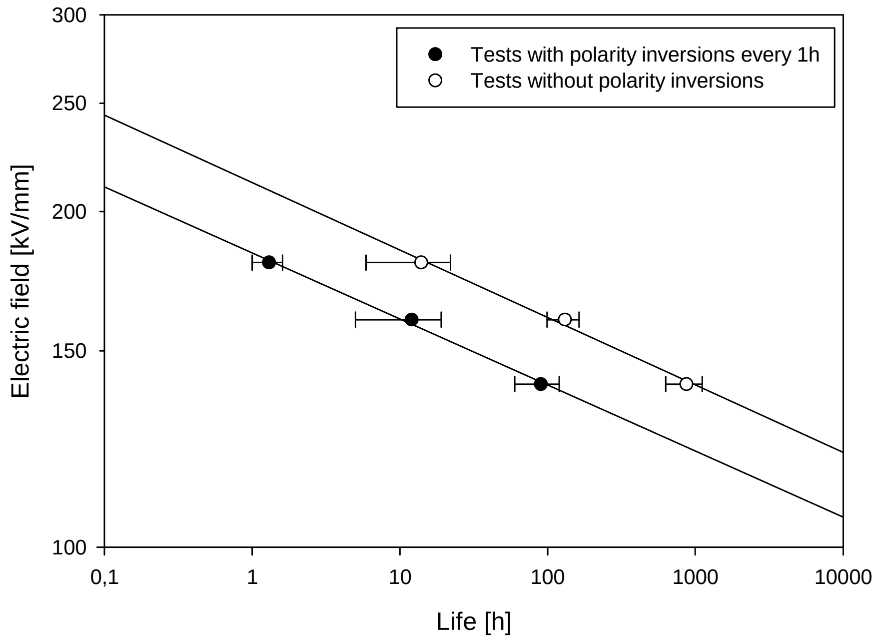
- **Changes field distribution from design value →** can increase value by 10-100% and even more!
- **Field increase at electrodes due to heterocharge** is quite dangerous → can bring the insulation to premature failure even at design field !
- **Homocharge** can become heterocharge after voltage polarity inversions (!)

The role of space charge

- Effect of polarity inversions



Electric field before, during and after polarity inversion

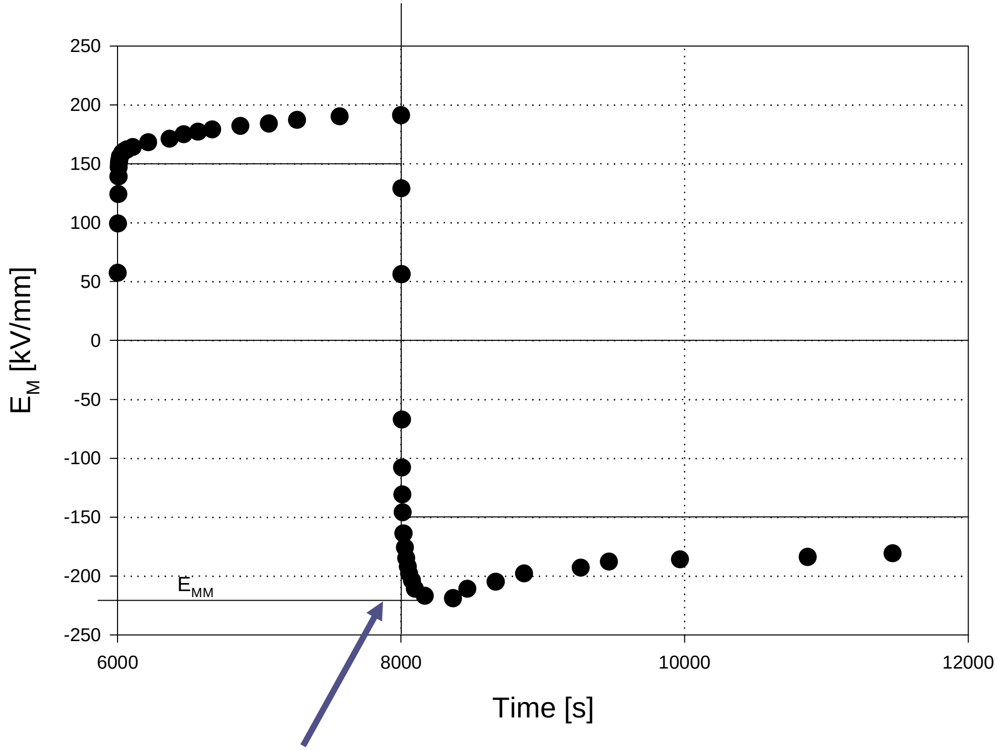


DC life tests on XLPE cable models with and without voltage inversions

Cable insulation accumulating homocharge fails sooner if fed by DC with polarity inversions

Space charge quantities

- Maximum (poissonian) field
  - Evaluated by means of space charge measurements



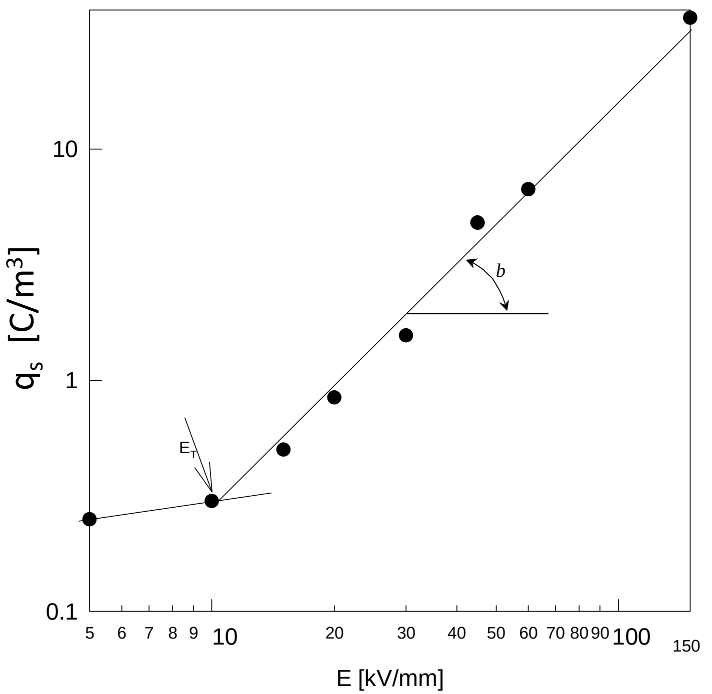
30% increase with respect to laplacian field, after inversion

Space charge quantities

- Total absolute stored charge density

$$q_S(E,t) = \frac{1}{d}\int_0^d \left|q_p(x,t)\right| dx$$

- Rate of space charge rise with field, *b*

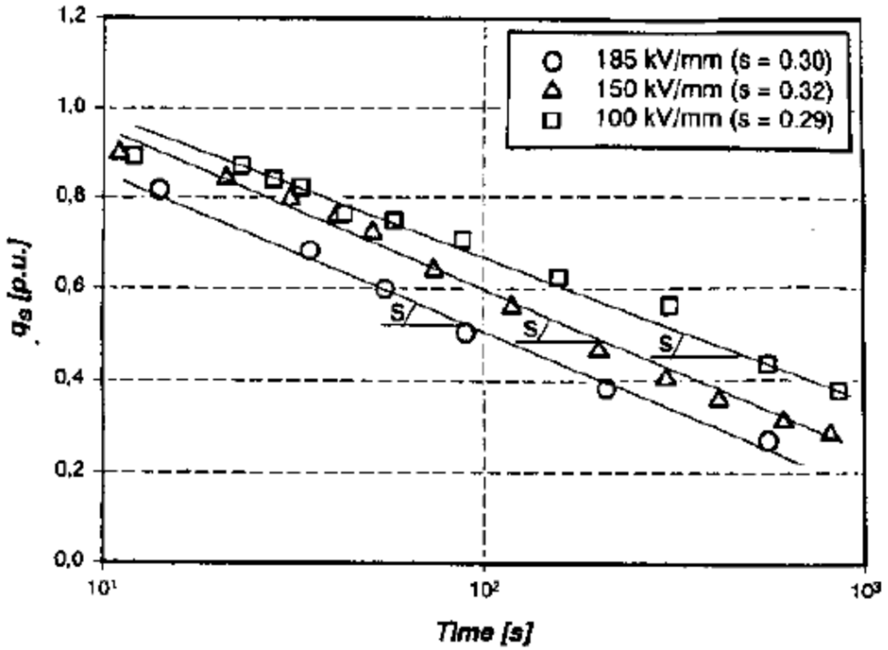


$$q_S(E) = A_0\, E^b$$

Close and Return

Space charge quantities

- Charge decay during depolarization
  - Slope of depolarization characteristic, *s(E)*



Life modelling

- Physical models
  - Thermodynamic approach: 'free energy' of degradation reactions… (see Eyring model)

$$R(S = T) = R_0 \frac{kT}{h} exp\left(\frac{-\Delta G}{kT}\right) \qquad L = \frac{A_L}{R(S)} = C\,\frac{h}{kT} exp\left(\frac{\Delta G}{kT}\right)$$

  - Example: DMM, Crine model
- Phenomenological models
  - Model parameters obtained by fitting life test data

Phenomenological models

- Traditional electro-thermal aging approach

R(E,T)

$$R(E) = C_E E^{n_0}$$

ARRHENIUS

$$R(T) = C_T \exp(\frac{-\Delta G}{kT})$$

$$L(E,T) = L_{ET} E^{-(n_0 - b_{ET} T)} \exp(-BT)$$

T = room temperature → the combined model becomes an IPM

$$L(E) = L_E E^{-n}$$

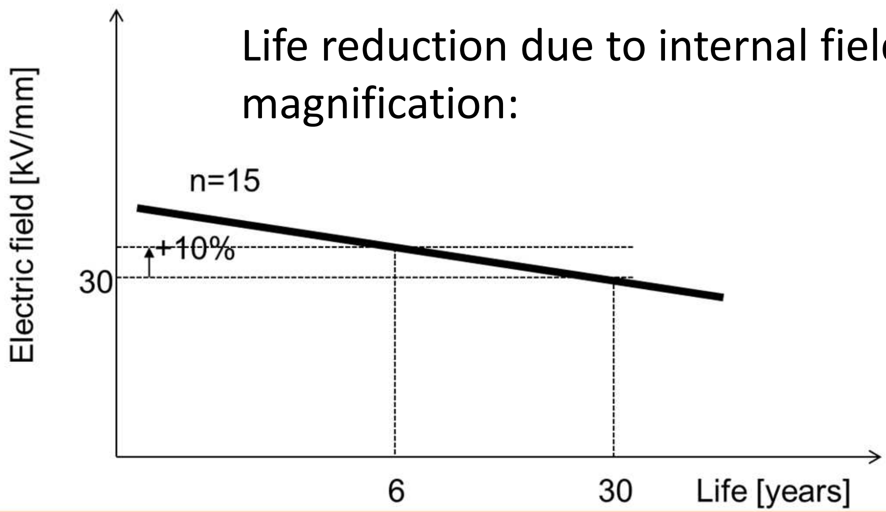
Electric life model

- **Without polarity inversion:**

$$L(E) = L_E E^{-n}$$

  - Space charge → internal field magnification
  - *E* can be the max field (poissonian)
  - Charge distribution → provide field amplification somewhere, e.g. **heterocharge** enhances the electrode field

Life reduction due to internal field magnification:



Electric life model

- **With polarity inversions**
  - Evaluation of life relative variation (L/L_i -1)

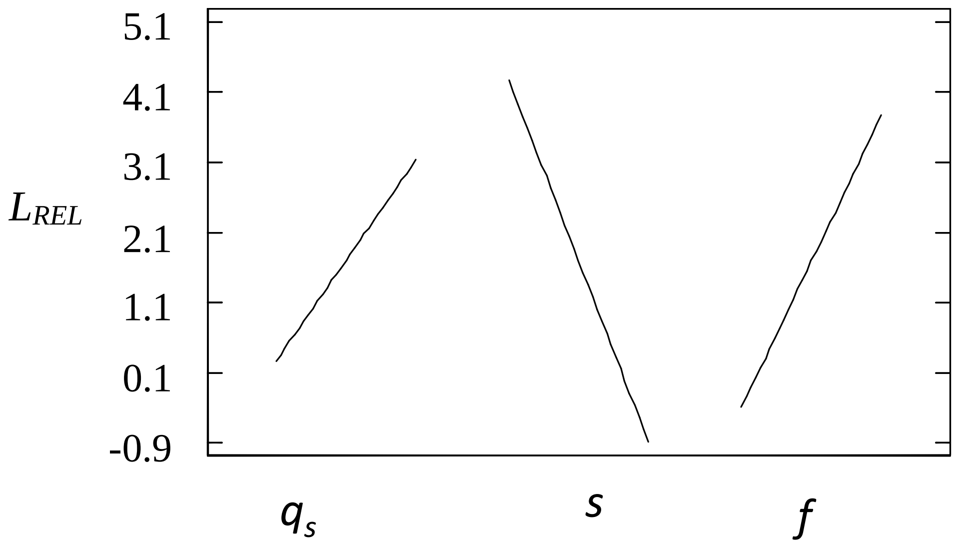
$$ln[(L/L_i)\text{-}1]= A_1 + A_2\, ln\,(q_S(E)) + A_3\, ln\,(s(E)) + A_4 ln\,(f)$$

  - Accelerated aging tests with and without polarity inversions
  - Space charge measurements to evaluate q_s and *s*
  - Multi-variable regression to estimate A_i coefficients

Extrapolation to low field can be not accurate

Electric life model

- **With polarity inversions**
  - Significance of model quantities
    - Main Effect plot → the larger the slope the stronger the effect of the factor on life variation $L_{REL} = (L/L_i)-1$



Electric life model

- **With polarity inversions**

$$\ln[(L/L_i)-1] = A_1 + A_2 \ln(q_S(E)) + A_3 \ln(s(E)) + A_4 \ln(f)$$

Hp: $q_S(E) = A_0 E^b$ $\quad s \approx const$

Applying exp:

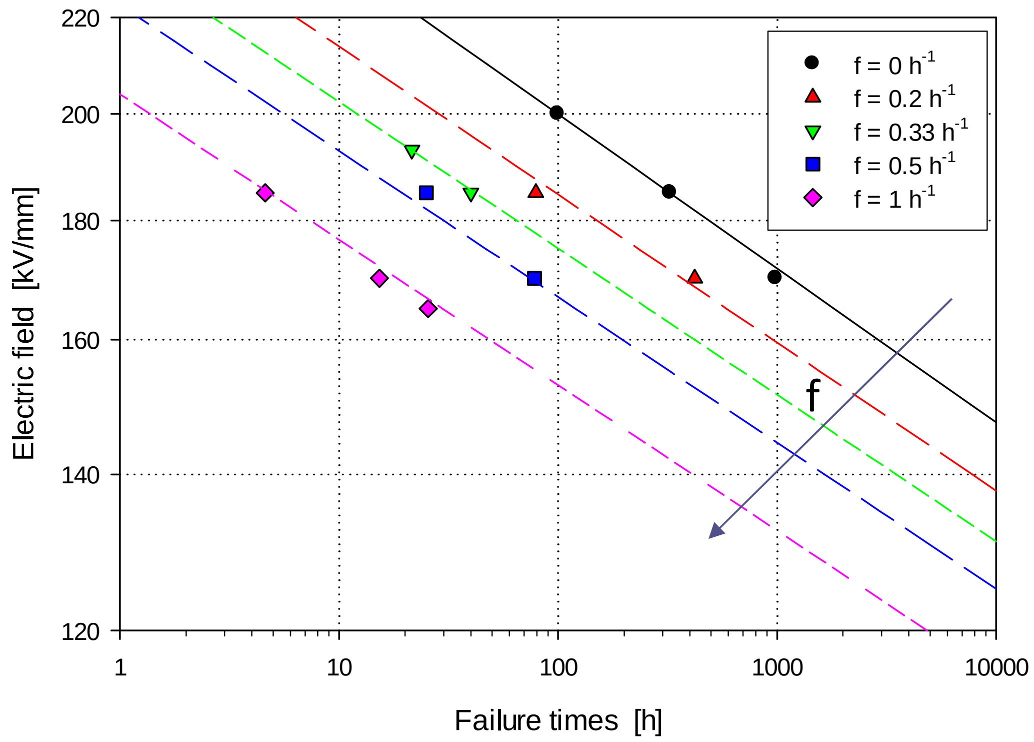
$$\frac{L}{L_i} - 1 = e^{A_1}\left(A_0 E^{bA_2}\right) s^{A_3} f^{A_4}$$

$c = bA_2 \qquad K = e^{A_1} A_0 s^{A_3} \qquad$ IPM: $L = L_0 E^{-n}$

$$L_i = \frac{L_0 E^{-n}}{1 + K E^c f^{A_4}}$$

Discussion

- Model fitting



$$L_i = \frac{L_0 E^{-n}}{1 + K E^c f^{A_4}}$$

Life tests on HDPE flat specimens at room T, with and without polarity inversions

Discussion

- Fitting quality depends on the number of parameters used in the model
  - in the case shown, good fitting of 12 data points to a 5-parameter model
- Model requirements:
  - (at least) 3 life tests necessary to evaluate the parameters of the IPM model
  - parameters c and K can be evaluated by SC measurements and A_4 by life tests with polarity inversions or, alternatively, all evaluated by life tests performed with different values of f and E

Conclusions

- Space charge under HVDC → electric field enhance → insulation reliability decrease → life modelling
- Effect of space charge on HVDC insulation depends also on converter technology
  - VSC: particular attention to heterocharge
  - CSC: most detrimental effect of SC with voltage polarity inversions (Homocharge becomes hetero).
    - If polarity repetition rate is not precisely known → probabilistic approach can be applied