



Dow Wire & Cable

Electrical Tree Initiation Revisited

S. Kisin

R.F. Eaton

C.F. den Doelder

P.J. Caronia*

Dow Wire & Cable

The Dow Chemical Company



* presenter

Presentation Outline

- Published Electrical Tree Models
- Simplified Electric Field Model
- Experimental Data
- Key Findings

Published Electrical Tree Models

- 3D models of electric field profiles using boundary element methods¹

Numerical calculations

- Models based on space charge trapping and charge recombination²

$$\left. \begin{array}{l} \text{div}(j)+d\rho/dt=0 \\ dE/dr=\rho/\epsilon\epsilon_0 \\ E=E(t); \end{array} \right\} \begin{array}{l} \text{simultaneous solving charge} \\ \text{migration equations; charge} \\ \text{trapping equations} \end{array}$$

- Percolation models³

$$\left. \begin{array}{l} \varphi = \varphi_0 - \sqrt{(e^3/\pi\epsilon\epsilon_0)}\sqrt{E} \\ V(r) = -(e^2/(4\pi\epsilon\epsilon_0 r)) - (e^2/(4\pi\epsilon\epsilon_0(d-r))) - eEr \end{array} \right\} \text{probability equations}$$

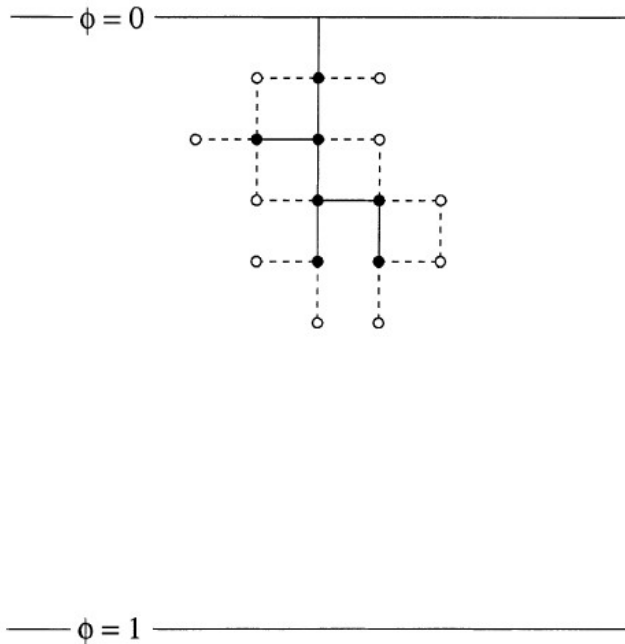
1- L. Cisse, S. S. Bamji, A. T. Bulinski, IEEE T. Dielect. El. Insul. 2002, 10, 176–180.

2- K. Wu, L. A. Dissado, IEEE T. Dielect. El. Insul. 2005, 12, 655–668.

3- K. Wu, L. A. Dissado, Ann. Rep. Conf. Insul. Dielect. Phen. 2004, 514–518.

Published Electrical Tree Models

- Stochastic models – Diffusion limited aggregation model (DLA)
Dielectric breakdown model (DBM)⁴



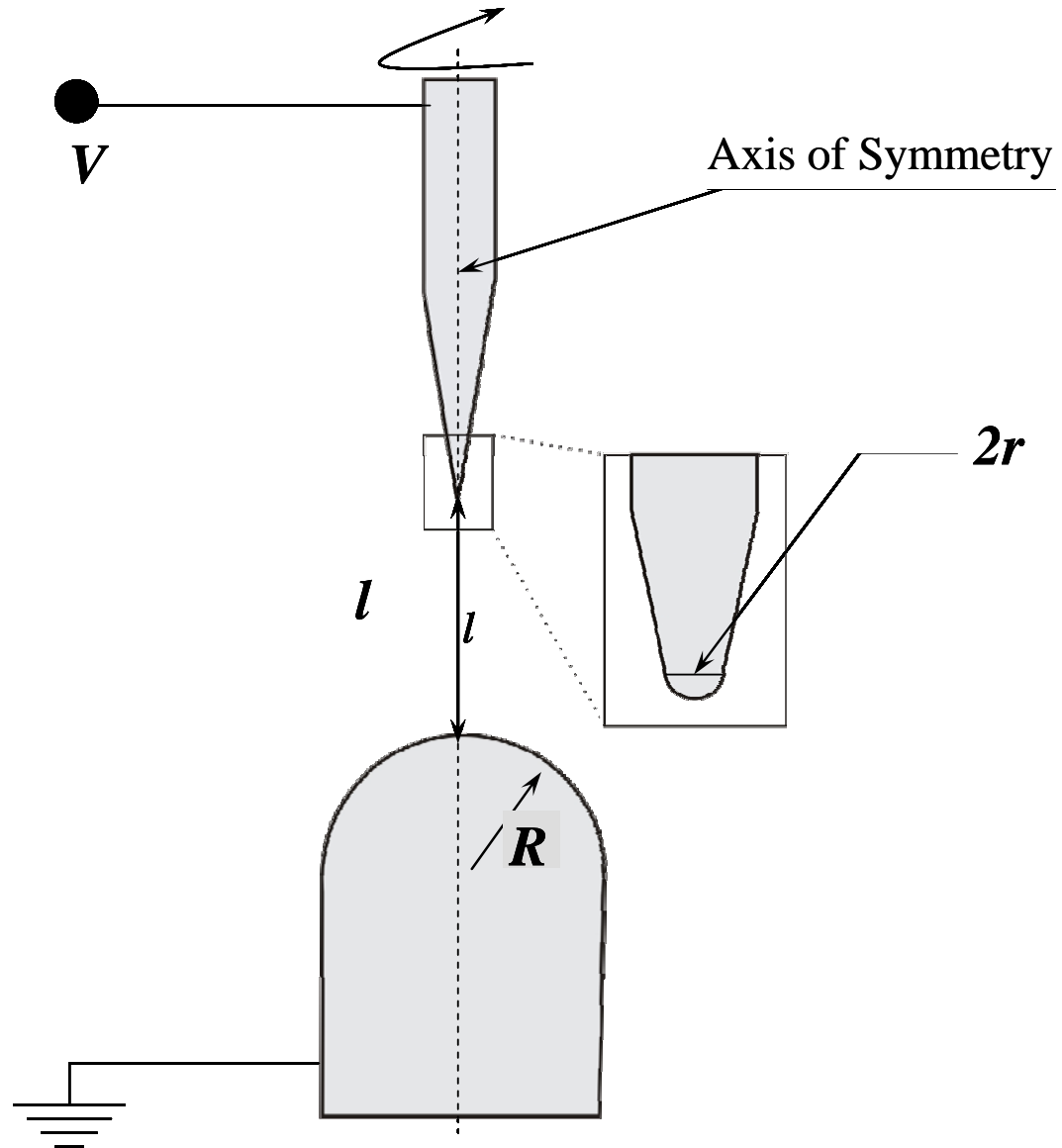
Tree represented by a fractal. In each (filled) point

$$\nabla^2 V_p = -\frac{\rho(x)}{\epsilon\epsilon_0}$$

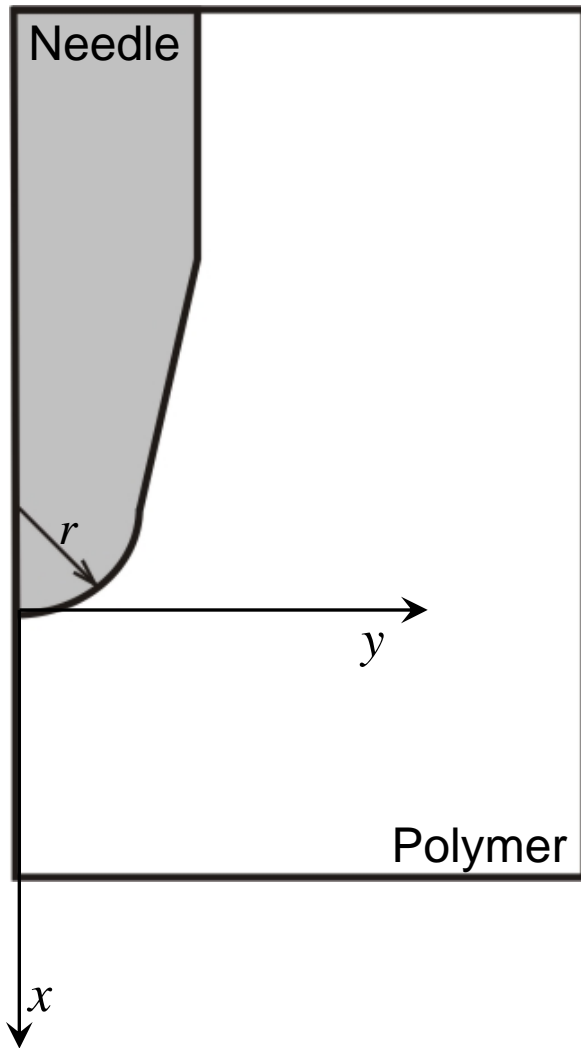
is solved, with addition of matching the solution to the next point and solving probability equations to determine the advancement of the tree (empty dots).

Laboratory Electrical Tree Initiation Test

- Field enhancing defects are simulated by sharp (needle-like) protrusions within the polymer
- Protrusions serve as electrodes generating strong divergent electric fields in the polymer
- A common test geometry is a double needle arrangement⁵
- 5 to 20 kV AC voltage applied
- Samples optically examined for tree initiation



Simplified Double Needle Treeing Test Geometry



Basic assumptions for the model:

1. R (dull needle radius) $\gg r$ so that the system geometry is close to needle-to-plane geometry
2. System has one axis of symmetry so we could use a simple model.
3. Used the sharp needle tip as the origin of the (Cartesian) coordinate system

Electric Field Calculation

General equation to describe electric potential in dielectric⁶

$$\nabla^2 V_p = -\frac{\rho(x)}{\epsilon\epsilon_0}$$

V_p -potential

ρ -injected space charge density

ϵ -dielectric constant of the polymer

ϵ_0 -dielectric permittivity of vacuum

The electric field gradient can be determined by :

$$E(x) = -\nabla V_p$$

Electric Field at the Needle Tip

The electric field at the tip can be expressed as :

$$E_{\text{tip}} = \frac{2V_0 \sqrt{\frac{r}{l}}}{r \ln \left(\frac{l + \sqrt{l^2 + 4r}}{r} \right)}$$

Prediction of Electric Field at Needle Tip

$$E_{\text{tip}} = \frac{2V_0}{r \ln\left(1 + \frac{4l}{r}\right)}$$

- Critical field for space charge injection in PE 1 GV/m⁷
- When $V_0 \geq 5.75$ kV then $E_{\text{tip}} \geq 1.0$ GV/m

Experimental Data⁸

Polyethylene samples stabilized with 0.5 %wt. of different polycyclic aromatic compounds.

Stabilizer	DNCV [kV]	MVD [kV·kg/mol]
None (reference sample)	8.5	–
o-Terphenyl	9.0	29
Naphthalene	10.0	19
Phenanthrene	10.0	26
Chrysene	11.2	38
Fluoranthene	14.0	44
Acenaphthylene	16.3	36
Pyrene	16.3	52
Anthracene	22.4	66

8- A.C. Ashcraft, R.M. Eichhorn, R.G. Shaw, *Laboratory Studies of Treeing in Solid Dielectrics and Voltage Stabilization of Polyethylene*, 1976 IEEE International Symposium On Electrical Insulation.

Quantum Mechanical Calculations*

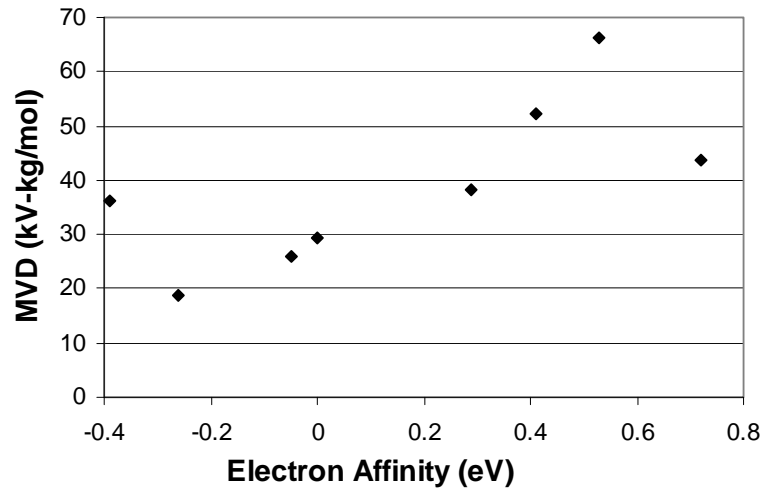
Objective : to identify the fundamental material properties that correlate additives impact on improved electrical treeing resistance

- Electron affinity – Energy difference between a neutral molecule and radical anion.
- Ionization energy – Negative value of the energy of the highest occupied molecular orbital of the neutral molecule

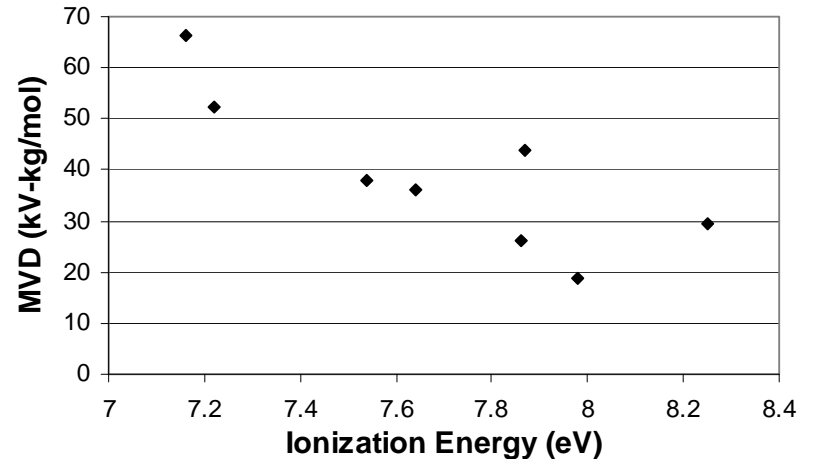
*Calculations done using Spartan molecular orbital package supplied by Wavefunction, Inc.

Quantum Mechanical Calculations

Electron Affinity



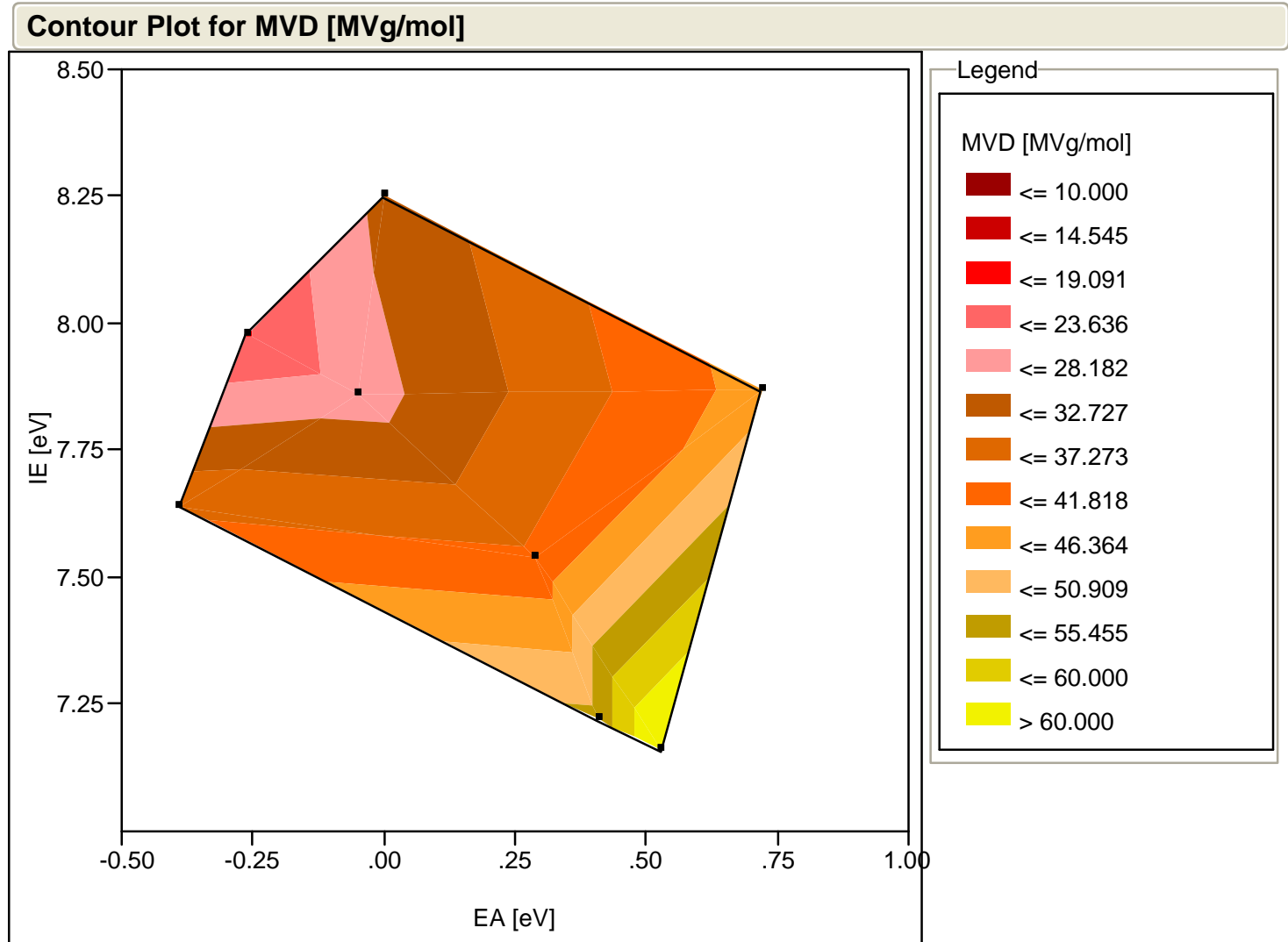
Ionization Energy



A single parameter does not explain the additive effect on the electrical tree initiation retardance

Fit of Quantum Mechanical Parameters to MVD

Two material parameters are a better model of the effects



Key Findings

- Resistance of PE to electrical tree initiation can be improved by use of voltage stabilizers with both :
 - high electron affinity
 - and
 - low ionization energy
- Both electron affinity and ionization energy can be estimated using a state of the art quantum chemistry (molecular orbital) simulation model
- These findings, along with studies into tree propagation, will improve capabilities to design advanced material formulations