

# Electrical Insulation Research Center

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## Cable Failure, Diagnostics and Rejuvenation

Steven Boggs

# The History – PE Cables

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- The Zeigler catalyst was invented in 1953 and mass production of HDPE started in the late 1950's.
- Chemically cross linked PE was invented by GE in 1963.
- The first generation of shielded PE cables started to fail after ~7 years from water trees caused by cotton tape conductor shields. Few remain in service.
- The second generation of shielded PE cables used “dirty” extruded shields, steam curing, and lasted a few years longer before starting to fail.
- Through subsequent generations of PE cables, the semicons, dielectric, and manufacturing have been improved to produce much more reliable cable.

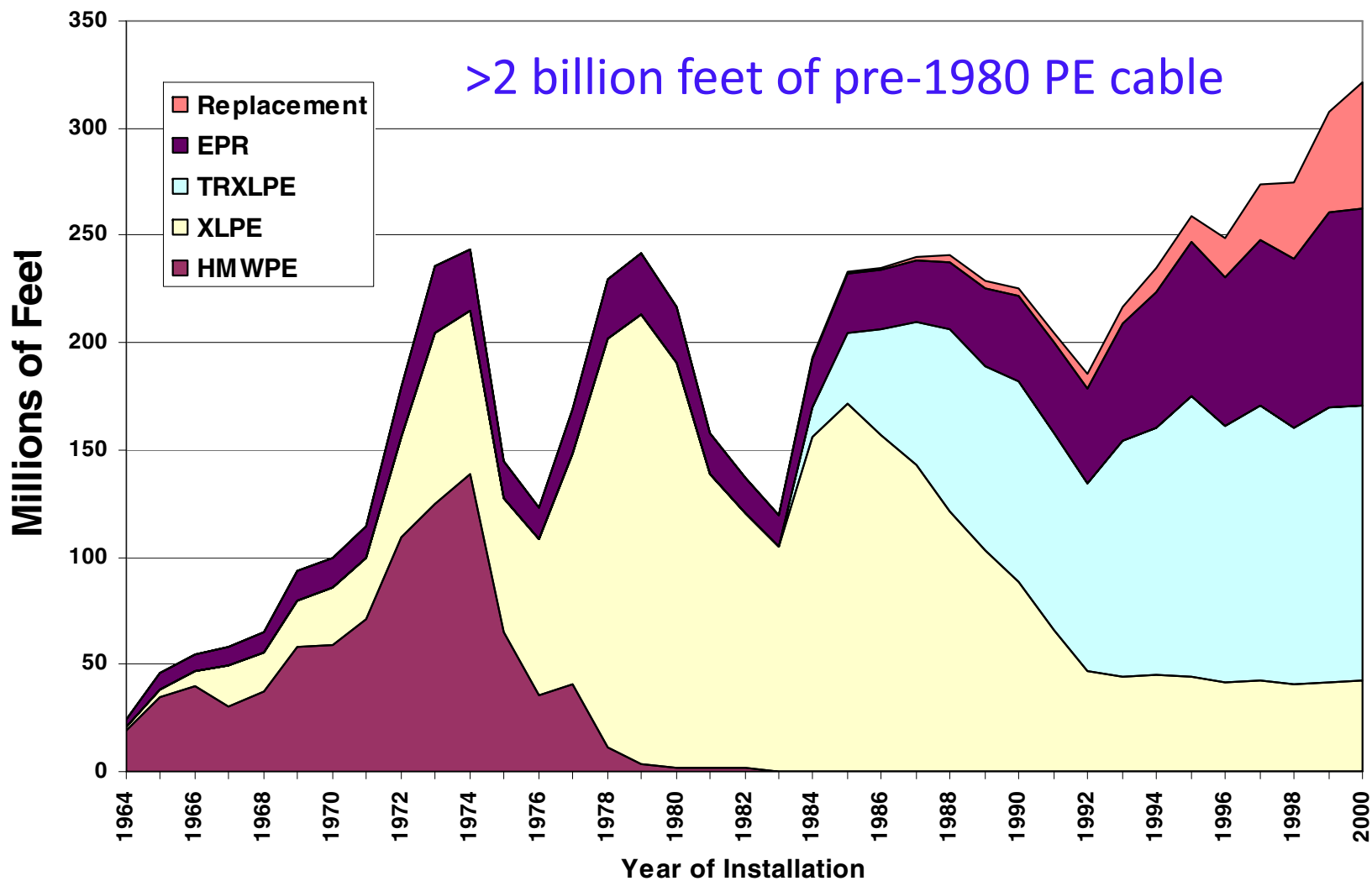
# The History – EPR Cables

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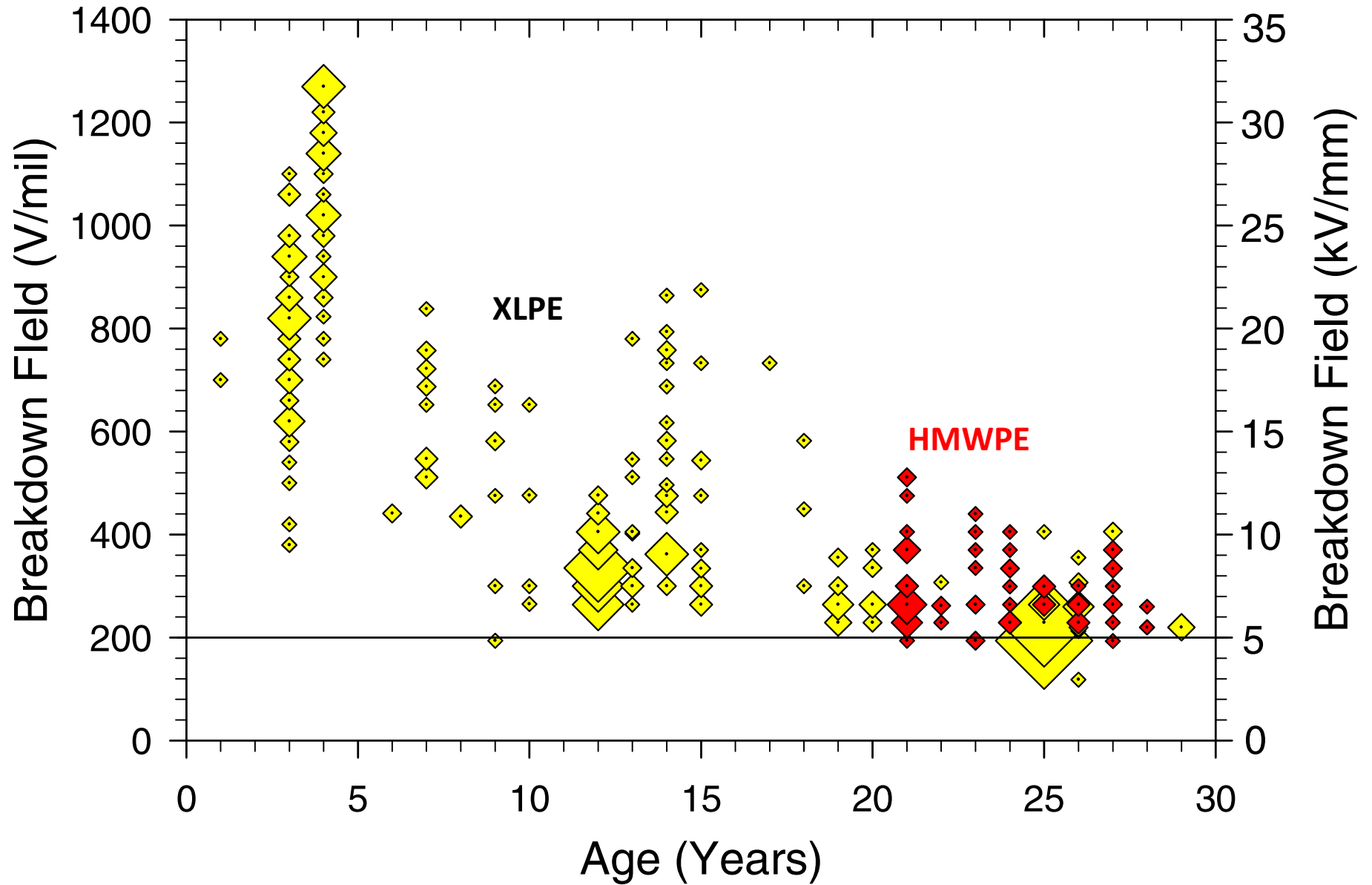
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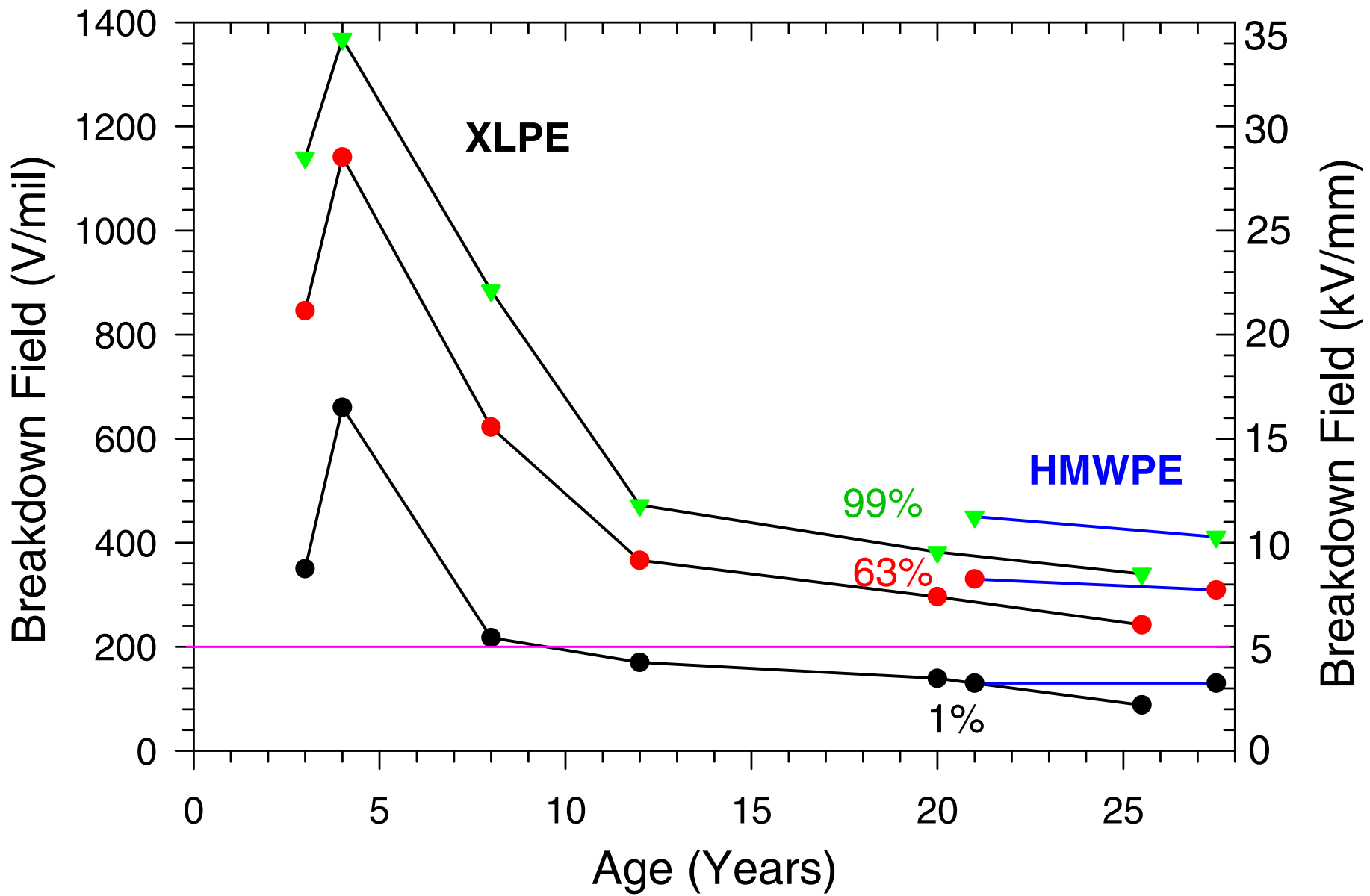
- The first generation of “black” EPR was introduced around 1962 and, while much more reliable than the first generation of PE cable, did not meet utility expectations.
- The second generation of “orange” EPR cable was introduced around 1970 and has provided very reliable service for over 35 years with no known systematic cause of failure.

# Medium Voltage Cable Installation History



# The Problem





# Why are some Years Worse?

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- Source of Supply
  - Utilities often put out yearly tenders for cable and the source varies from year to year
- Location of Installation
  - Regional expansion varies from year to year, and some locations may have better cable environments than others
- If the cause of such variations can be identified, it may be important to decision making

# The Cause

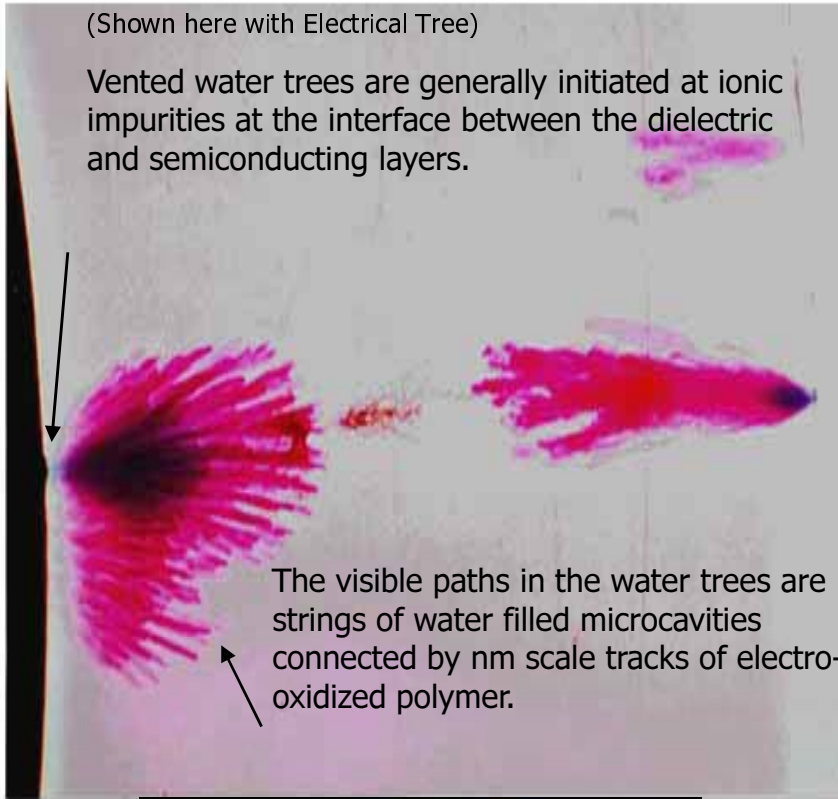
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- Electrochemical degradation (“water treeing”), which occurs in hydrophobic polymers which can be electro-oxidized to a substantially more hydrophilic state.
- “Vented” water trees tend to grow from ionic impurities at the semicon-dielectric interface
- “Bowtie” water trees tend to grow from cavities and impurities in the dielectric.

## Vented Water Tree

(Shown here with Electrical Tree)

Vented water trees are generally initiated at ionic impurities at the interface between the dielectric and semiconducting layers.

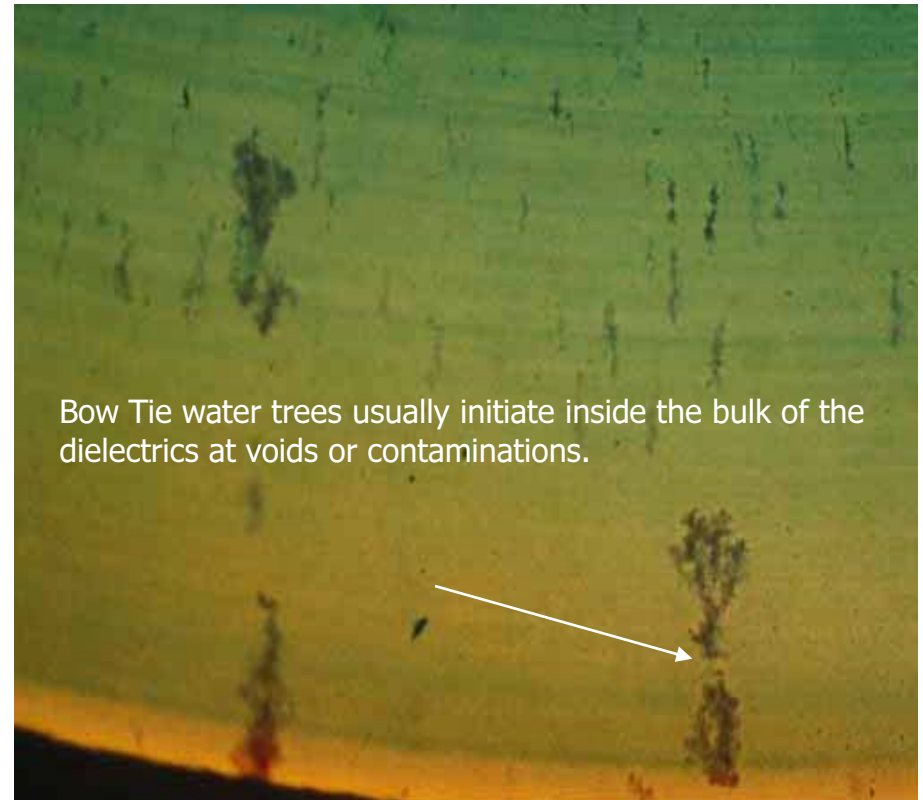


The visible paths in the water trees are strings of water filled microcavities connected by nm scale tracks of electro-oxidized polymer.



Steam cured XLPE cable had a “halo” of microvoids in the middle of the insulation that gave rise to very large numbers of bowtie trees, the spatial correlation of which could compromise impulse breakdown

## Bow Tie Water Trees



Bow Tie water trees usually initiate inside the bulk of the dielectrics at voids or contaminations.

# Model for Water Tree Growth in TR-XLPE

## What is a Water Tree?

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- A water tree is a pattern water-filled cavities connected by electro-oxidized tracks which is self-propagating because the electro-oxidized polymer is substantially more hydrophilic than the base polymer, which causes water to condense from the base polymer into the electro-oxidized regions.
- Formation of a water tree requires a polymer which can be electro-oxidized from a highly hydrophobic state to a substantially more hydrophilic state.

# History of Water Treeing

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- First recognized in 1969
- Laboratory investigations tended to be carried out on samples grown at very high field.
  - Mechanical water trees can grow, and the degree of chemical vs mechanical damage depends on the electric field.
  - Spectroscopic sensitivity was limited (no micro FTIR)
  - Most of the investigators were EE's, not chemists.
- Only when investigators started to look at field grown trees did they see chemical evidence of electro-oxidation.
- By the time significant progress was made, the funding agencies were sick of sinking money into water treeing with little to show for it.

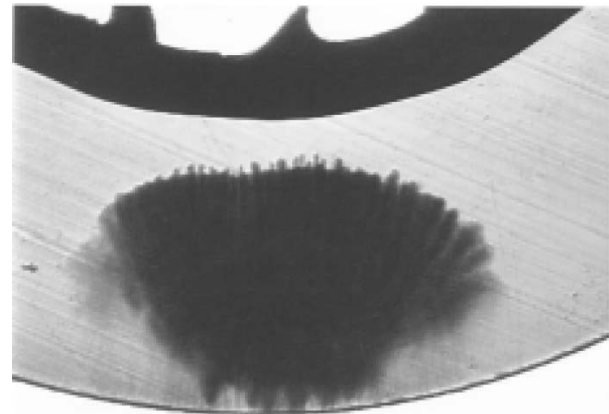
# Technical Aspects of PE-Based Shielded Distribution Cable are Dominated by Electro-oxidation

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- Requirements to grow a water tree
  - AC field above about 1 kV/mm
  - Hydrophobic polymer which can be electro-oxidized to substantially more hydrophilic
  - Water, but not very much
  - A source of ions to provide the appropriate electrical conductivity
    - Not too high, and not too low

Water tree in cable taken from the desert of Saudi Arabia

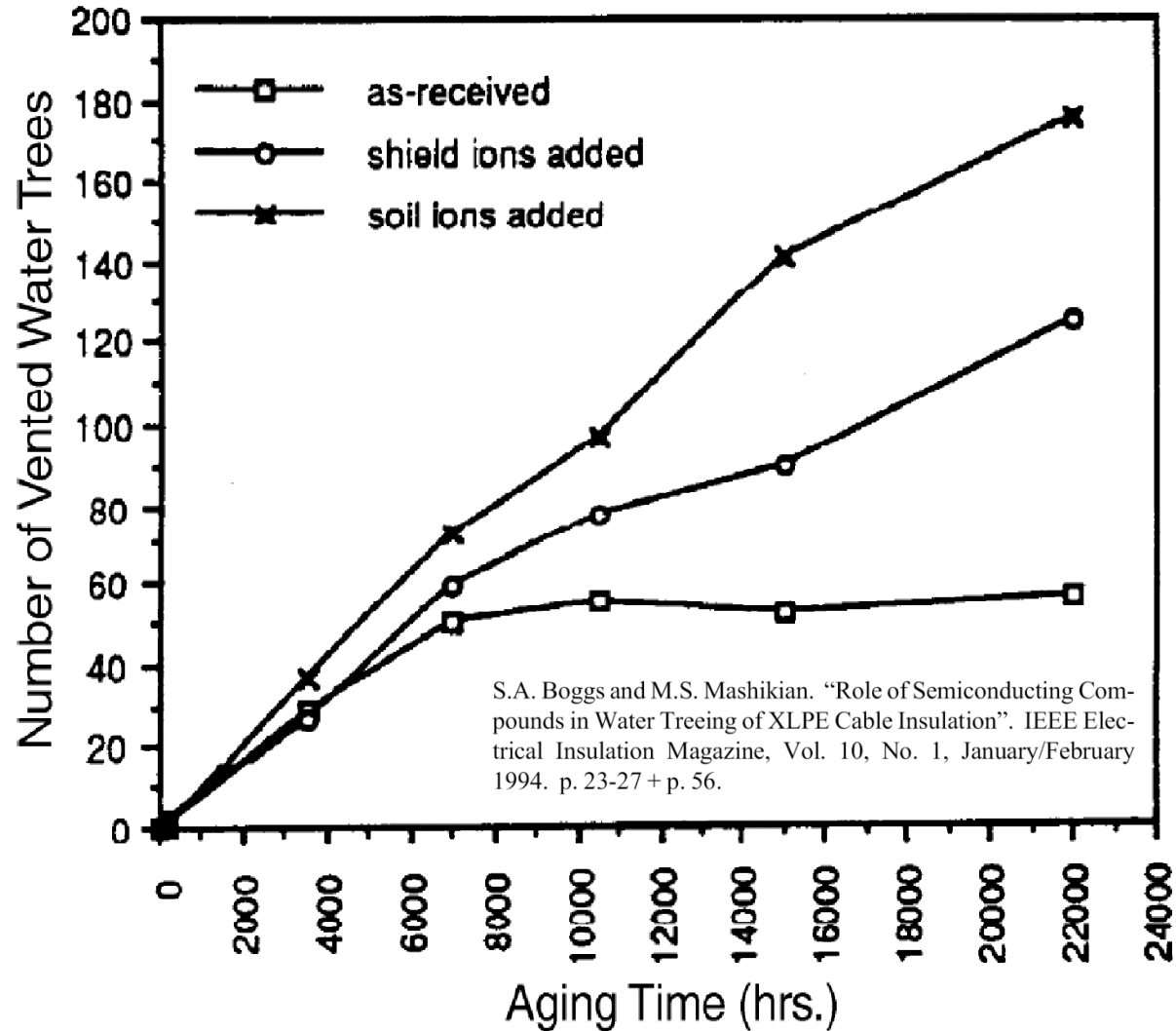


# “Facts” About Water Trees

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- At moderate electric fields, water trees grow from ionic impurities, not stress enhancements
- Growth of a water tree at moderate electric fields requires a source of ions
- Long term growth of bowtie trees is probably limited by diffusion of water through the polymer
- The tendency to grow water trees goes as approximately the square of the electric field
- Water tree growth tends to increase roughly linearly with frequency to at least 3 kHz.

# Water Treeing Stops Without Ions



# Characteristics of a Chemical Potential for Water Treeing

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1. Results in self-propagation through the dielectric
2. Requires an electric field
3. Frequency dependent
4. Depends heavily on ion concentration

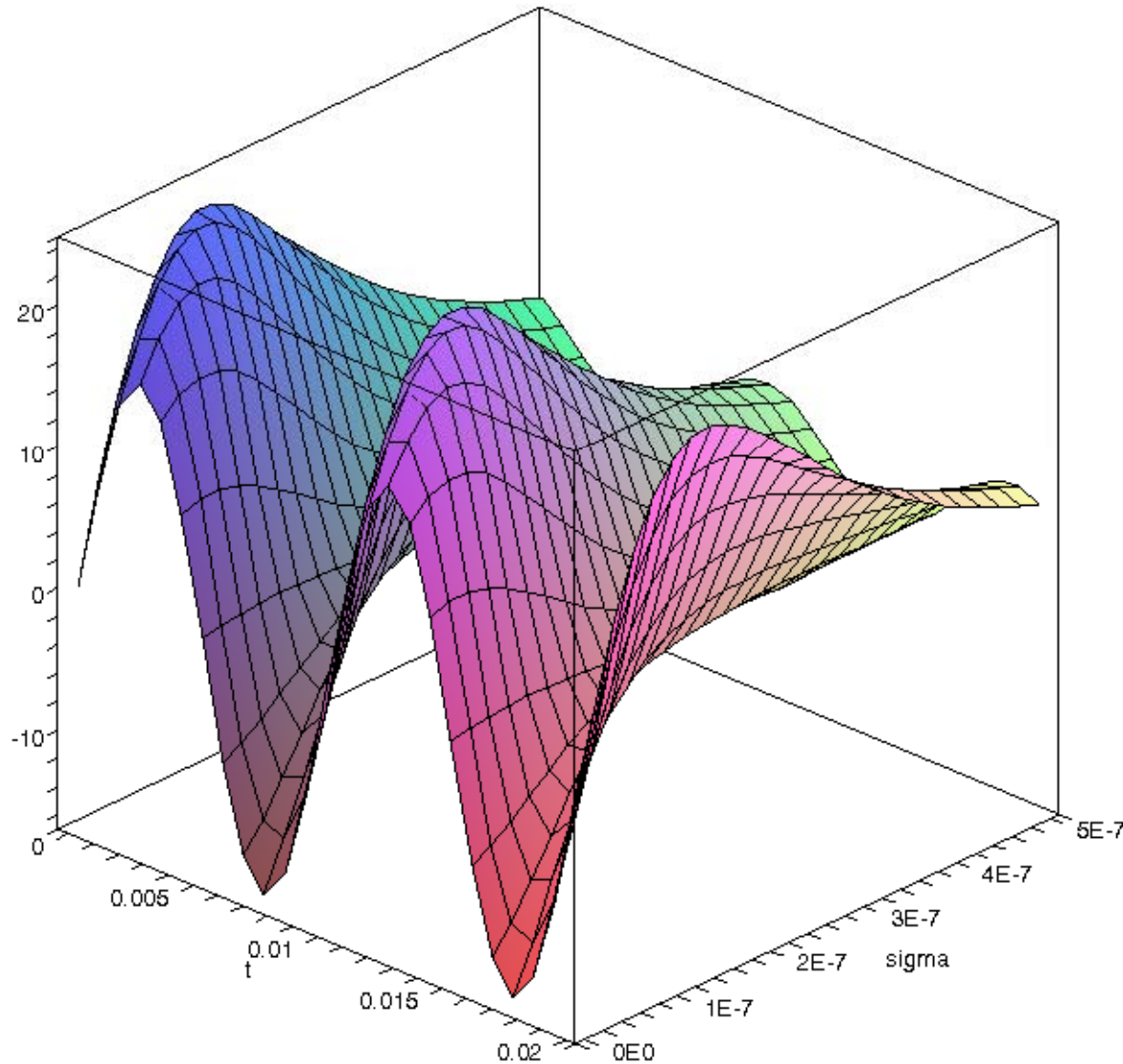
# Basis for Computation

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$$\Psi_E(t) = \Psi_{field}(t) = \frac{1}{2} \int \epsilon E(t)^2 dV$$

$$\mu_i(t) = \frac{\partial \left\{ \frac{1}{2} \int \epsilon E(t)^2 dV \right\}}{\partial n_i} = \frac{1}{n_w} \frac{\partial \left\{ \frac{1}{2} \int \epsilon E(t)^2 dV \right\}}{\partial \sigma} \frac{\partial \sigma}{\partial c_i}$$

# Chemical Potential for Sphere



What is the relevant chemical potential?

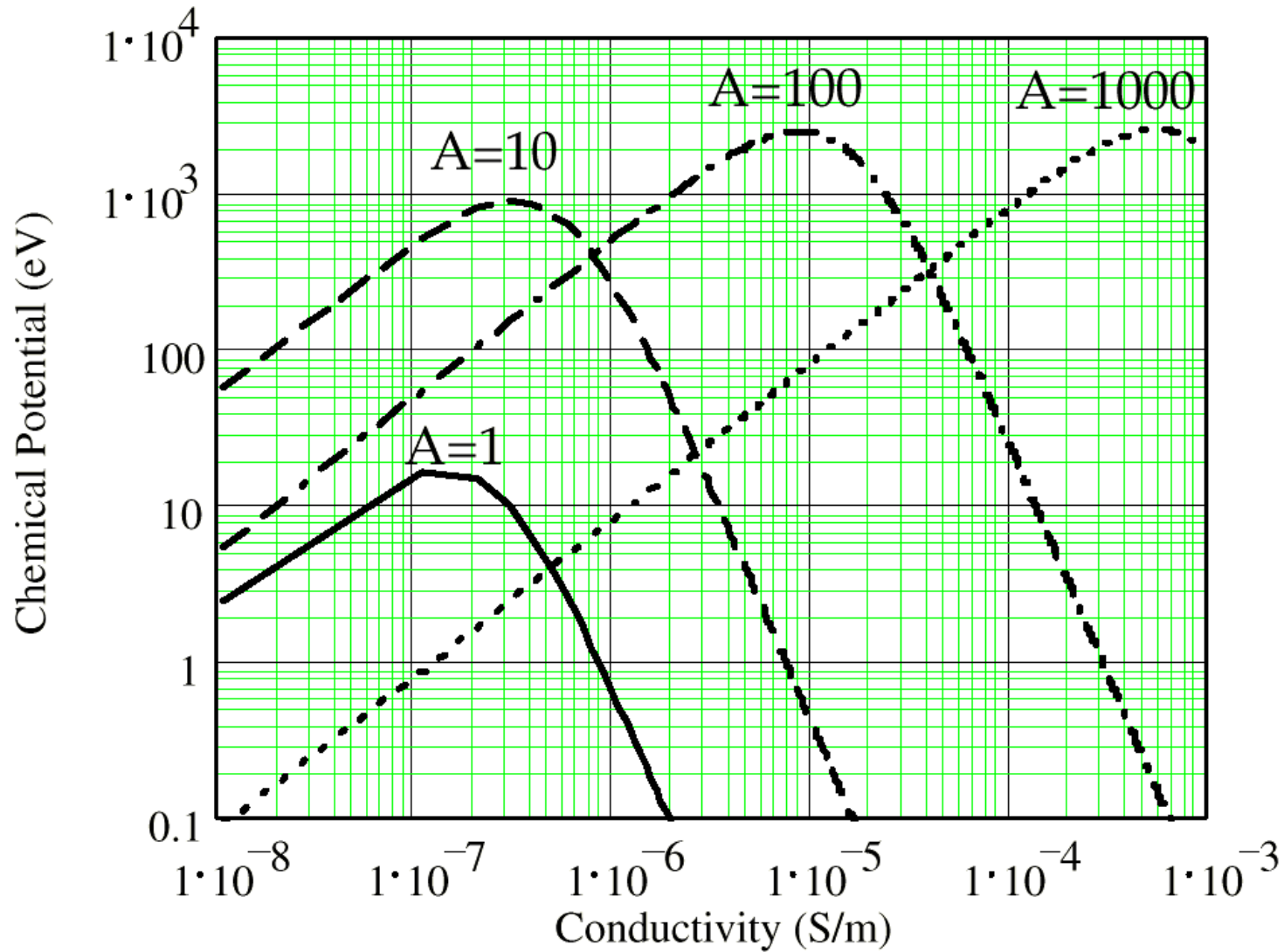
Positive Peak or DC Offset?

Total energy or energy in polymer?

Zeller believed the DC offset was the relevant potential.

But for a rapid, irreversible reaction, it might be the positive peak.

# Chemical Potential for Water Treeing

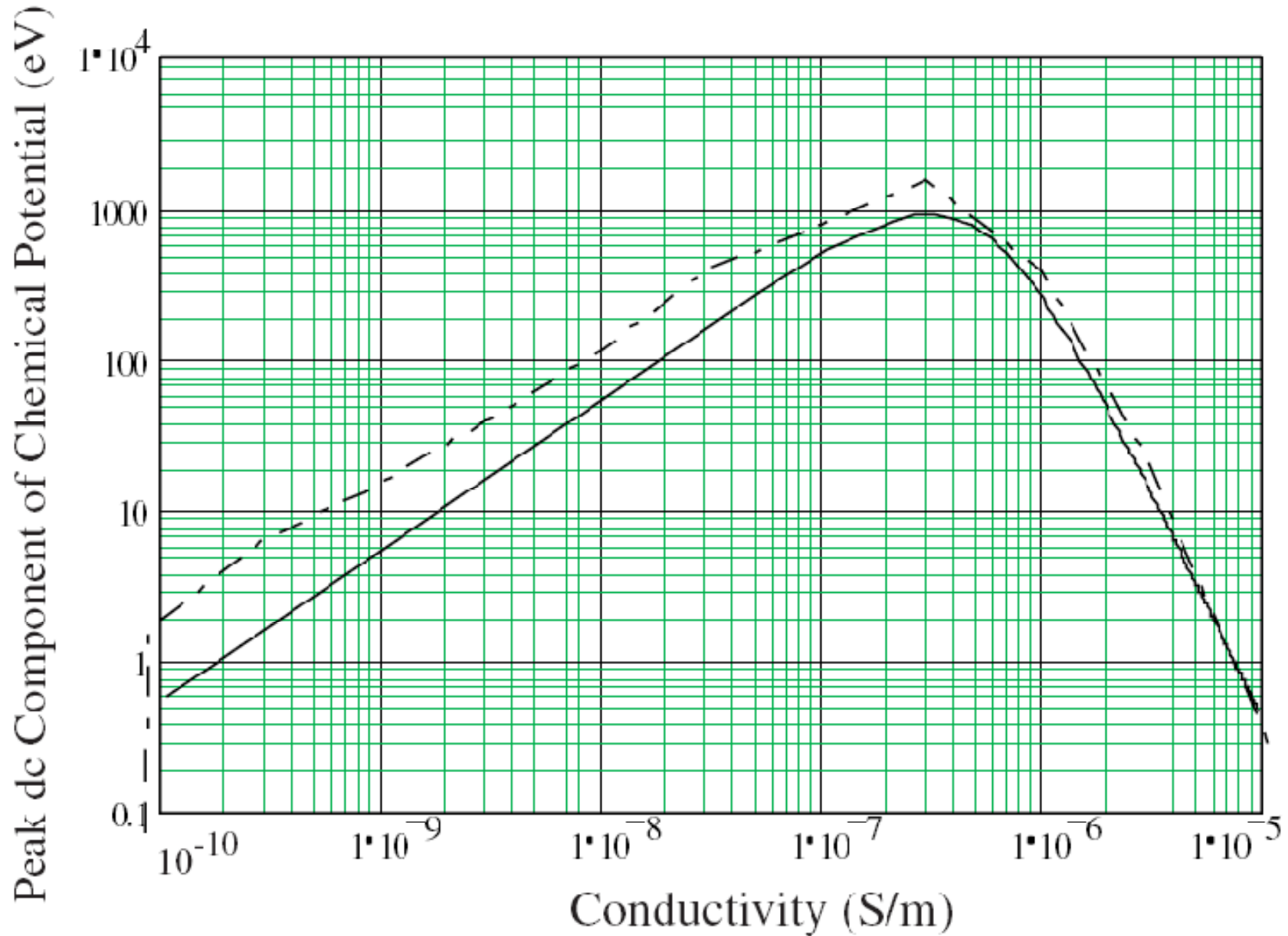


# Numerical Method

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- Use program for transient nonlinear FEA
- Compute several cycles with a water conductivity,  $\sigma$
- Compute several cycles with a water conductivity  $1.05\sigma$
- Compute energy at each time, take difference, and convert to chemical potential

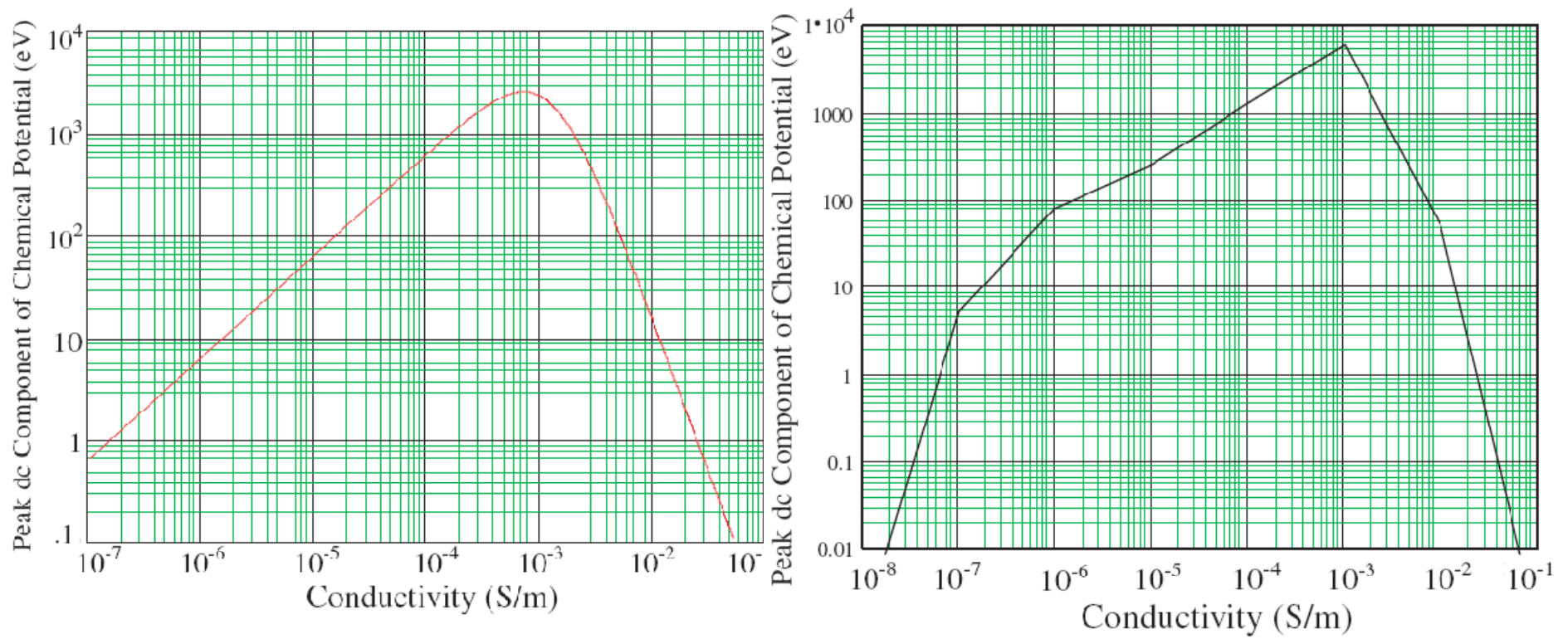
# Numerical & Analytical Computation



# Analytic Approximation (Zeller) and Numerical Computation of Chemical Potential for Two, 1 $\mu\text{m}$ Diameter Spheres Connected by a 10 nm dia., 5 $\mu\text{m}$ Long Channel.

Background field: 5 kV/mm

Chemical potential goes as square of field.



# Chemical Potential

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- Zeller's explanation for chemical potential seems likely and is a major step forward.
- The chemical potential can be computed numerically for axisymmetric configurations.
- The chemical potential is typically large enough to drive electro-oxidation over several orders of magnitude of water conductivity
- But knowledge of the chemical potential does not imply knowledge of the chemistry.

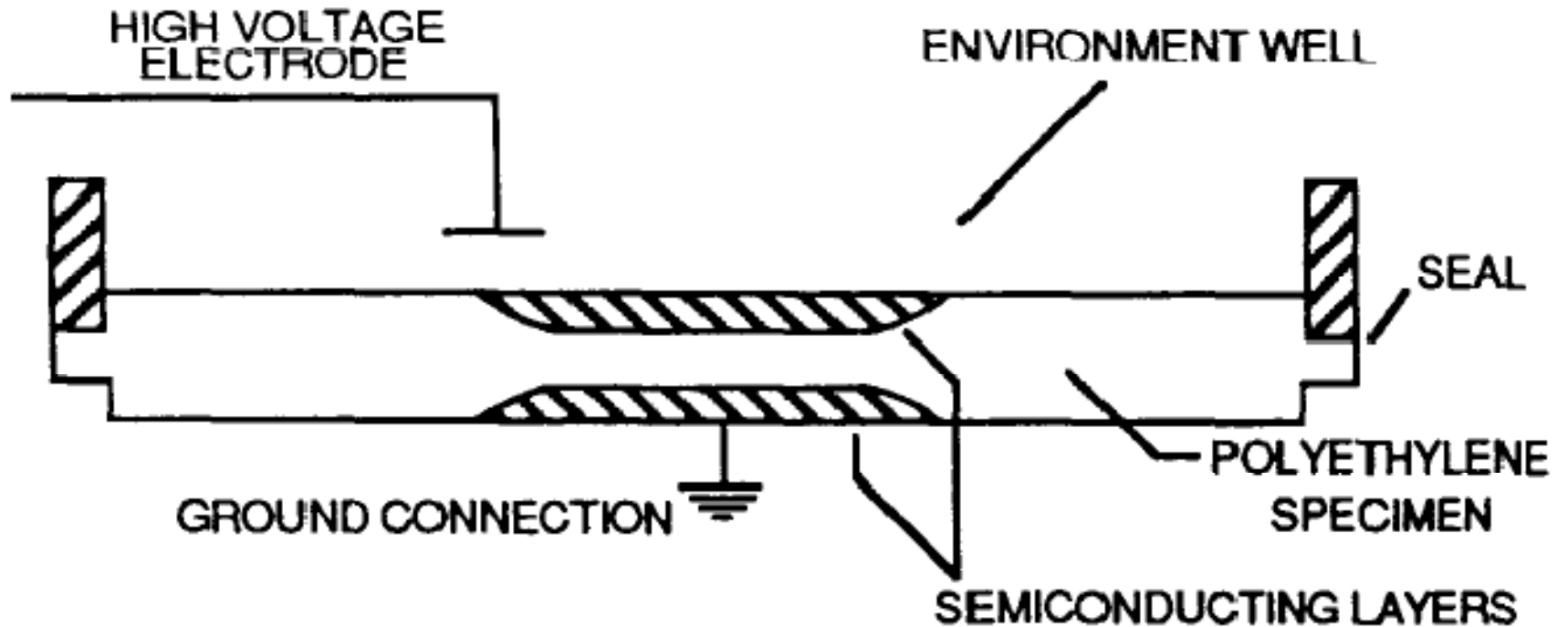
# Laboratory Growth of Water Trees

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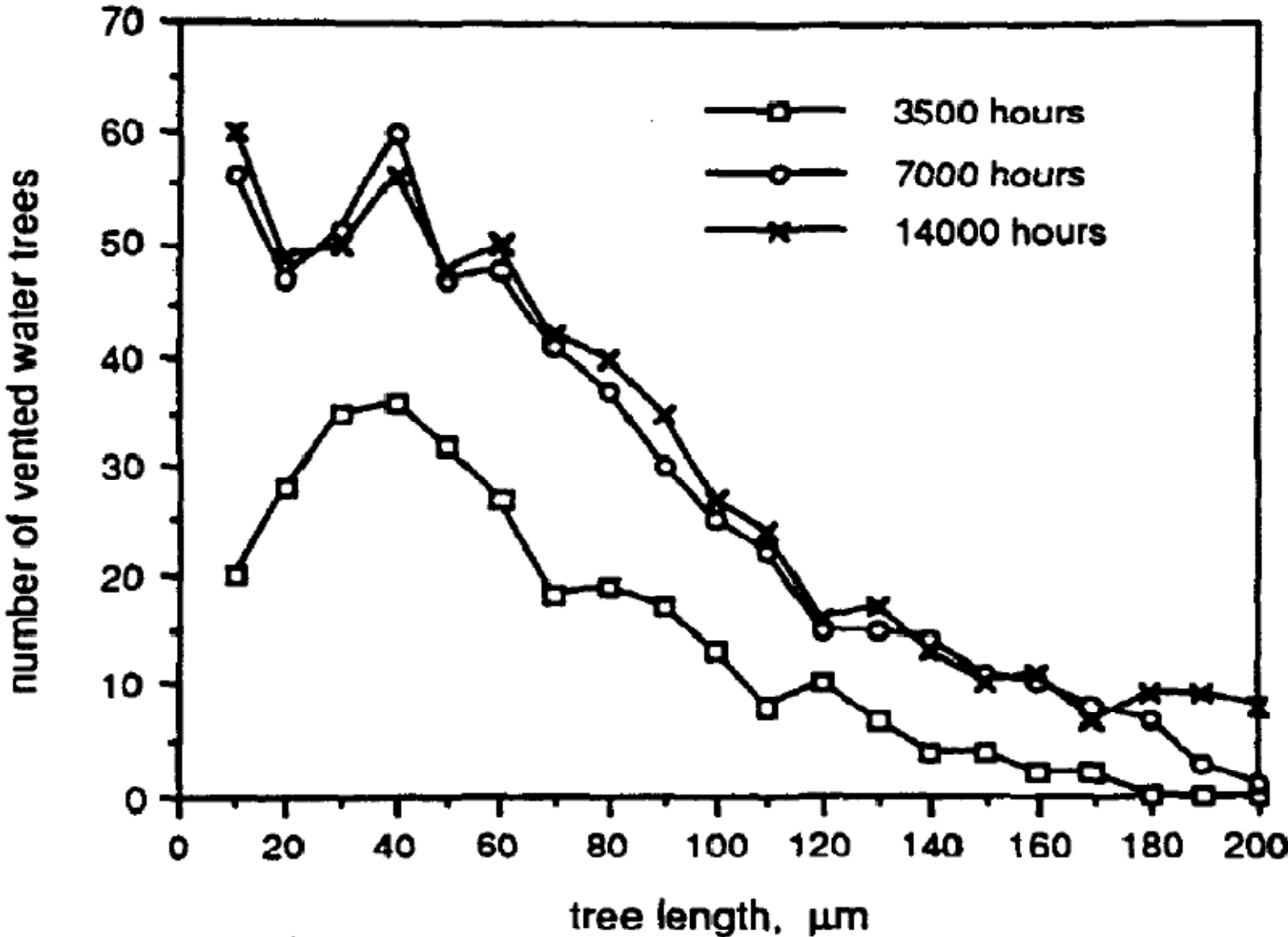
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- Water trees grow from water needle electrodes readily and rapidly but are more electro-mechanical than electrochemical
  - Test used for very preliminary screening of materials
- A good simulation of field conditions requires semicon electrodes and takes months to grow.
  - Provides a comparative test with good correlation to field experience.

# Lab Test for Water Treeing



# Vented Tree Length Distribution vs Time



# Mechanisms of Water Tree Resistance

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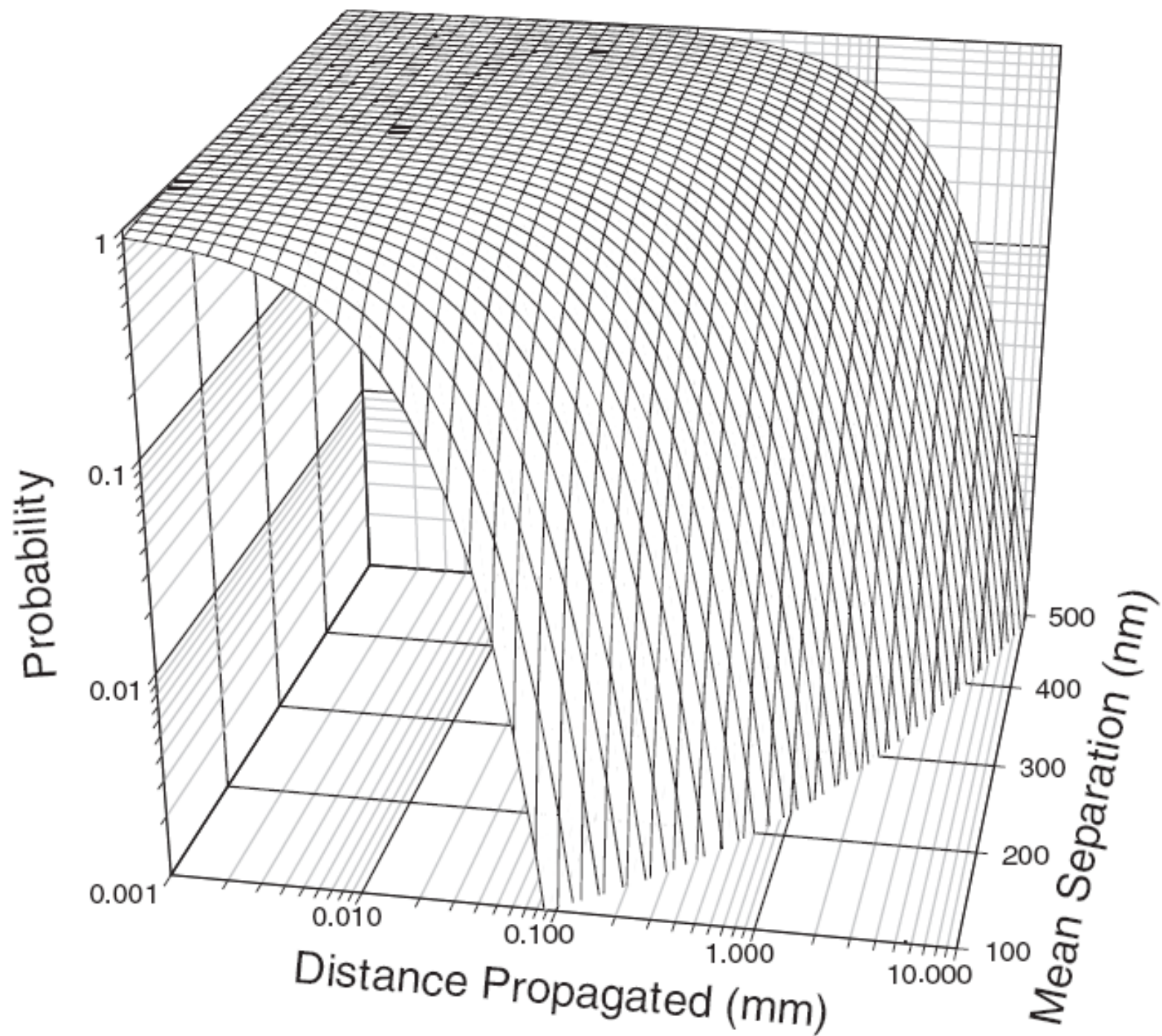
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- Make the polymer more hydrophilic
- Make any water in the polymer very conductive
  - Add a salt to the polymer
- Make any water in the polymer nonconductive
  - Place an ion “filter” in the system

# TR-XLPE

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- An early experimental compound from used powdered NaCl in the XLPE, which was effective.
- Present TR-XLPE involves a hydrophilic additive
  - One assumption would be that this additive stops water tree channels by inhibiting condensation of moisture in the electro-oxidized region.
  - This can be treated as a mean free path problem.



# Paths to Inhibit Water Tree Growth

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- Low water conductivity
  - Filter the water (mineral filled jacket)
  - Clean semicons, jacket, and blocked conductor
- High water conductivity - add salt to the polymer
- Hydrophilic system (TR-XLPE and EPR)
- Low water permeability “semicons”
- Water tree growth is a balance between field effects and hydrophobicity.
  - For example if you take TR-XLPE in thin wall model cable, you can grow water trees through the wall

# Water Trees and Diagnostics

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- Water trees increase dielectric loss ( $\tan(\delta)$ )
- Water trees cause dielectric absorption
  - Absorption of charge which is released, *slowly*, if the sample is shorted
- Water trees cause (small) harmonic currents
- Water trees decrease insulation resistance
  - But only if they grow all the way through
- Water trees cause formation of electrical trees which generate PD.

# What is being Measured?

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- A water tree is much more conductive than the polymer.
  - In the trip region  $\tau$  must be comparable to power frequency
    - Such a time constant implies that the current and voltage are out of phase substantially, i.e., dielectric loss
  - In the root region, a dielectric time constant in the range of  $\mu\text{s}$ 
    - Important for the effect of lightning impulses on water trees.
- In the water tip region, a gradient of conductivity occurs from the water tree to the base polymer
- Current density and position-dependent resistivity imply formation of space charge.

$$\zeta(x) = J \varepsilon \frac{d\rho(x)}{dx}$$

$J$ =current density

$\varepsilon$ =dielectric constant

$\rho$ =resistivity

# What is Measured?

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- Under AC voltage, variation in conductivity near the water tree tip causes dissipation & increases  $\tan(\delta)$
- For isothermal relaxation or recovery voltage, space charge causes a current after the cable is shorted for a few seconds
- In all cases, an ***average*** property is being used to diagnose an ***extreme*** value
  - This only works if a correlation has been established between the average property and the extreme value.
  - This correlation may be cable or system specific, depending on operating conditions

# Insulation Resistance

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- Unless the water tree has grown ALL the way through the dielectric, a change in IR can seldom be observed.
- Under field conditions, leakage paths caused by accessories pose a major problem.
- Good way to locate water trees which have grown through the insulation in the lab.
- Generally TERRIBLE diagnostic under field conditions.

# Impulse Reflection from Water Trees

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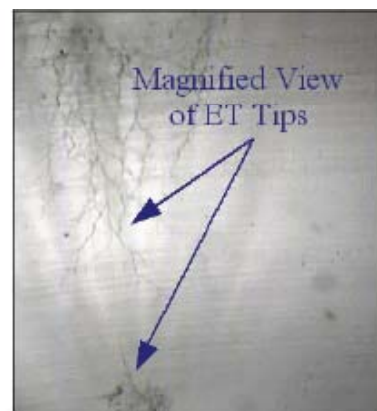
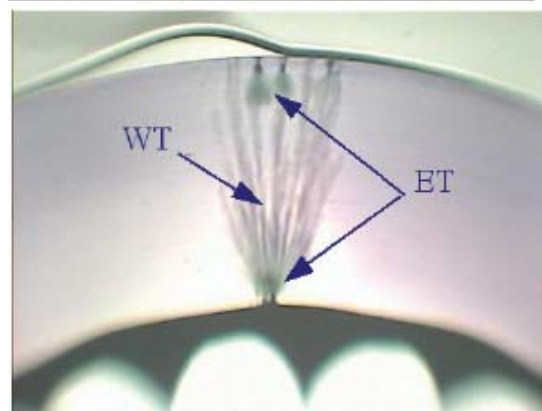
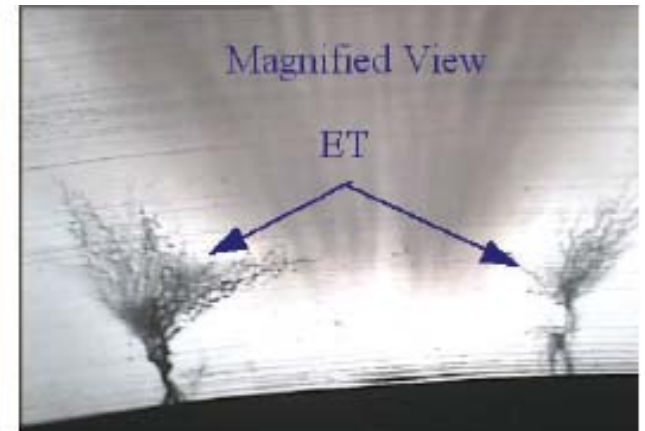
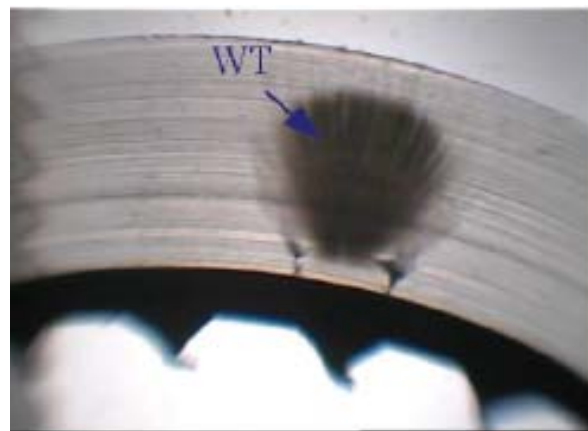
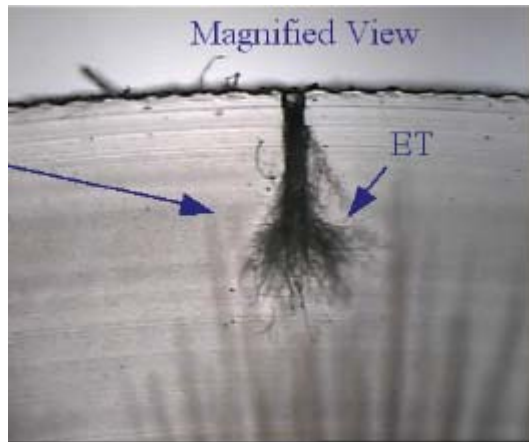
- DC voltage was applied to cause space charge at water trees, then a pulse was sent down the cable, and reflections were detected from the water trees.
- This approach was developed in the Russia and applied in North America but damaged the cable.
- When AC is applied, the space charge causes a field enhancement for the reverse polarity which tends to initiate electrical trees.

# Water Trees and PD

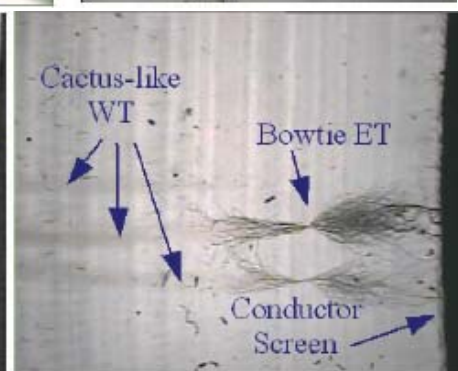
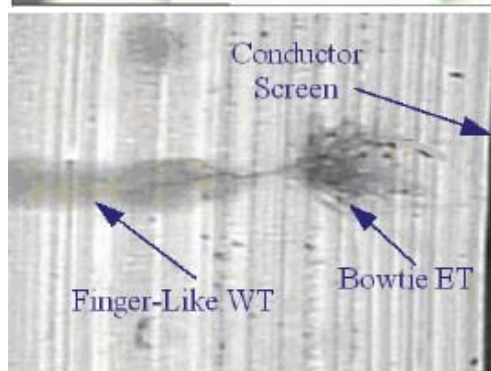
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- All past work indicates that water trees do not cause partial discharge
- However, non-PD electrical signals have been observed from water trees under laboratory conditions by Dorris et al.
  - Consistent with rapid yielding of the polymer causing a step increase in capacitance.
- Electrical trees can be associated with water trees

# Water Trees with Electrical Trees



- The electrical trees were detected in the field with PDIV of 2 to 2.5 pu.
- The electrical trees were detected at the same location two or three years in a row.
- This suggests that a heavily water treed cable is likely to have some electrical trees which may not grow to failure rapidly.

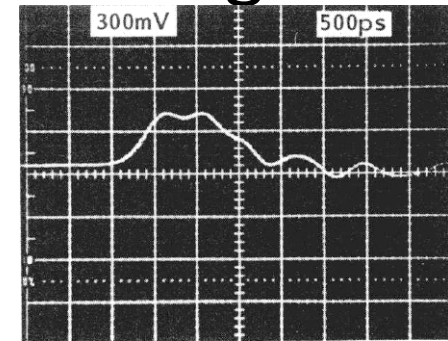


M. S. Mashikian and A. Szatkowski, "Medium Voltage Cable Defects Revealed by Off-Line Partial Discharge Testing at Power Frequency". IEEE EI Magazine, Vol. 22, No. 4, July/Aug 2006. pp. 24-32.

# Water Trees & Electrical Trees

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- We have very little knowledge about electrical trees grown at low fields ( $\sim 2$  kV/mm)
  - Researchers do not have sufficient patience
  - At laboratory stresses, electrical trees normally progress to failure rapidly
- Evidently, electrical trees in medium voltage distribution cable can last for years
- But are the trees active at 1 pu?
  - If not, how did they grow?
  - Probably the PD at 1 pu is too small to detect in the time domain under field conditions. At higher fields, multiple discharges cascade down tree channels.



# Frequency Domain PD Detection

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- PD detection is generally more sensitive, if less quantitative, when carried out in the frequency domain.
- Cablewise conducts PD detection in-service and in the frequency domain to improve sensitivity
- Discharge is normally observed for any heavily water treed cable and is an indication of cable condition.
- Water trees do not generate discharge, so this must be caused by electrical trees.

# Conclusions – PE Diagnostics

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- Diagnostics based on averaged parameters are only of value if a statistical correlation has been developed with typical cable condition. The degree to which such correlations can be transferred from one system to another is not known.
- PD from electrical trees associated with water trees is a clear indication of poor cable condition
- Diagnostics based on non-PD electrical signals, if real, appear promising but are not yet developed.

# How Big is My Problem?

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- If we analyze historical data, we can estimate future failure rates based on an assumed in-ground population
  - But how much as already failed and been replaced?
  - The number of splices in direct buried cable is often much greater than utility records show
  - In a duct-based system, this implies that more cable may have been replaced than utility records indicate
  - Thus the in-ground population of low quality cable may be smaller than utility records suggest.

# Options

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- Replace
  - Impractical in the short term
  - Need basis to prioritize replacement
  - Field testing can provided limited insight
- Rejuvenate
  - About half the cost of replacement
  - Requires that neutral be in acceptable condition
  - Has a good track record for reducing failure rates
- Wait until failure

# Replace – but Where?

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- Routine Field Test Programs (e.g., PPL)
  - Conduct continuous, system wide tests
    - PD,  $\tan(\delta)$ , depolarization current, etc.
  - With criteria for accept, rejuvenate, replace
  - Requires taking circuits out of service
  - Over time, the failure rate has been reduced substantially
- In-Service Test Programs
  - PD & concentric neutral assessment is possible in-service (without an outage)
  - Objective is typically to prioritize replacement or reduce the likelihood of failure on critical circuits

# Present State-of-the-Art

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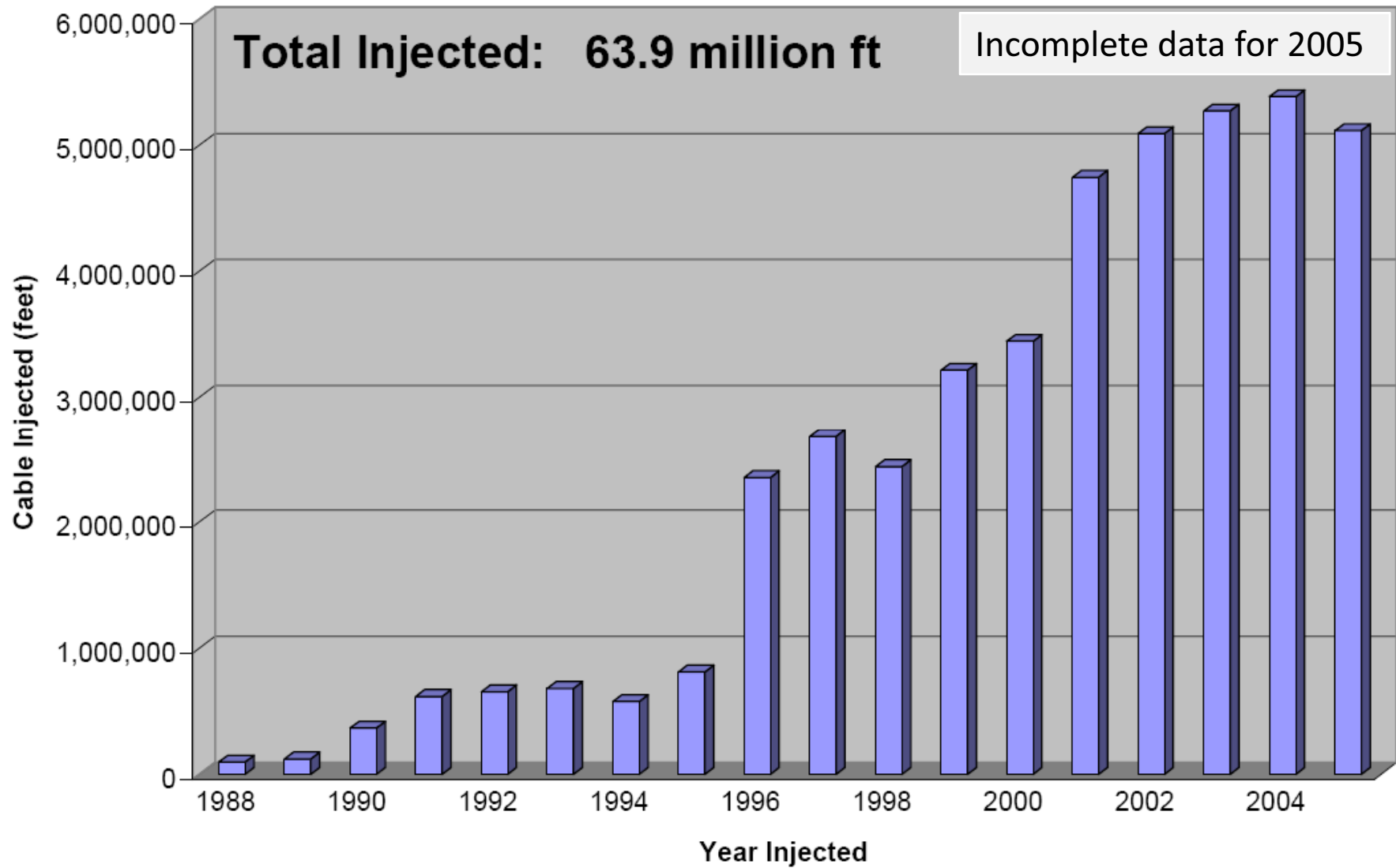
- A range of approaches to field PD measurement are being marketed
- While they differ in detail, they can generally diagnose unambiguously very bad cable and very good cable - the devil is in the details between
- Field PD measurement is most effective to address a known problem
- For use to assess overall condition, PD measurements are best combined with other techniques such as dielectric loss, spectroscopy, etc.

# Silicone Injection Cable Rejuvenation

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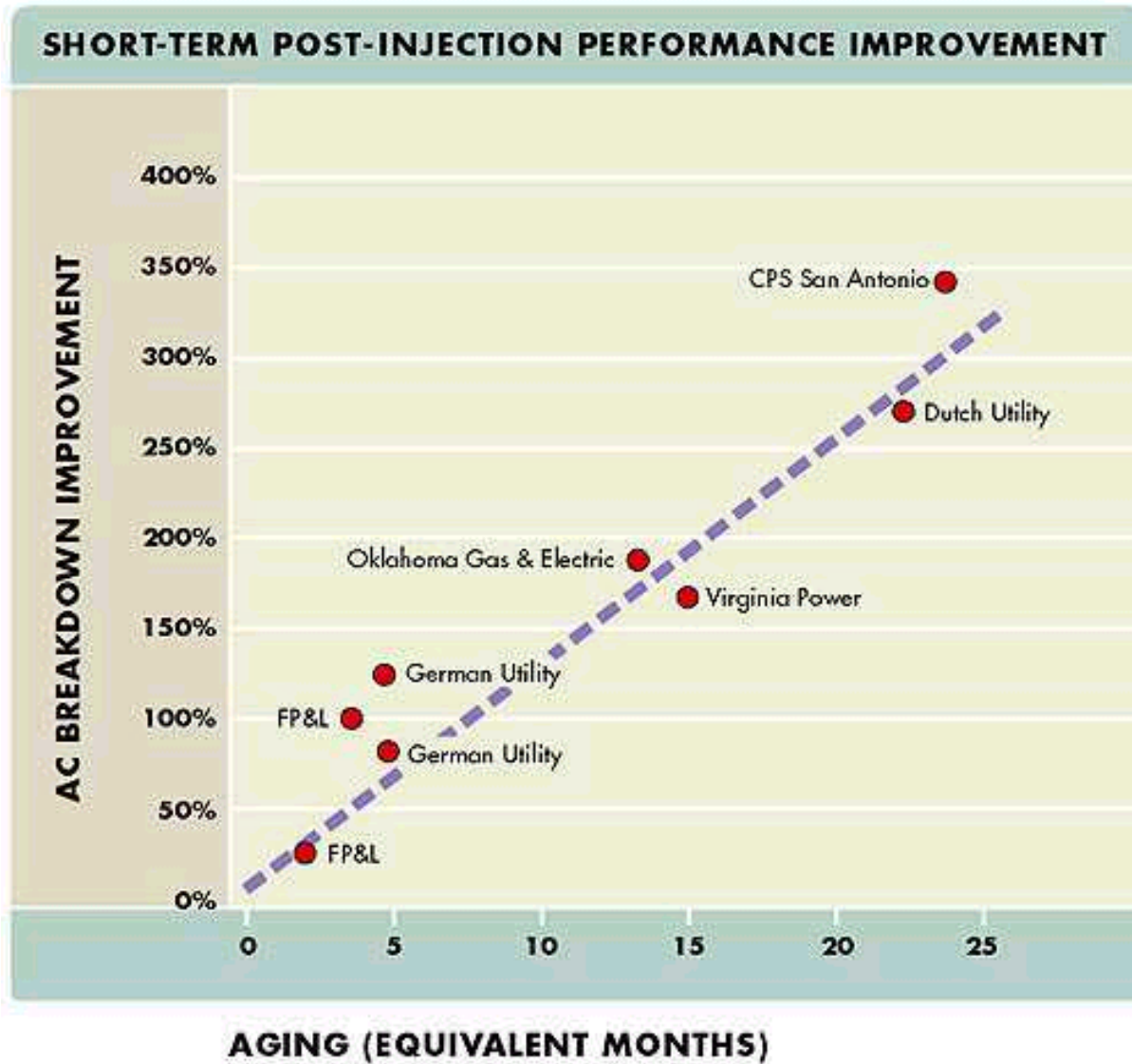
- Commercialized by Dow Corning in 1987.
- Inject a low molecular weight silicone into the conductor strands which then diffuses into the dielectric and gels through a reaction with moisture in the dielectric, thereby replacing water trees with gelled silicone.
- Applied widely as a lower cost alternative to replacement when the neutral is in acceptable condition.

## Injected Power Cable -- USA



William R. Stagi, "Silicone Injection Technology", IEEE Latin American Conference, 2006

# Dielectric Strength Improves Over Time



Data as published in REE, August 1996, p.73

Treatment cost is in the range of \$8/ft compared with replacement costs of \$20 to \$50/ft.

Over the past 20 years, 80 million cable feet have been treated, 99+% of which is still in service and failure-free.

# Conclusion

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- In the long run, most of what remains of the >2 billion feet of pre-1980 PE cable will have to be rejuvenated or replaced prematurely.
- We have a huge technical and economic problem, but one which may not be as large as our records show, as we really do not know how much of this cable remains in the ground.
- We have to start from the cable as it is – all we can do technically is develop better ways to prioritize rejuvenation and replacement.

# What Can Technology Contribute?

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- We need a (preferably in-service) diagnostic which is sensitive to the worst water trees rather than the present diagnostics which tend to react similarly to many small trees or a few large trees.
- Do water trees act as nonlinear mixers for high frequency radiation in the cable? If so, this effect is probably a strong function of tree length.
- Certainly water trees generate harmonic currents, which suggests nonlinearity.