Theoretical basis 2: Breakdown mechanisms and statistics

John Fothergill

‘‘Electrical breakdown is a subject to which it is difficult to apply our usual scientific rigour. A well-designed insulator in the laboratory breaks down in service if the wind changes direction or if a fog descends.’’

Solymar and Walsh (1984)

Scope

A personal view of Electrical breakdown, degradation and ageing

Common breakdown mechanisms in polymers

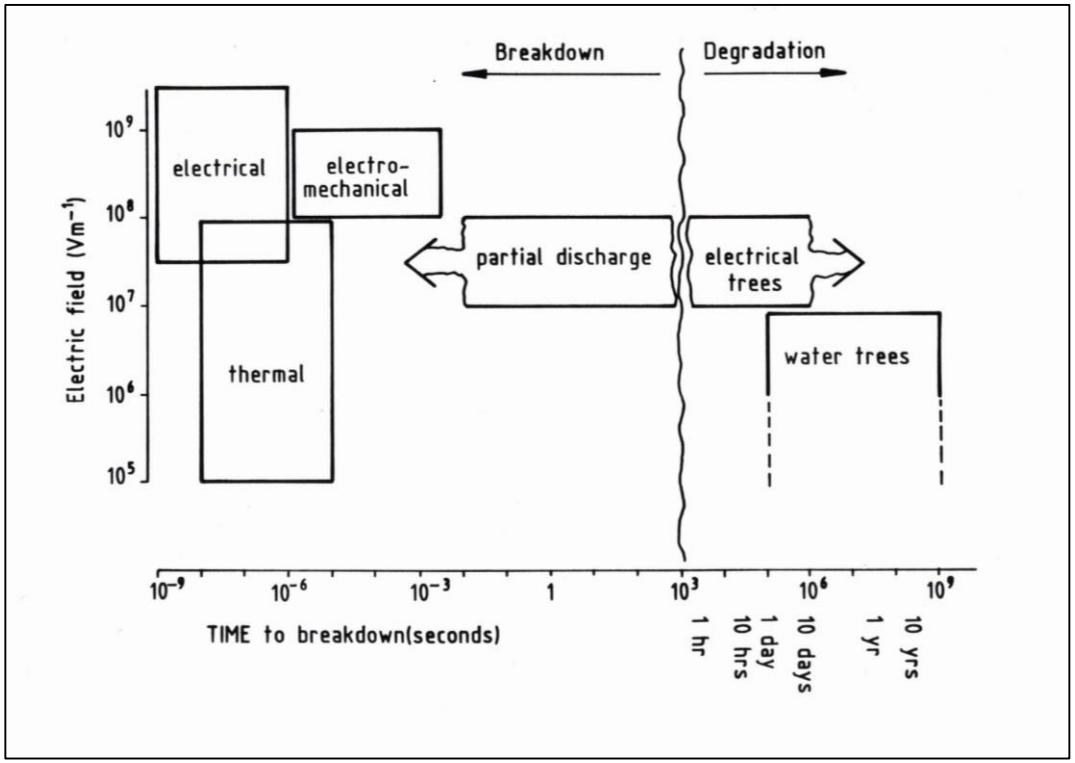
Analysing breakdown statistics.

Contents

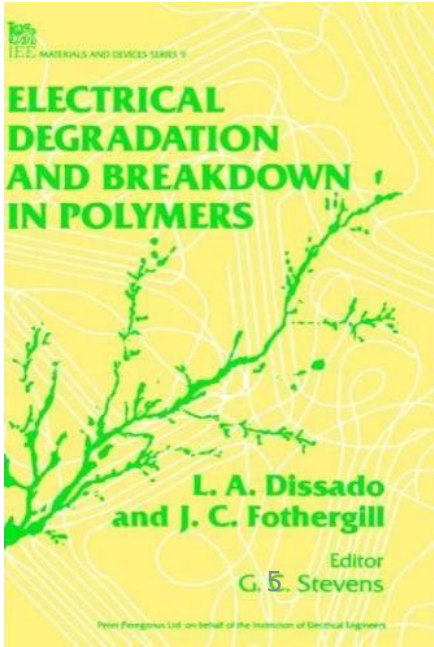
- Electrical breakdown, degradation and ageing
- Some general features of breakdown
- Thermal breakdown
- Electromechanical breakdown
- Avalanche breakdown and the Paschen Curve, solid state avalanches
- Intrinsic breakdown
- Breakdown statistics
  - Types of electrical breakdown tests
  - Analysis of failure data
  - Weibull analysis
  - Extrapolation to service conditions
  - Weibull versus other distributions

Breakdown, Degradation and Ageing

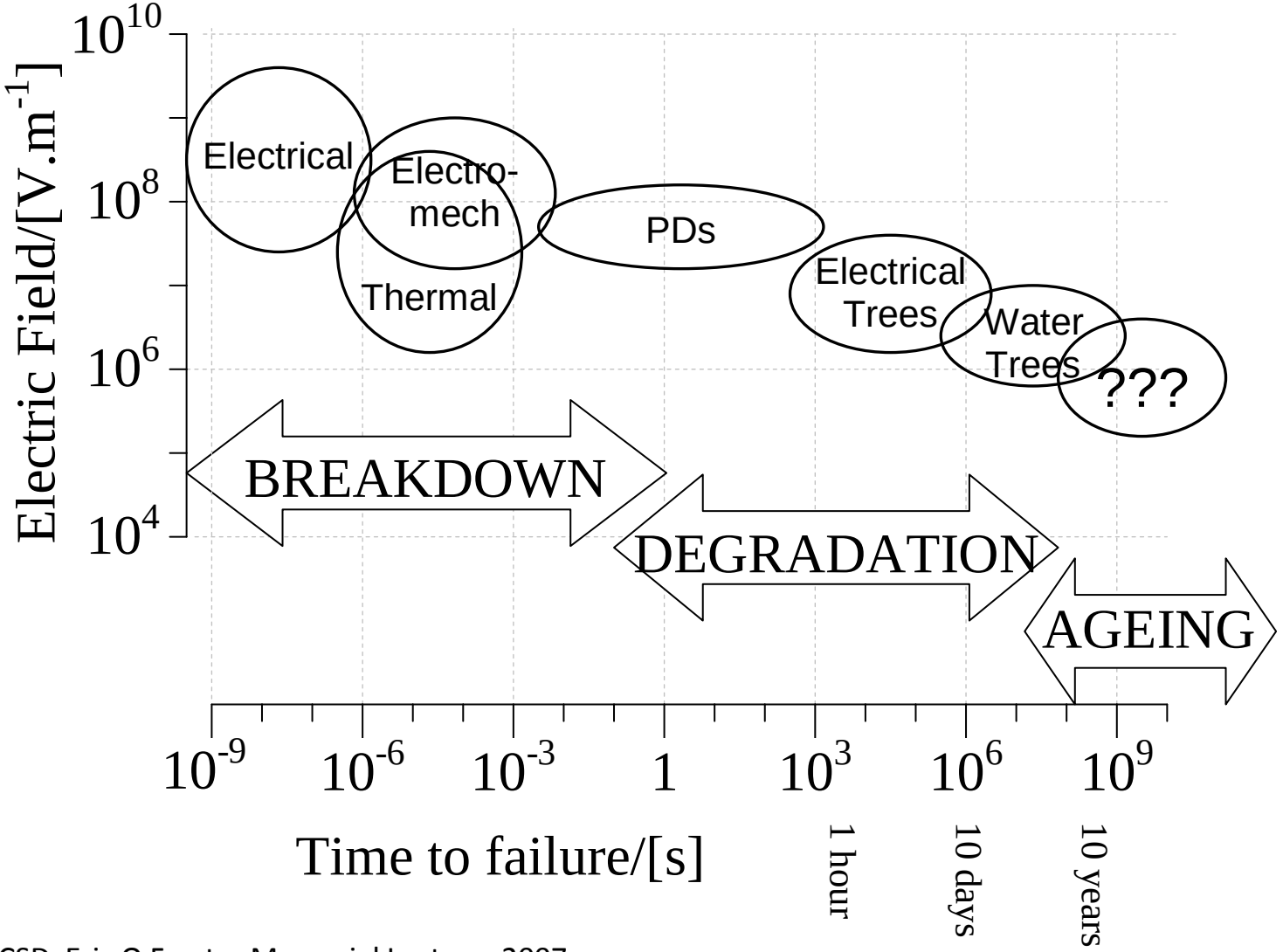
Breakdown, Degradation and Ageing



"Fig. 3.8 Times and electric fields at which various electrical breakdown mechanisms are operative. Note the lack of clear distinction between 'breakdown' and 'degradation'"



Breakdown, Degradation and Ageing

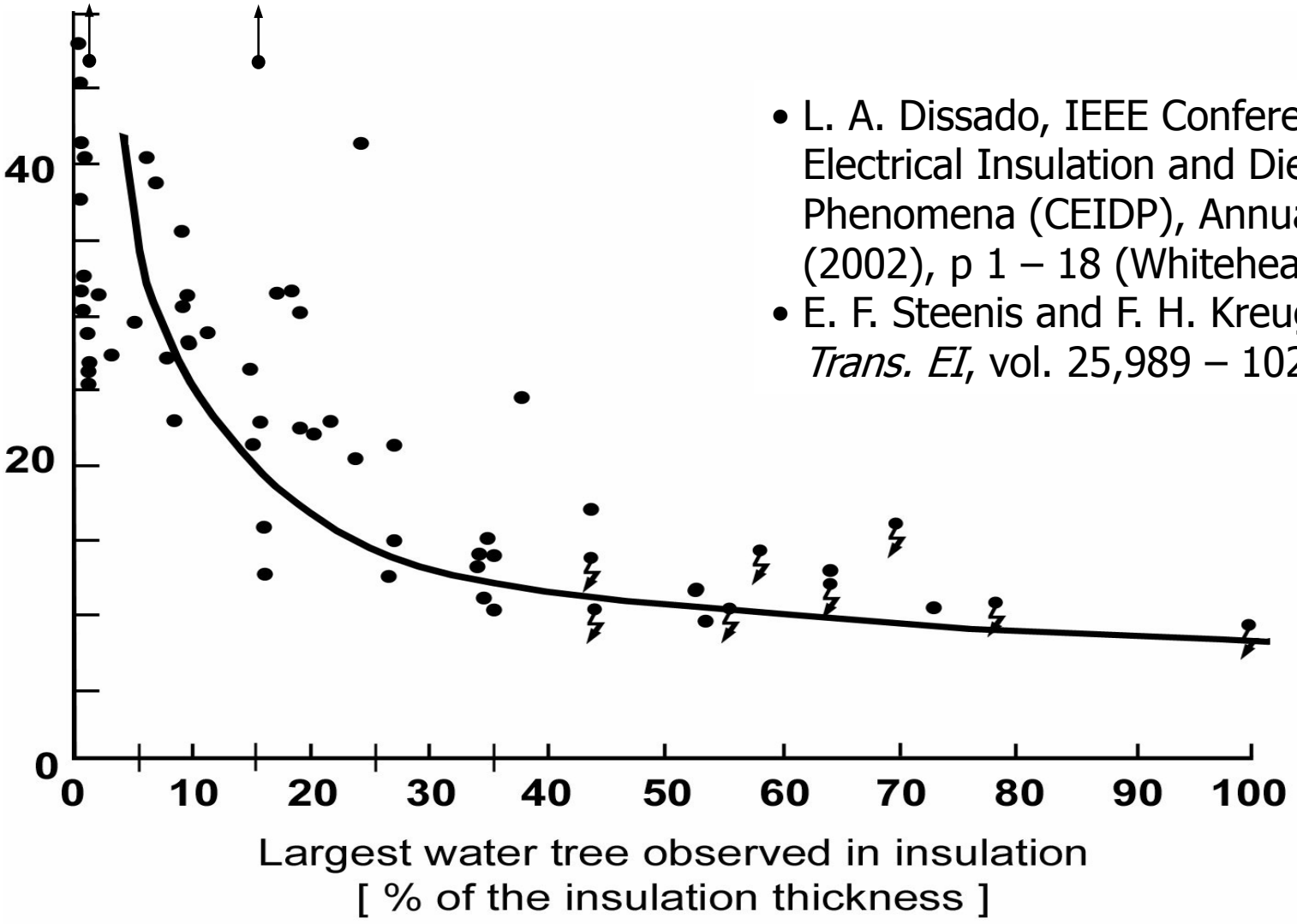


JC Fothergill, ICSD, Eric O Forster Memorial Lecture, 2007

Breakdown, Degradation and Ageing

	Breakdown	Degradation	Ageing
Effect	**Catastrophic:** Insulation cannot be used afterwards	**Leads to breakdown:** Reduces breakdown strength	**A change in the dielectric that may lead to degradation:** May not reduce breakdown strength
Speed	**Fast:** Occurs in << 1s	**Less that required service life:** Hours to years Degradation is likely to be self-reinforcing	**Continuous process:** Whole of service life Ageing may not be self-reinforcing
Evidence	**Direct observation:** Hole through insulation	**Observable directly:** May require microscopic or chemical techniques (FTIR etc)	**Difficult to observe:** May even be difficult to prove existence
Place	**Continuous filament/hole:** bridges electrodes	**Occurs in weak parts:** May form fractal structures	**Assumes to occur throughout the affected insulation**
Size	**>mm:** Comparable with thickness of insulator	**>μm:** But may form larger structures	**>nm:** molecular scale
Examples	Thermal, electromechanical, avalanche, intrinsic – could be more than one	Electrical trees, water trees, partial discharges	Bond scission, nano-void formation, trap formation, chemical changes (e.g. oxidation)

Degradation does lead to breakdown



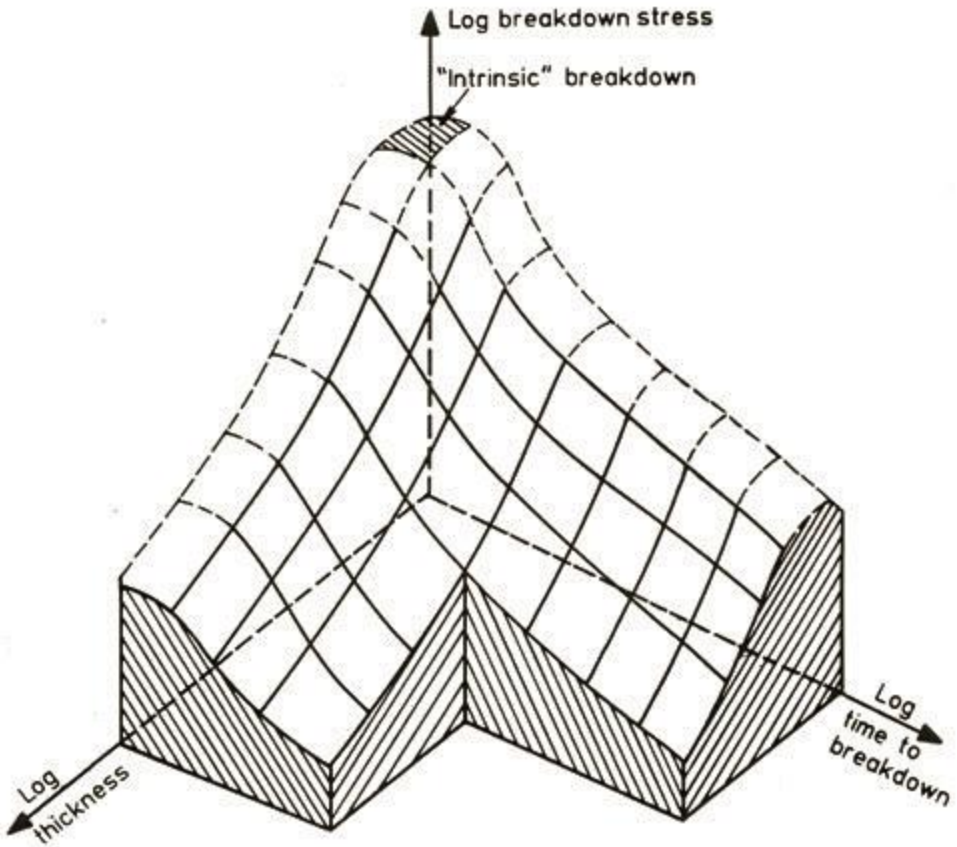
- L. A. Dissado, IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Annual Report, (2002), p 1 – 18 (Whitehead lecture)
- E. F. Steenis and F. H. Kreuger, *IEEE Trans. EI*, vol. 25,989 – 1028, 1990

Features of breakdown

Common Features of Breakdown

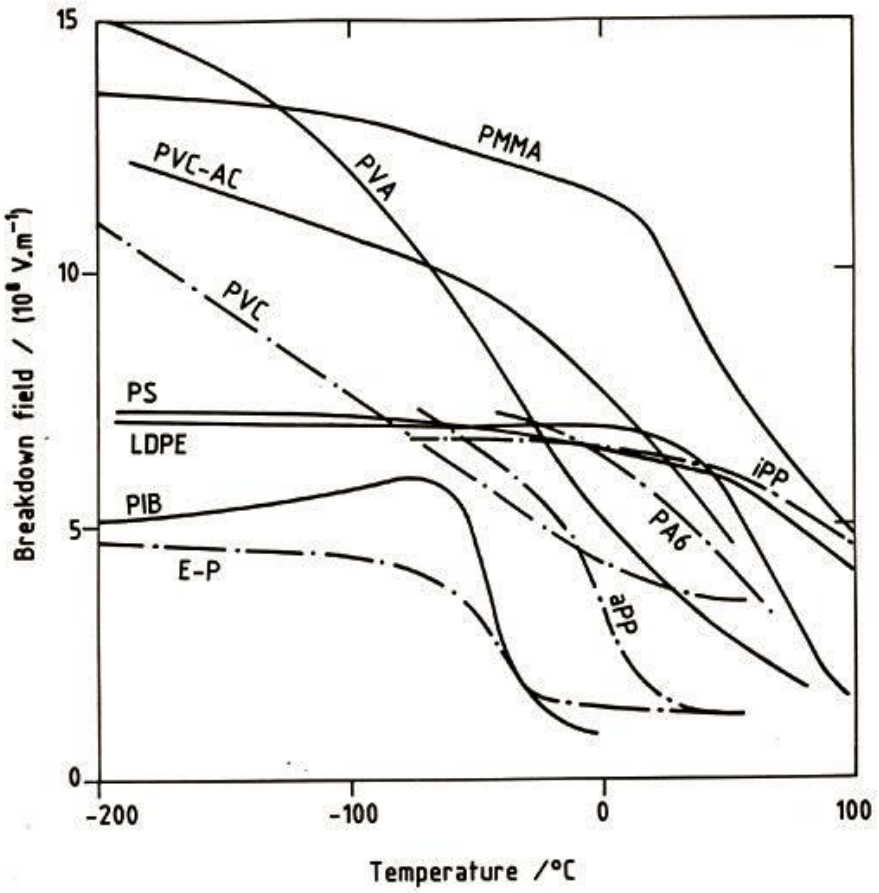
- Current instability above a given electric field
- Local destruction of insulation
- Positive feedback mechanism:
  - Increase in local power →
    - Change in some material property →
      - Further increase in local power …
- Typical breakdown fields are >10^8 V/m, i.e. >100 kV/mm (= 100 V/μm = 100 MV/m)
  - These may be effectively lowered by contaminants, electrode protrusions, voids and space charge accumulation in the insulation.

The Effect of Thickness and Time



After A. Jonscher, R. Lacoste, *IEEE Trans. Elec. Insul*., **EI-19(6),** 567-577. (1984)

Breakdown Strengths



After A. Jonscher, R. Lacoste, *IEEE Trans. Elec. Insul.*, **EI-19(6),** 567-577. (1984)

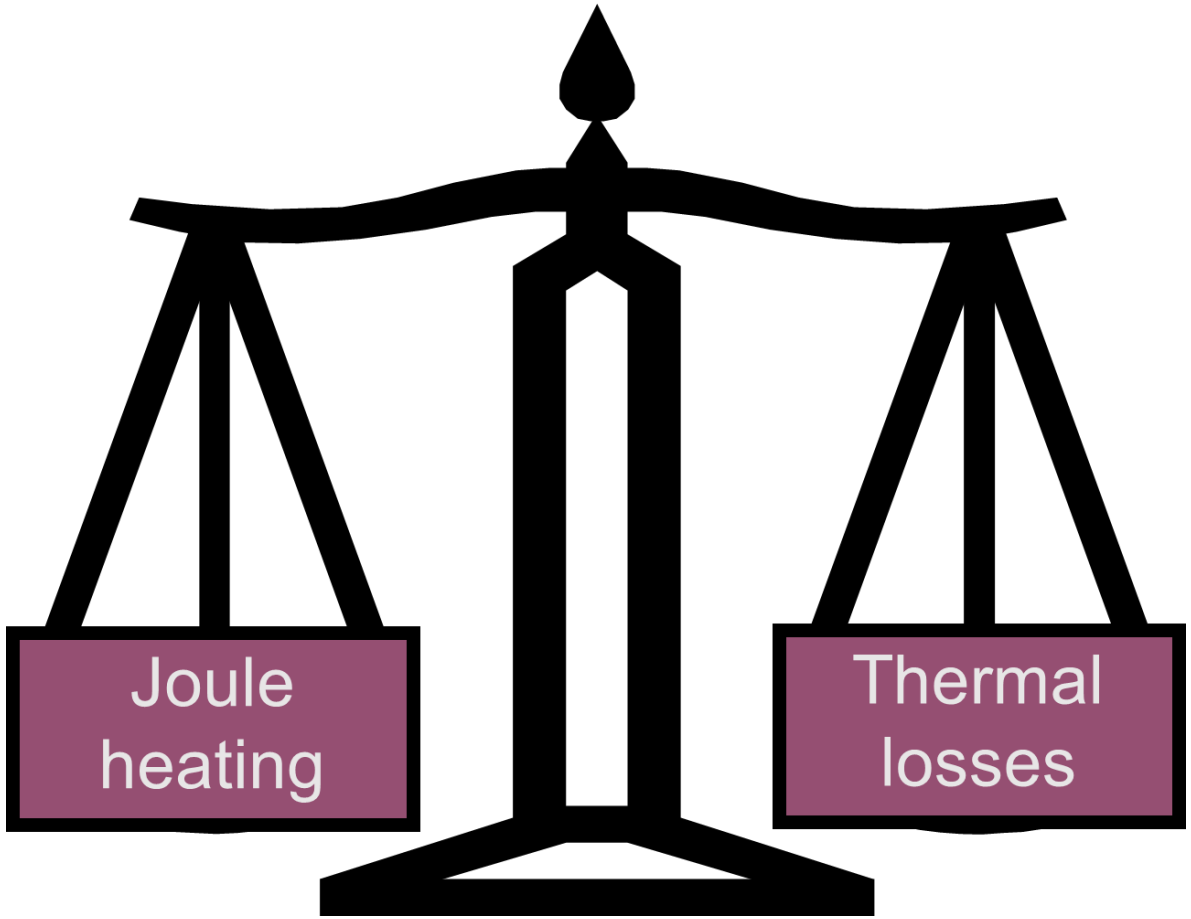
Thermal breakdown

Thermal Breakdown

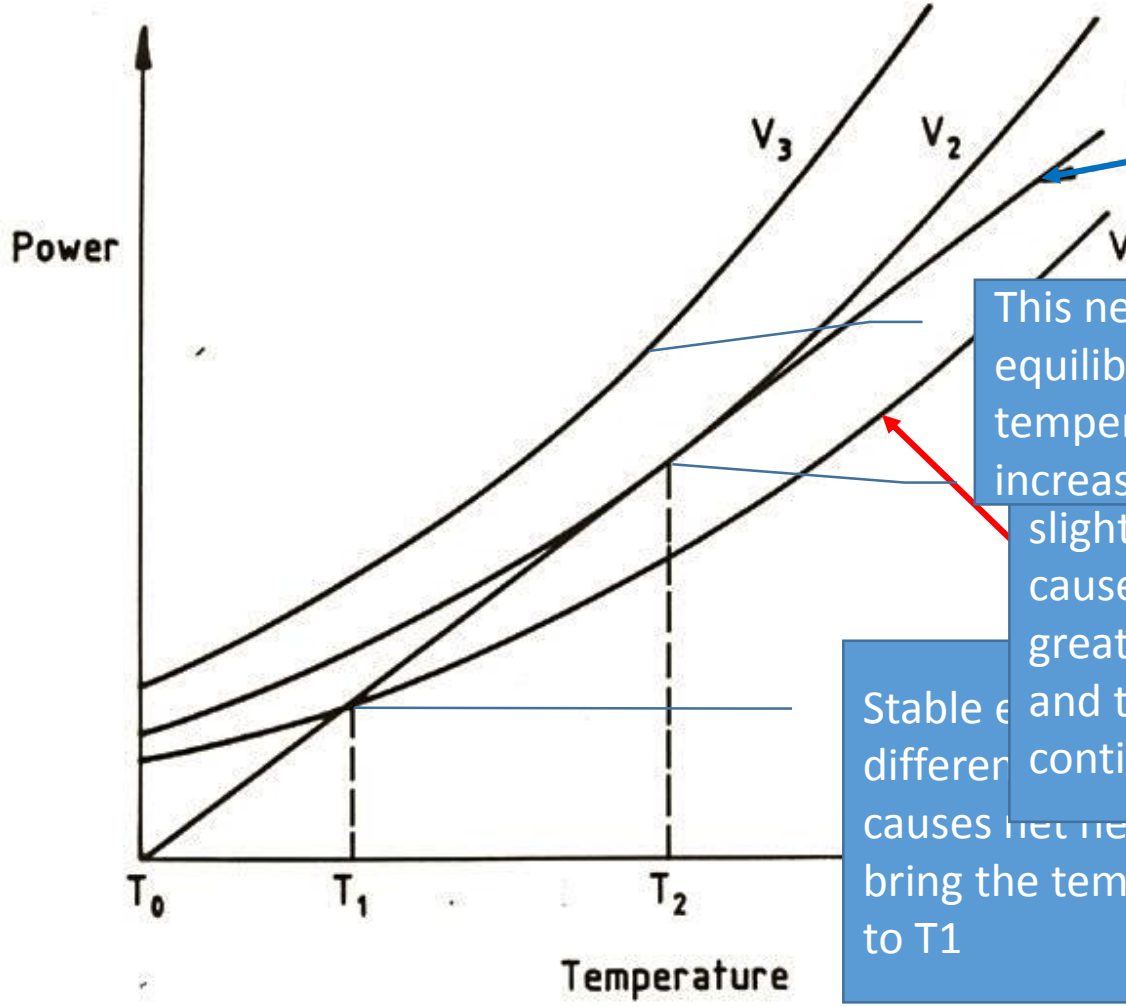
- (Local) electrical power dissipation causes (local) heating to above a critical temperature (e.g. The melting temperature) and this results in failure.
- An increase of temperature may also lead to a reduction in breakdown strength.

Current	→	temperature	→	conductivity
Increase		increase		increase

A Thermal Balance



Power and Temperature



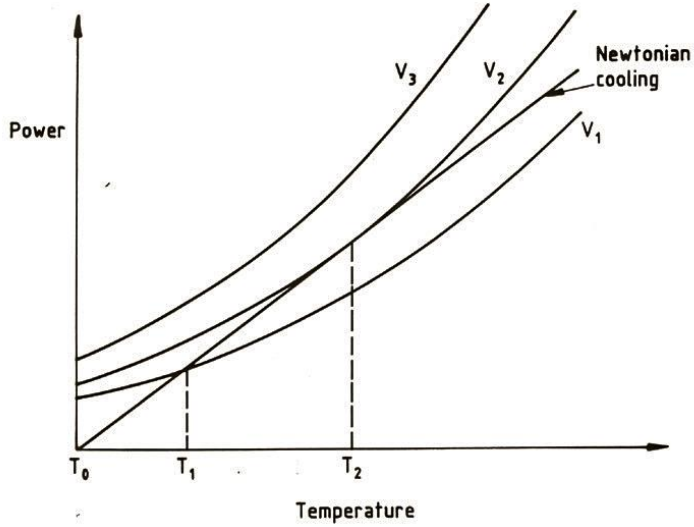
Newtonian cooling – i.e. rate of power loss is proportional to excess temperature

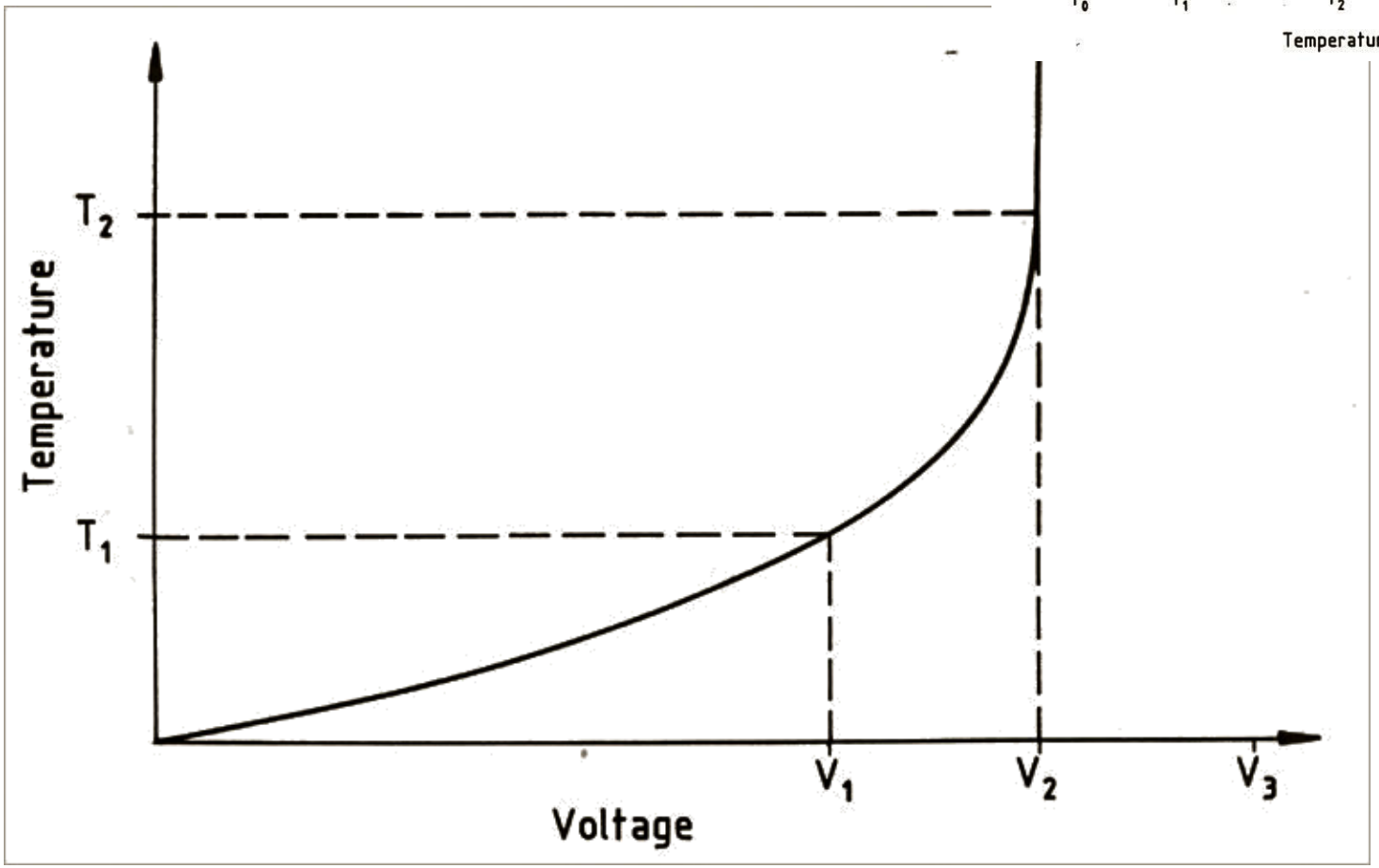
This never reaches equilibrium – the temperature continues to increase

slight increase in temperature cause sthe heating to be greater than the cooling – and the temperature continues to increase.

Stable e
differer
causes net heating/cooling to bring the temperature back to T1

Temperature and Voltage





“Maximum Thermal Voltage”

Polymer	Maximum Thermal Voltage (MV RMS at 50 Hz)
PVC (plasticized)	0.1 – 0.2
PAV	0.9
PE	3 – 5
Polystyrene	5
Acrylic resin	0.3 - 1

Whitehead, “Dielectric Breakdown of Solids” Clarendon Press, 1951

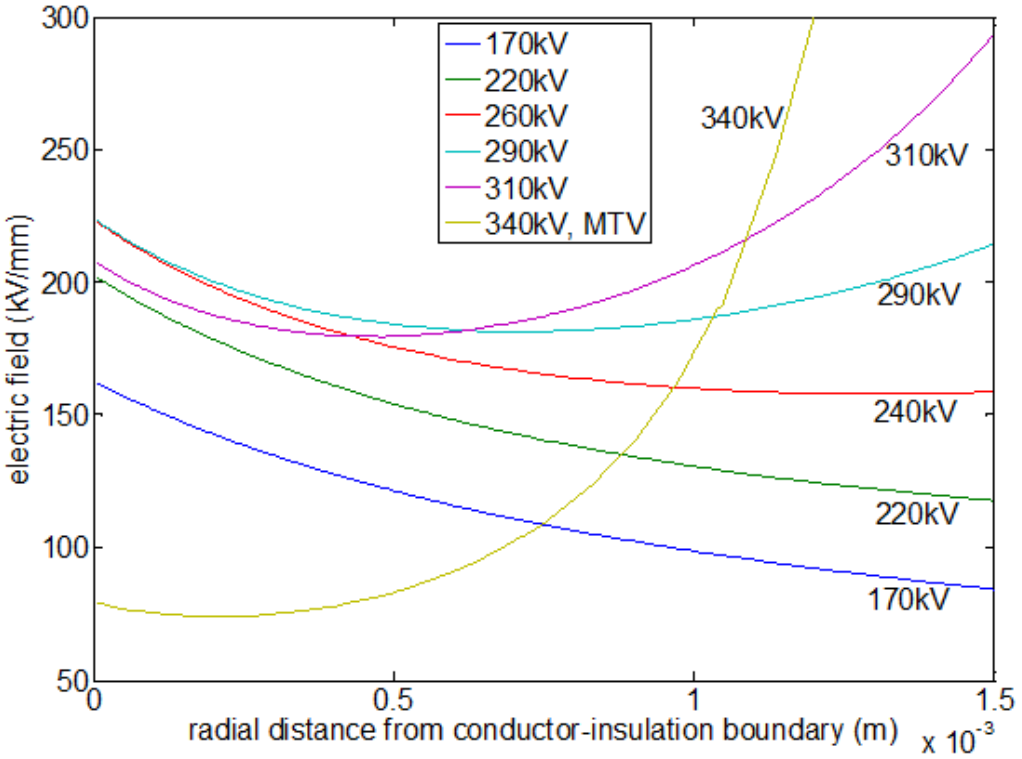
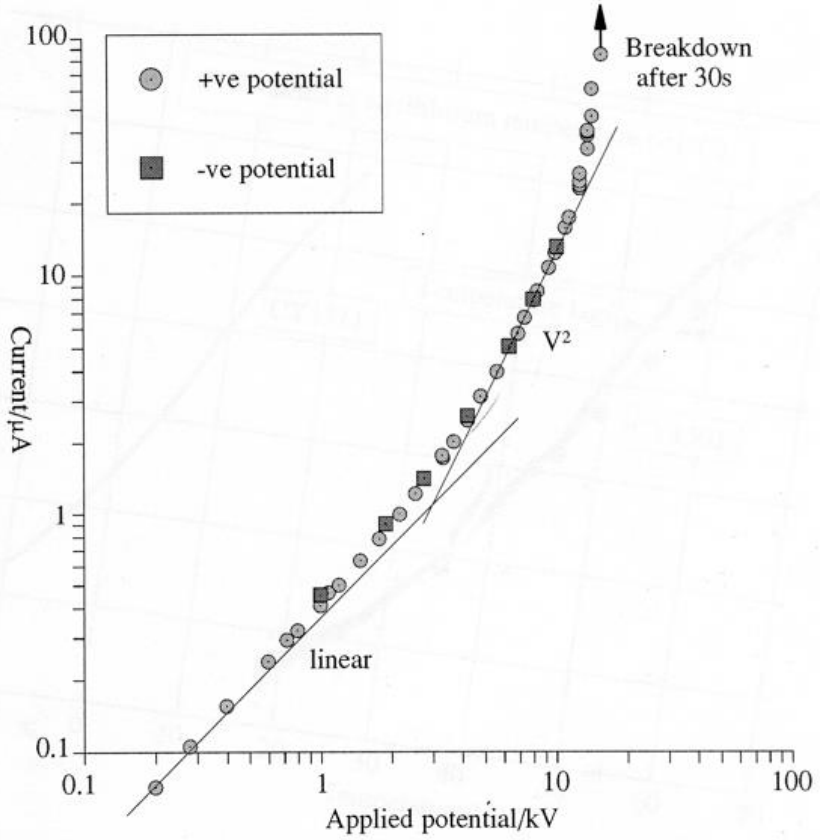


Figure 6.14 Electric field distribution in the insulation of cable AAA under different voltages, when the ambient temperature is 293K

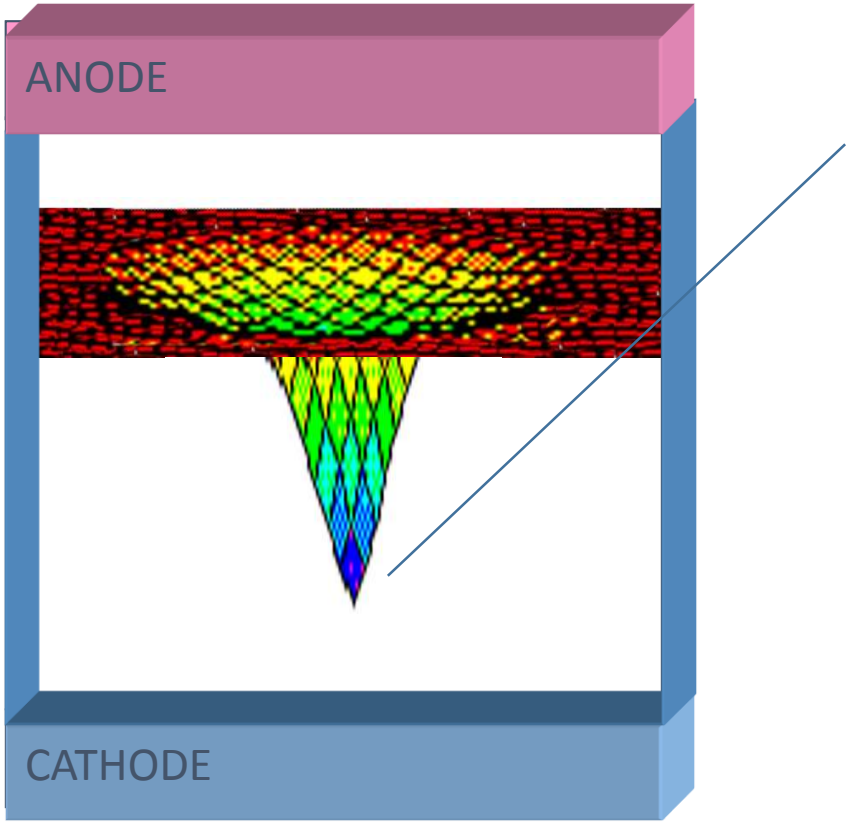
Computer simulation, Tong Liu, PhD thesis

Thermal Breakdown(?): Epoxy Resin



Work by John Alison and Virginie Griseri

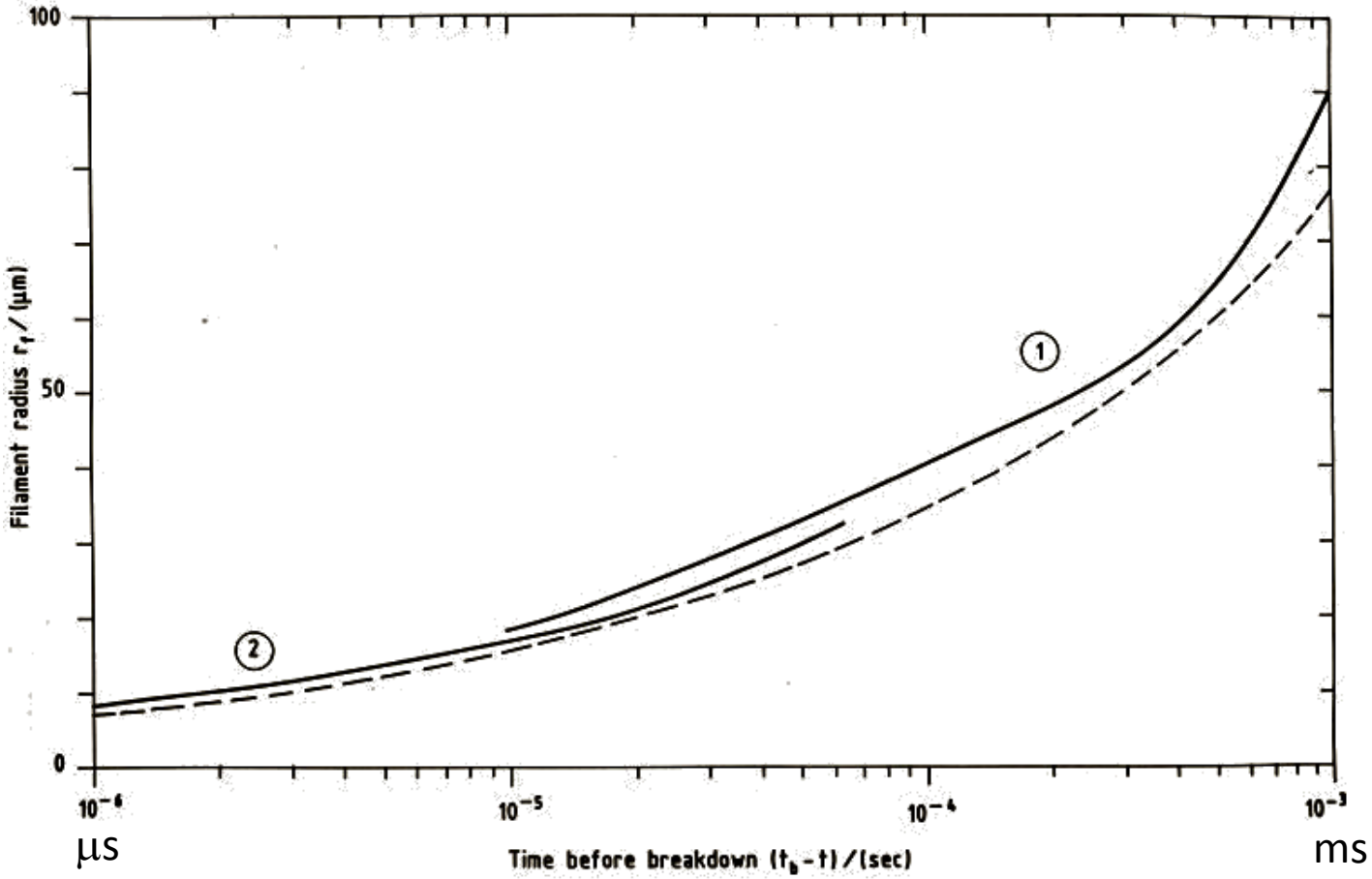
Likely to get instabilities occurring:



Hotspots could give rise to a more conductive channel

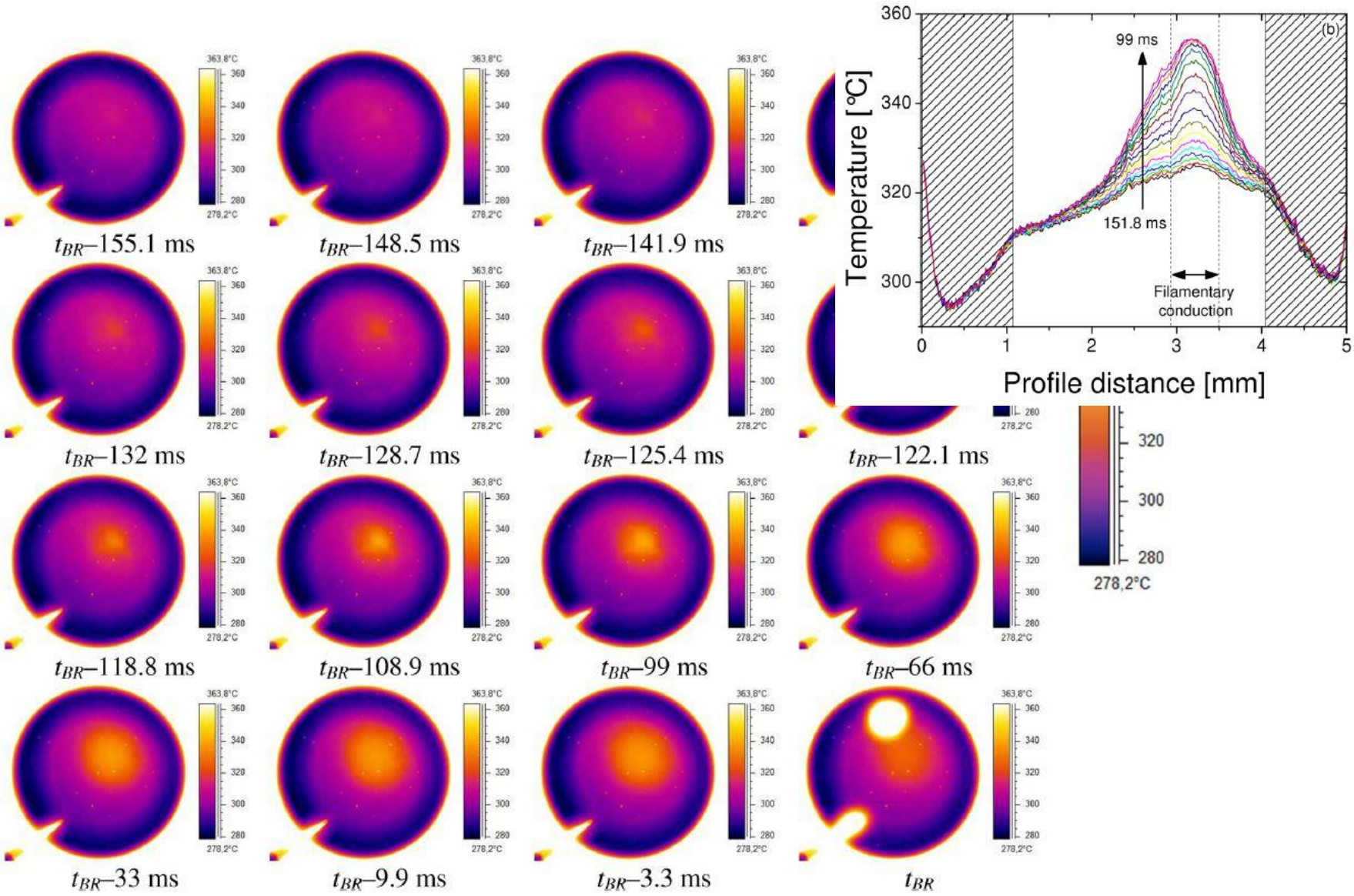
- Which would increase the field in front
- And make it even hotter

Filamentary thermal breakdown



Effective radius of the filamentary path as a function of time BEFORE breakdown

T. Mizutani *et al*, *IEEE Trans. Elec. Insul.*, **EI-22(4)**, 473-477 (1987)

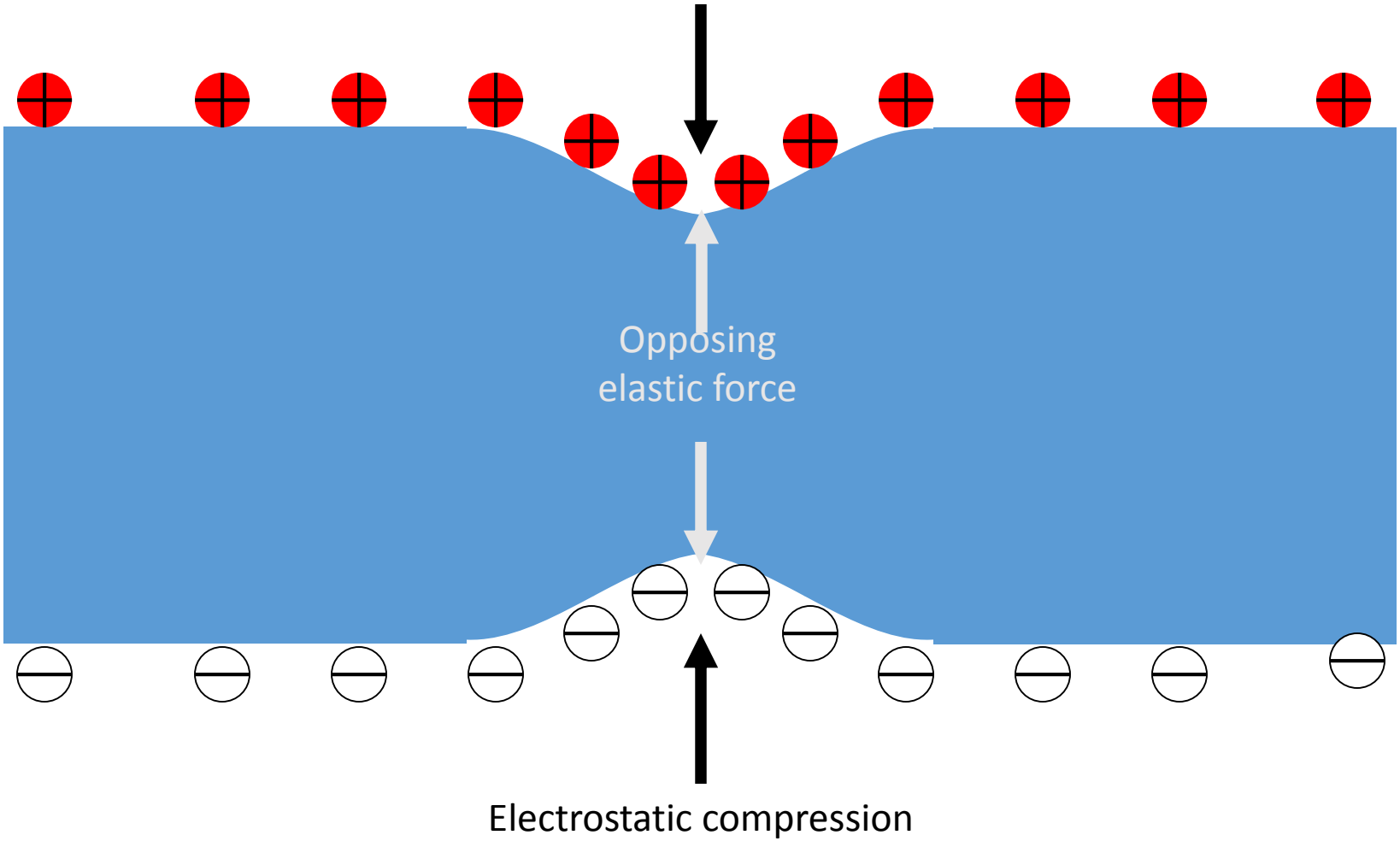


Localised Joule heating detection in the last 155 ms before the PI film thermal breakdown. The electrode diameter is 5 mm. The frame recording speed was 300 FPS (each image 3.3 ms). Only a selection of images is presented.

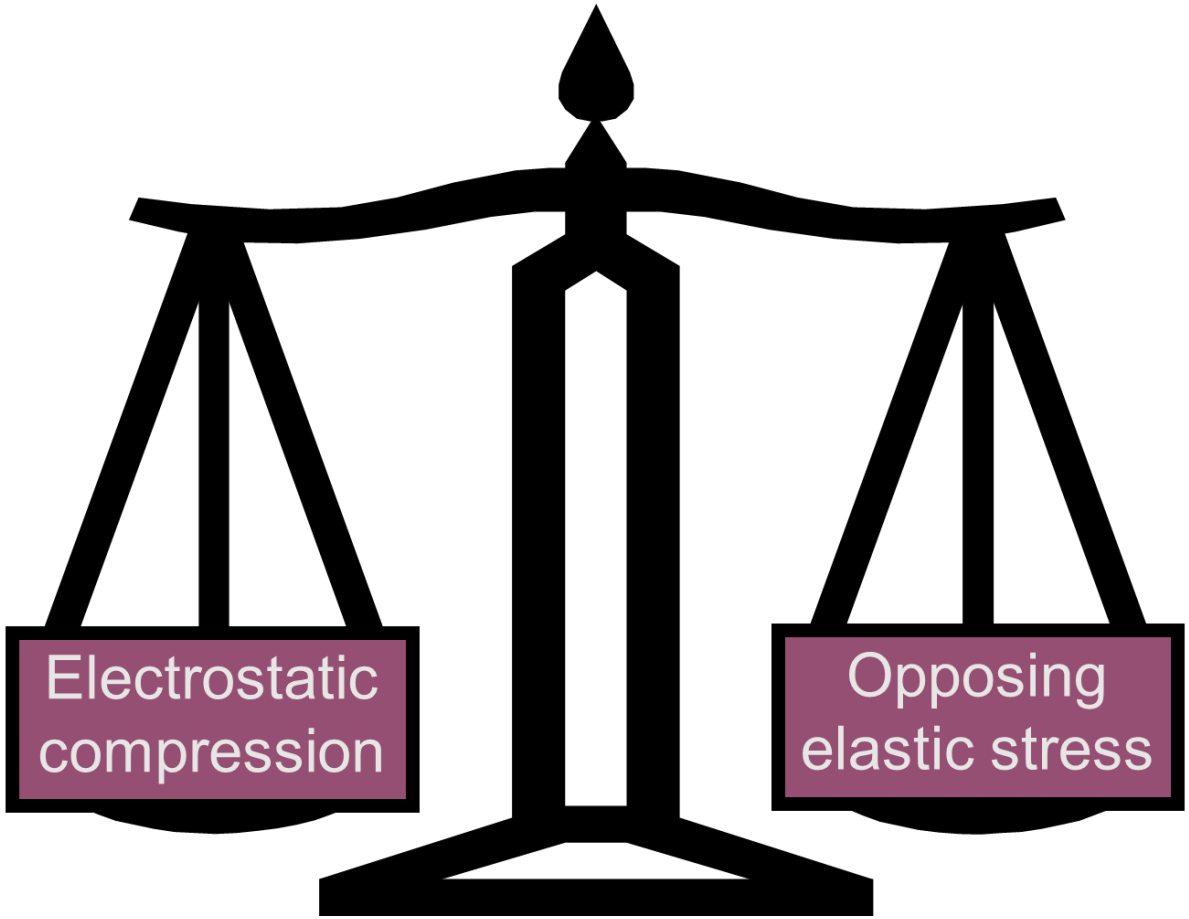
S. Diaham, G. Belijar, M.-L. Locatelli, and T. Lebey, Appl. Phys. Lett. 110, 162902 (2017)

Electromechanical breakdown

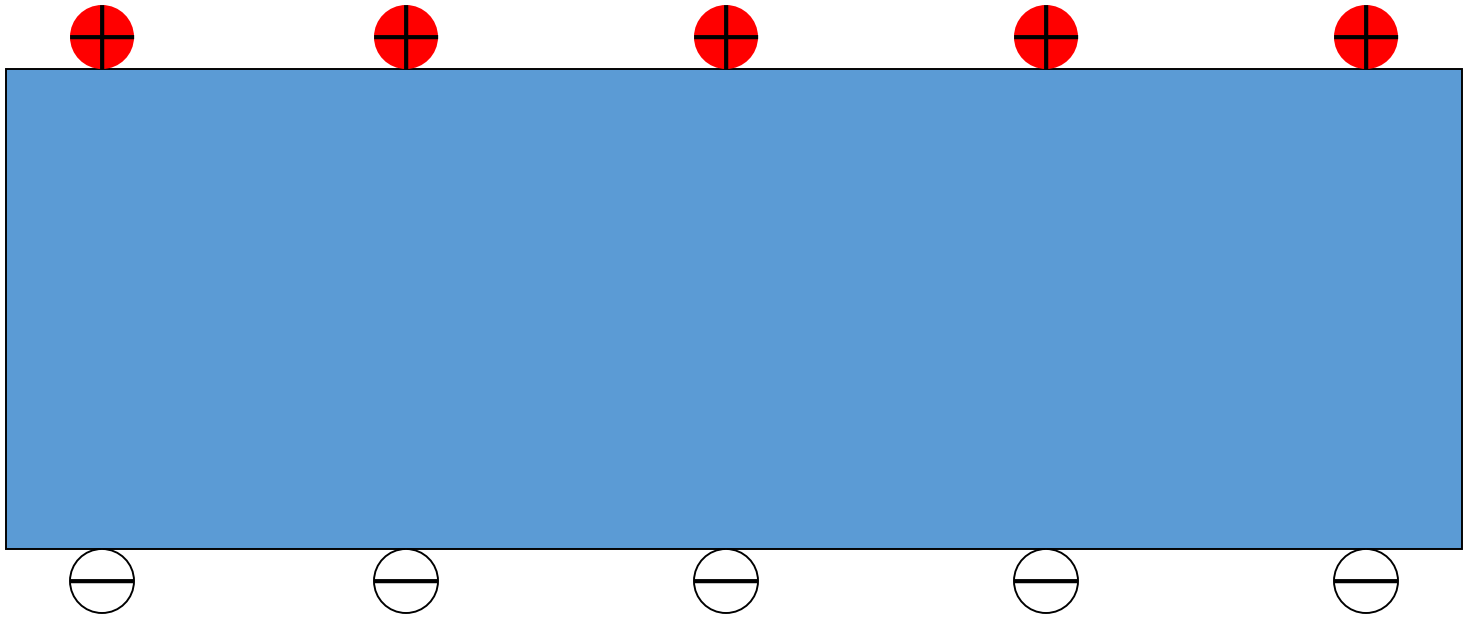
Electromechanical Breakdown

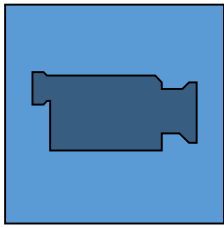


An Electromechanical Balance



Garton and Stark Model

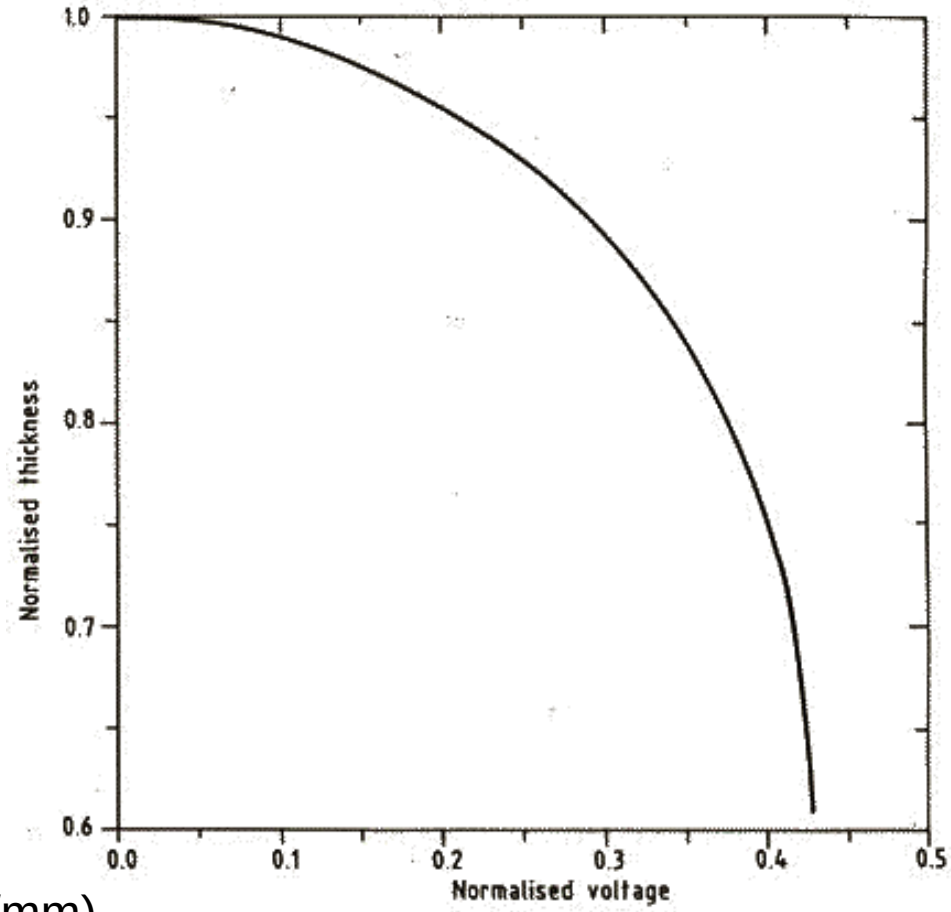




CG Garton and KH Stark, Nature, 1955, **176**, 1225-6

Garton and Stark Model

$$V_{breakdown} \propto \frac{\sqrt{Y}}{d_0}$$



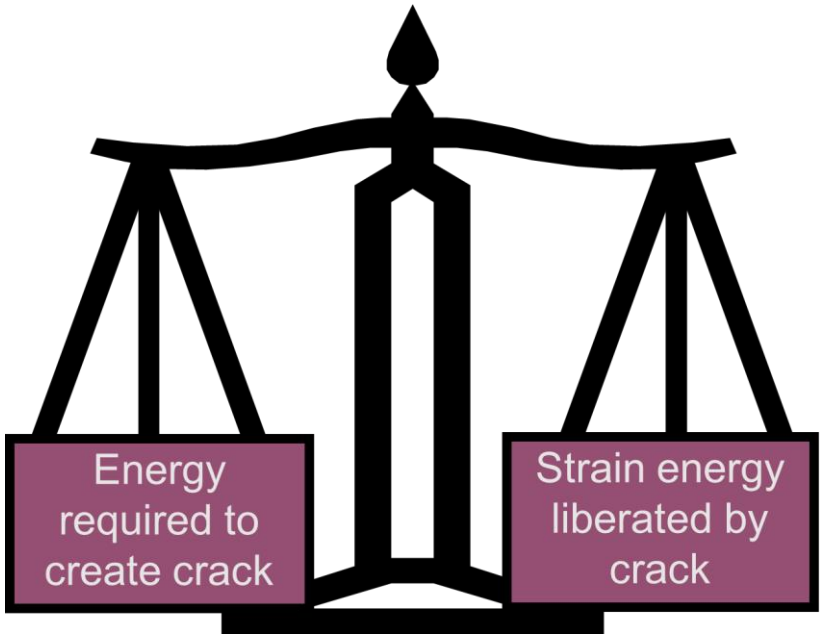
Y =Young's modulus
d_0 = initial thickness

$V_{breakdown}$ → very big! (>2000 kV/mm)

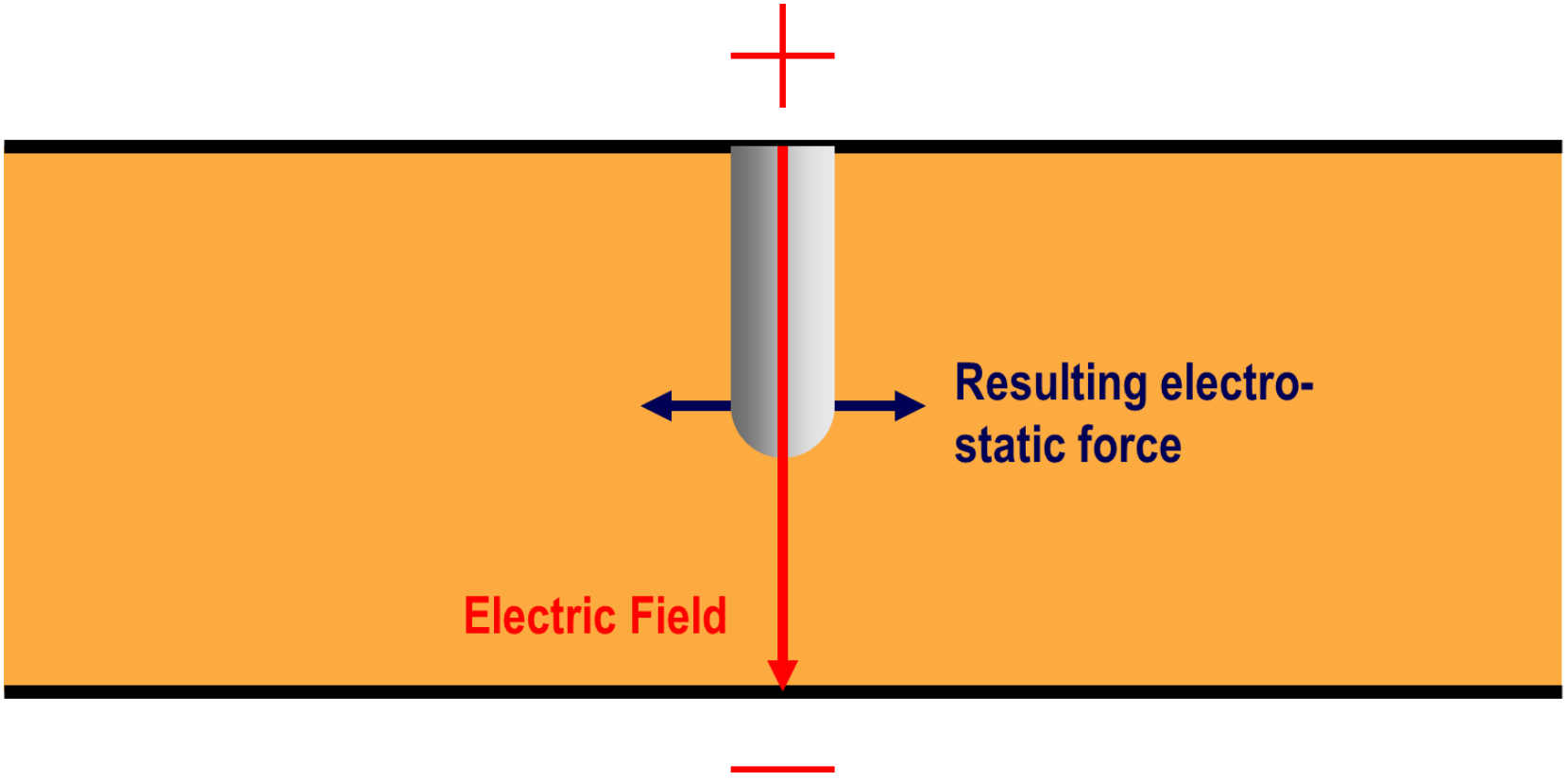
CG Garton and KH Stark, Nature, 1955, **176**, 1225-6

Filamentary Theories

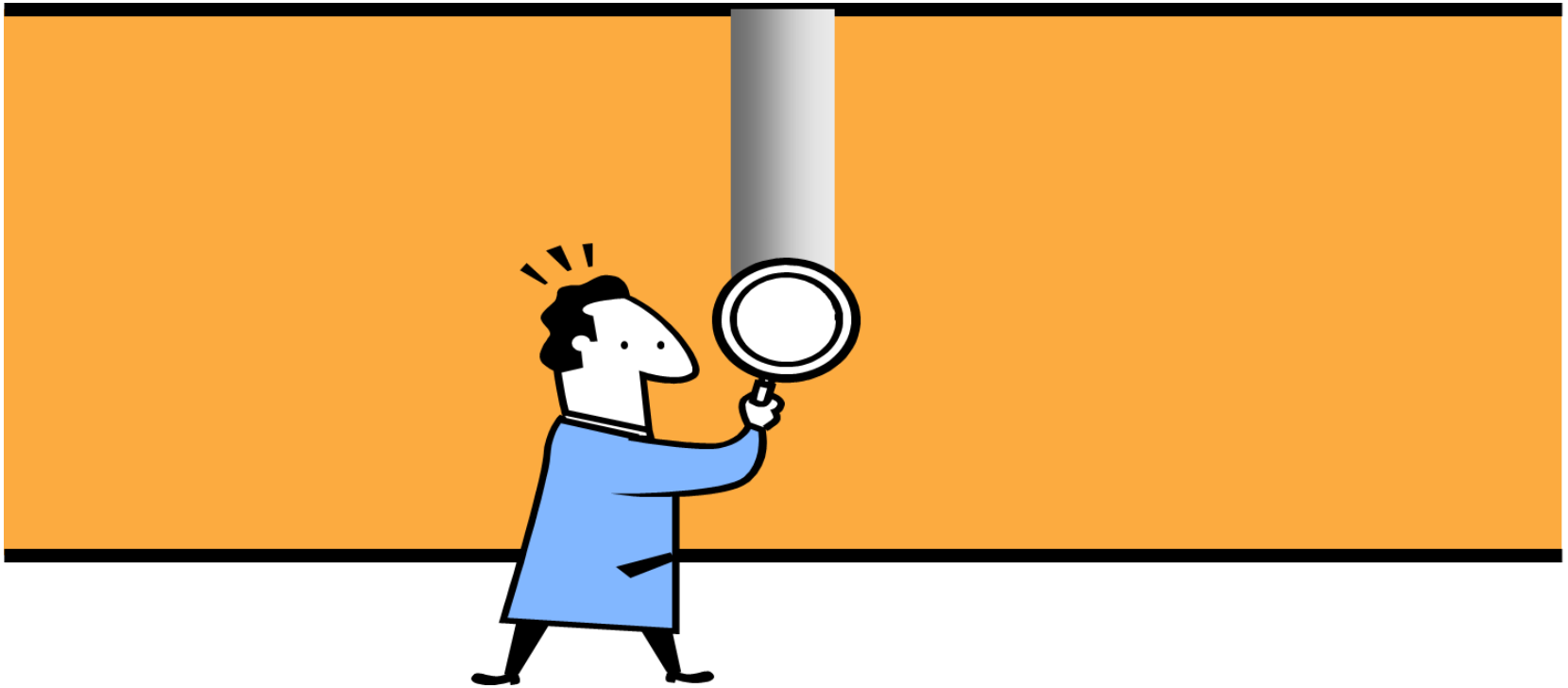
- Zeller *et al*: "Electrofracture" (lower fields)
- Fothergill: "filamentary electromechanical breakdown" (higher fields)
- Similar to "Griffiths" criterion for mechanical crack propagation



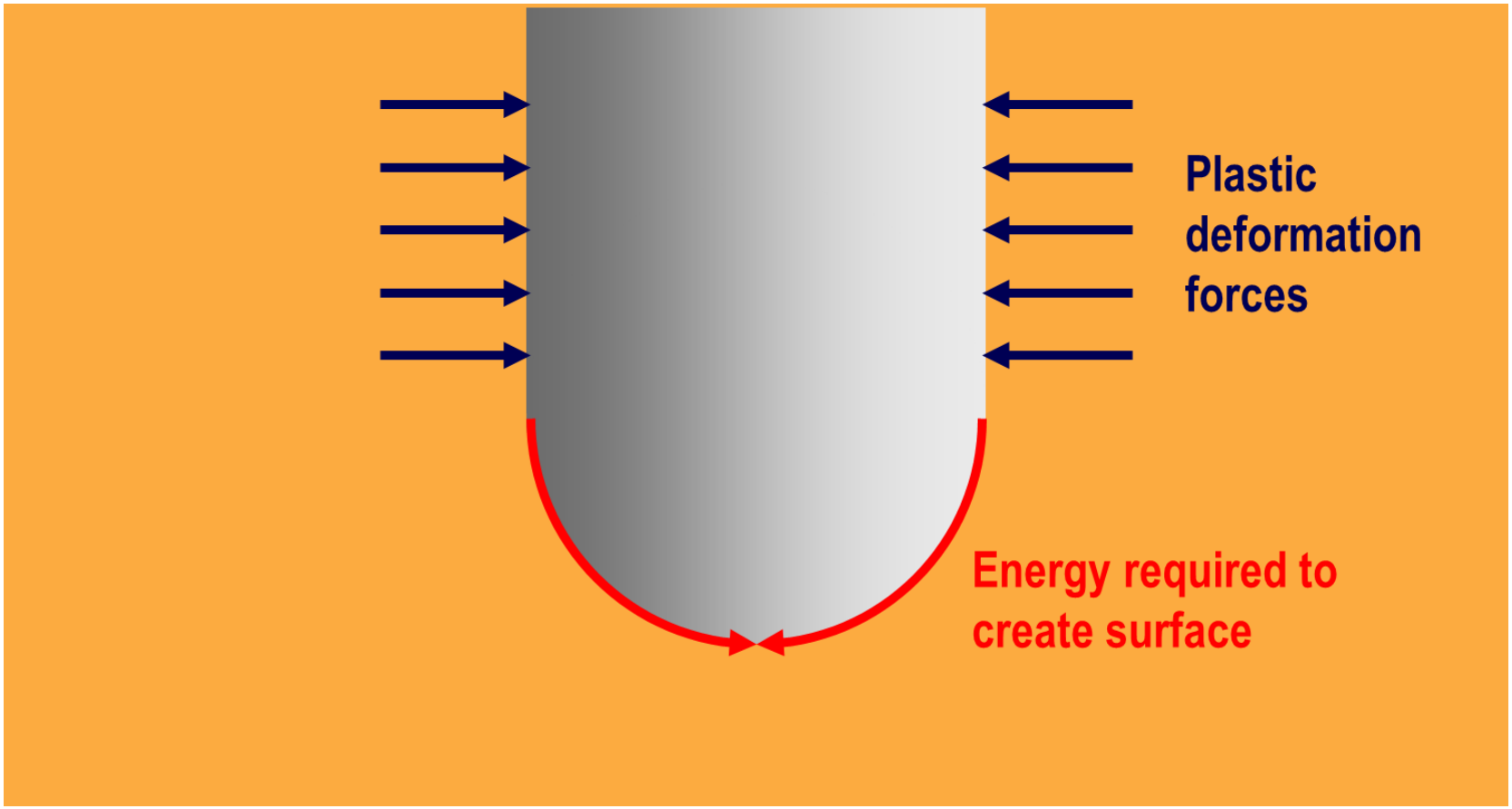
Electro-Mechanical Forces – creating crack



Mechanical Forces
- opposing crack creation



Opposing Mechanical Forces



Dependence on Young's Modulus

- Zeller *et al*: "Electrofracture" (lower fields)

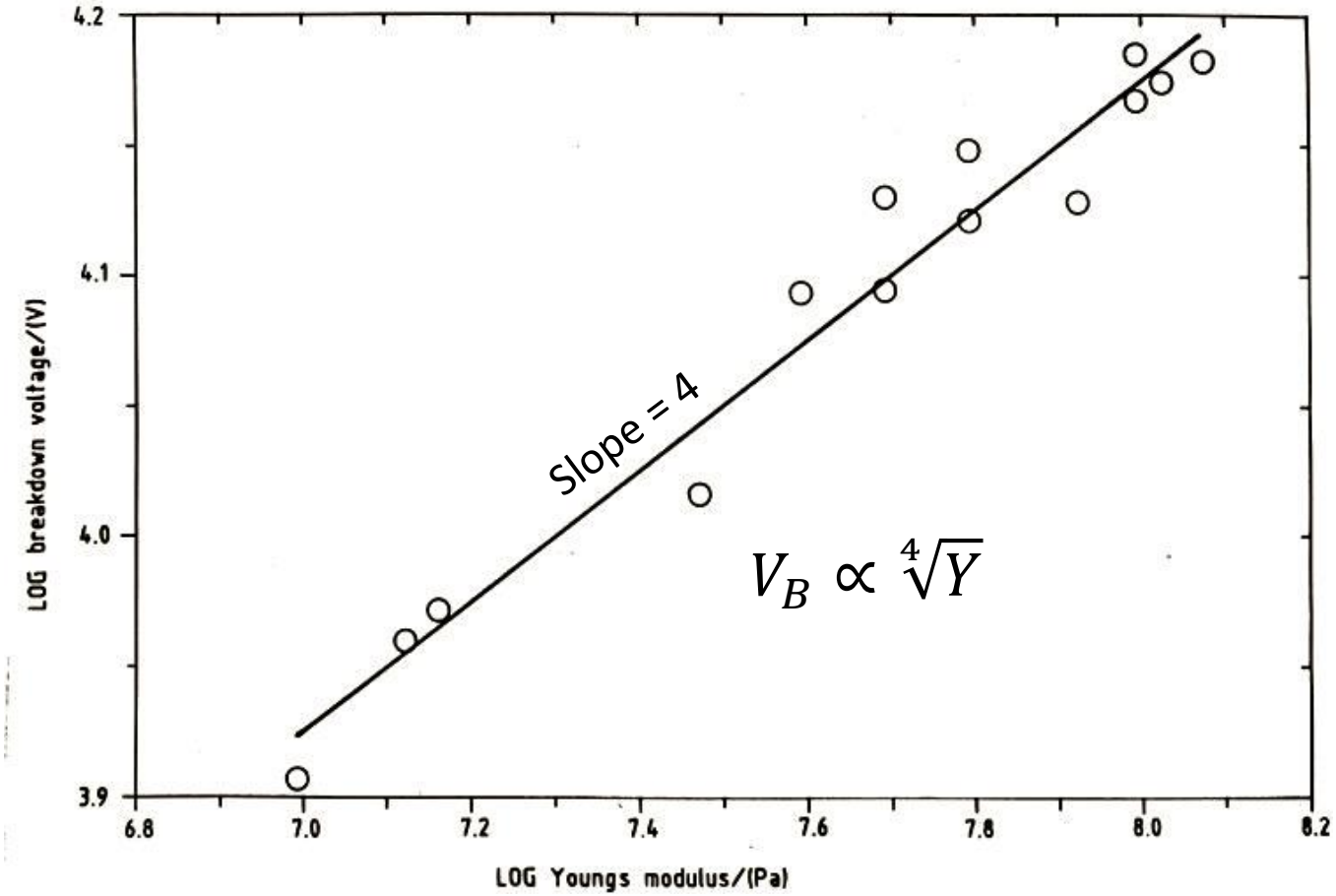
$$E_{breakdown} \propto \sqrt[2]{Y}$$

(Similar to Garton and stark model)

- Fothergill: "filamentary electromechanical breakdown" (higher fields)

$$E_{breakdown} \propto \sqrt[4]{Y}$$

Evidence for High Field Model



Evidence for filamentary electromechanical breakdown in thin films of polyethylene.

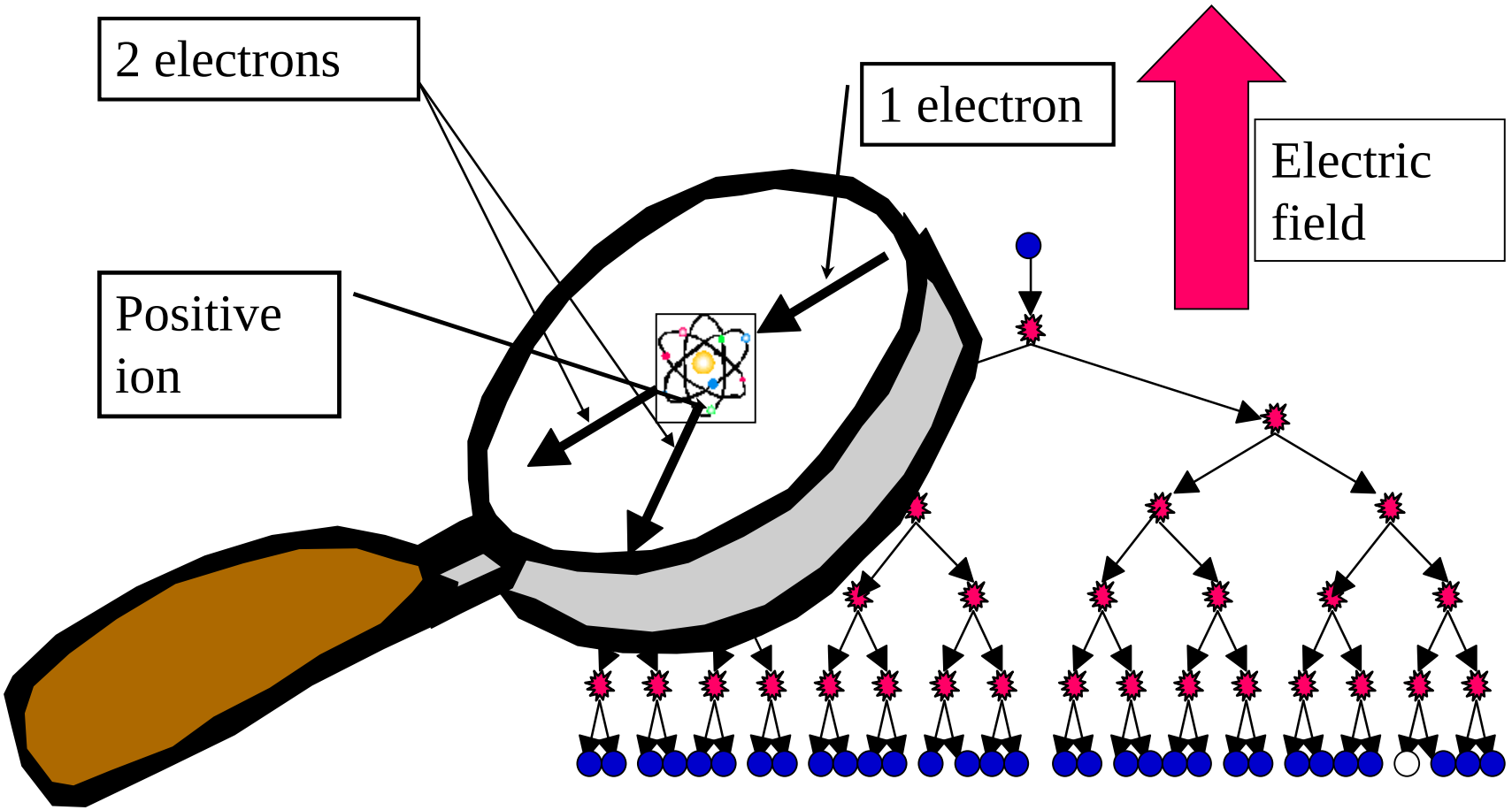
M. Hikita *et al.*, *Jpn. J. Appl. Phys.*, **24**, 988-996 (1985)

Avalanche breakdown

Avalanche Breakdown

- Avalanche breakdown relies on “impact ionisation”. Electrons with a high energy collide with trapped or bound electrons. There is sufficient energy for both electrons to be free after the collision.
- If the field is sufficiently high, both electrons rapidly gain enough energy to cause a second generation of collisions resulting in four electrons.
- The chain reaction may continue until local destruction of the material ensues.

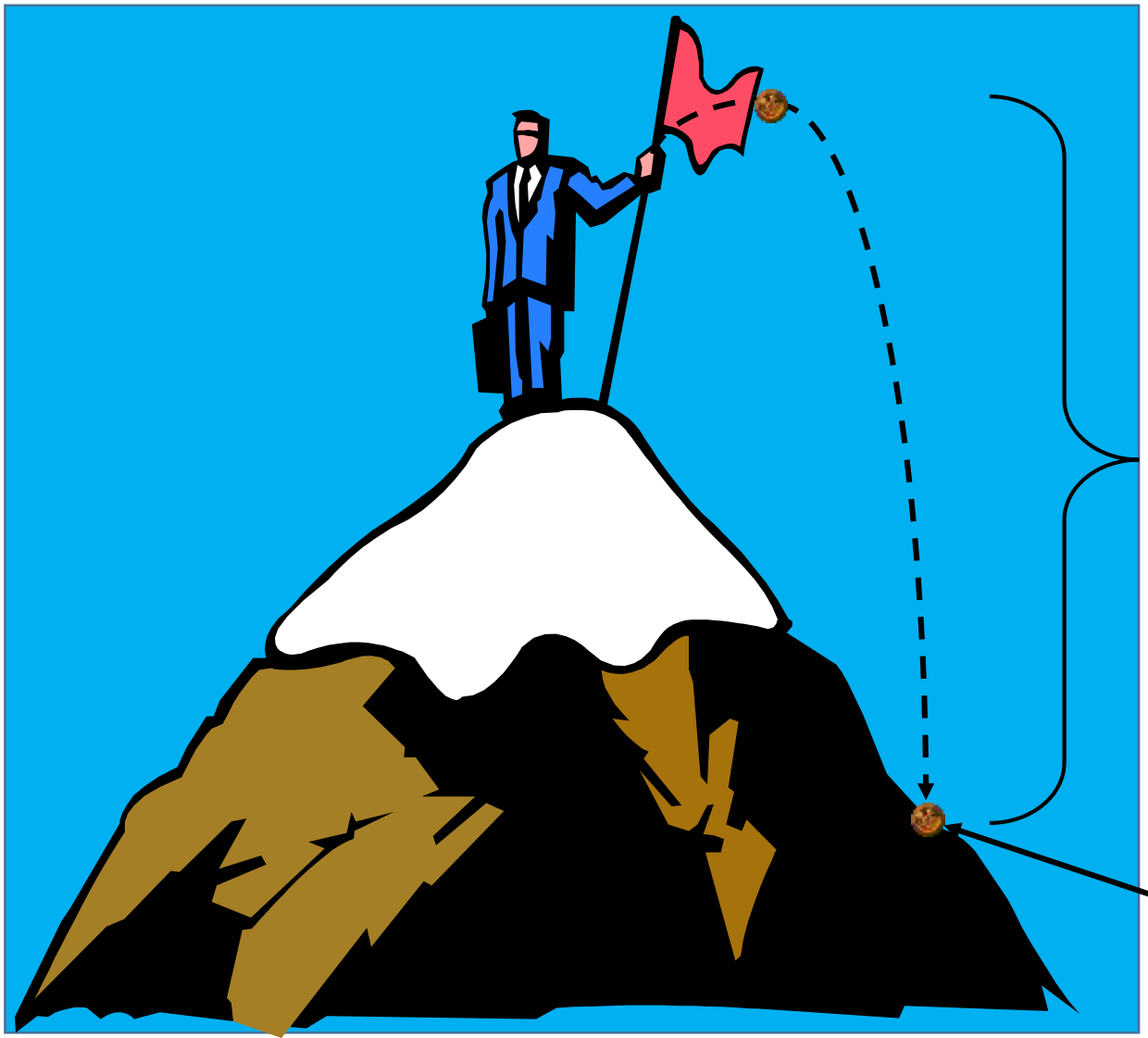
Avalanche Breakdown (in Solid) ≈ Discharge (in Gas)



To Start an Avalanche …

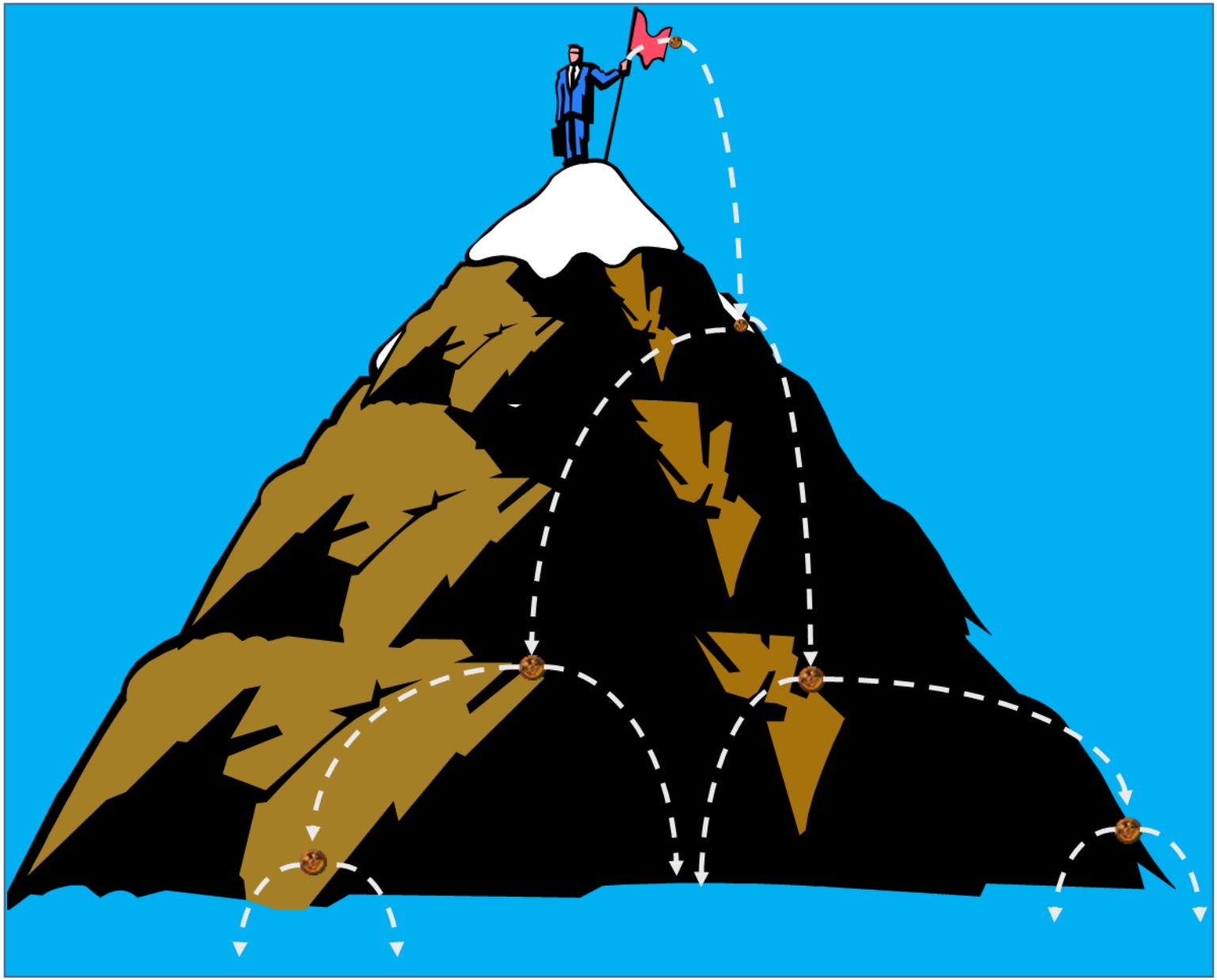
… first drop a stone off a mountain…

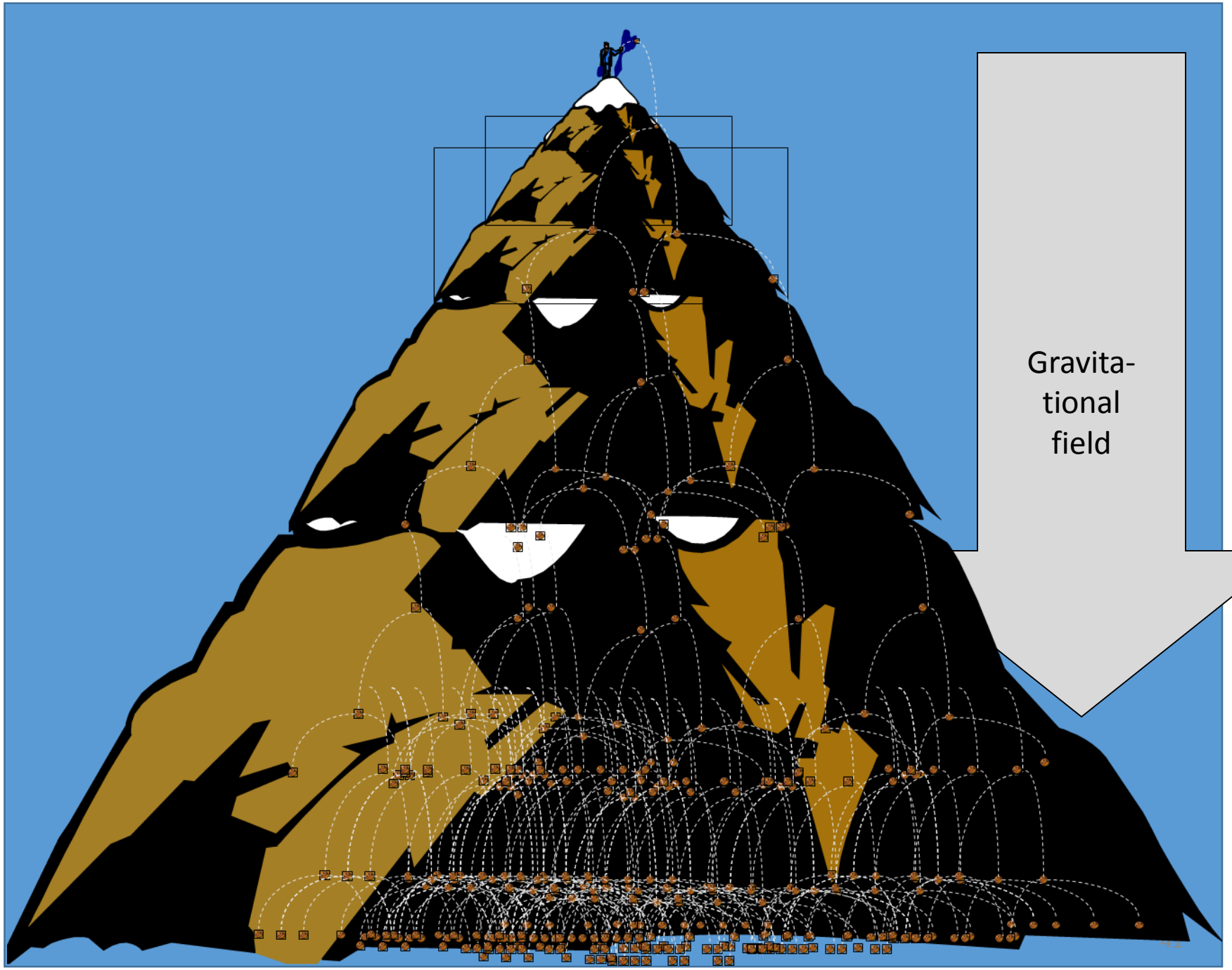
… choose a steep tall hillside …



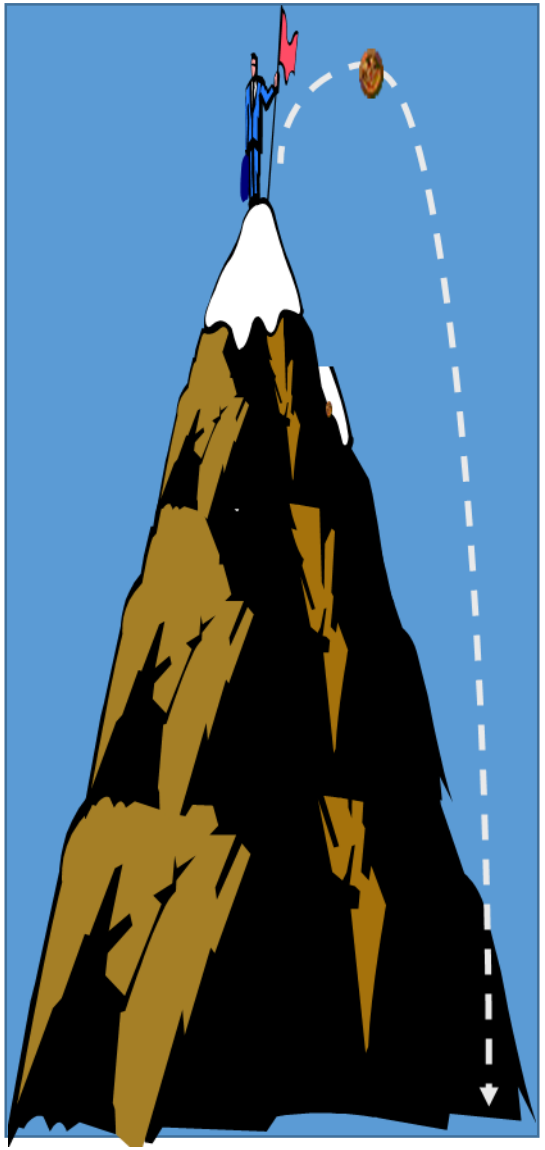
The potential energy gained must exceed the energy required to dislodge another rock

Another rock!




Gravita-
tional
field

If your mountain is too steep …



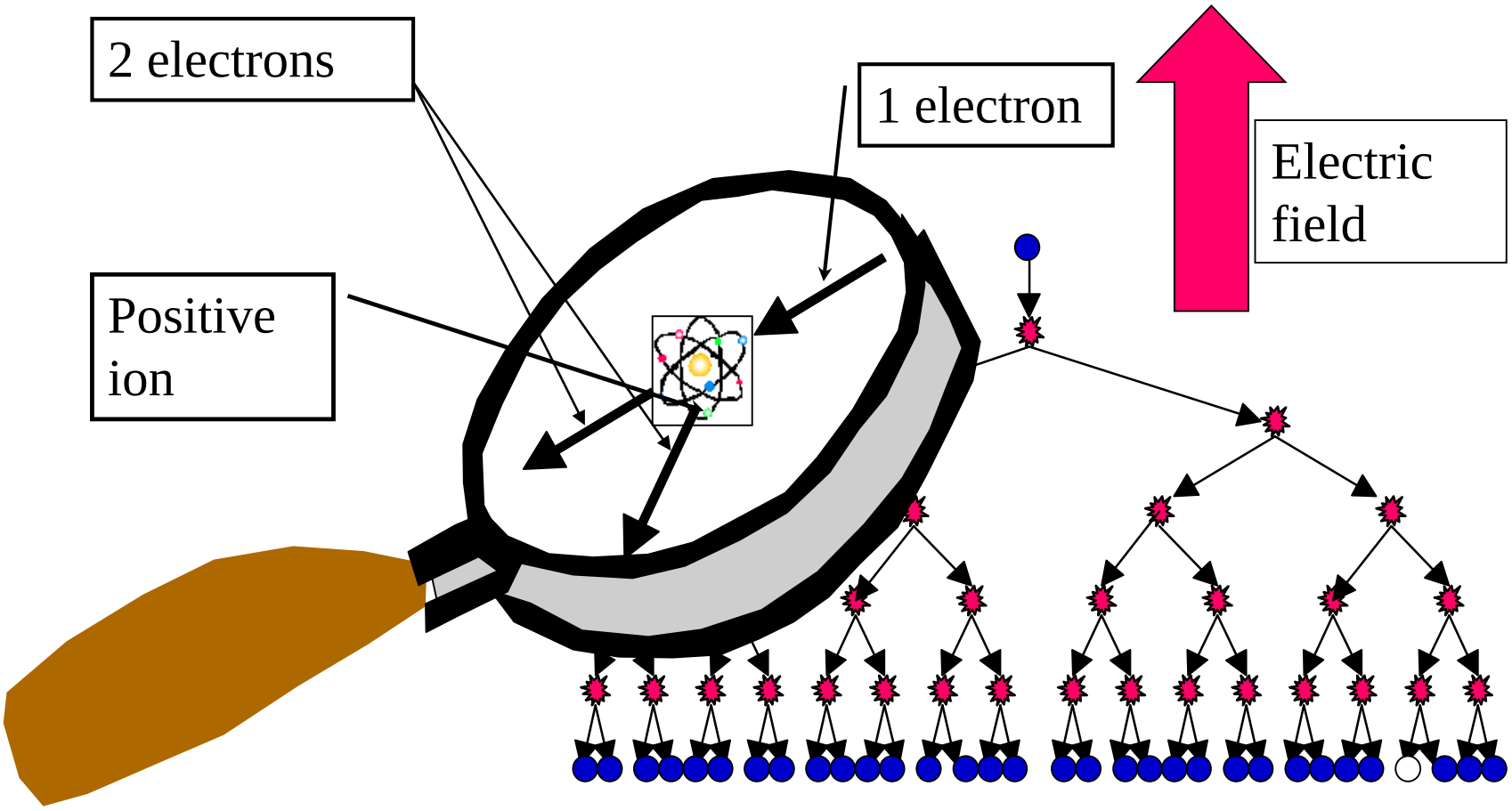
… or just not high enough …

… then you won't hit enough rocks on the way down to cause an avalanche.

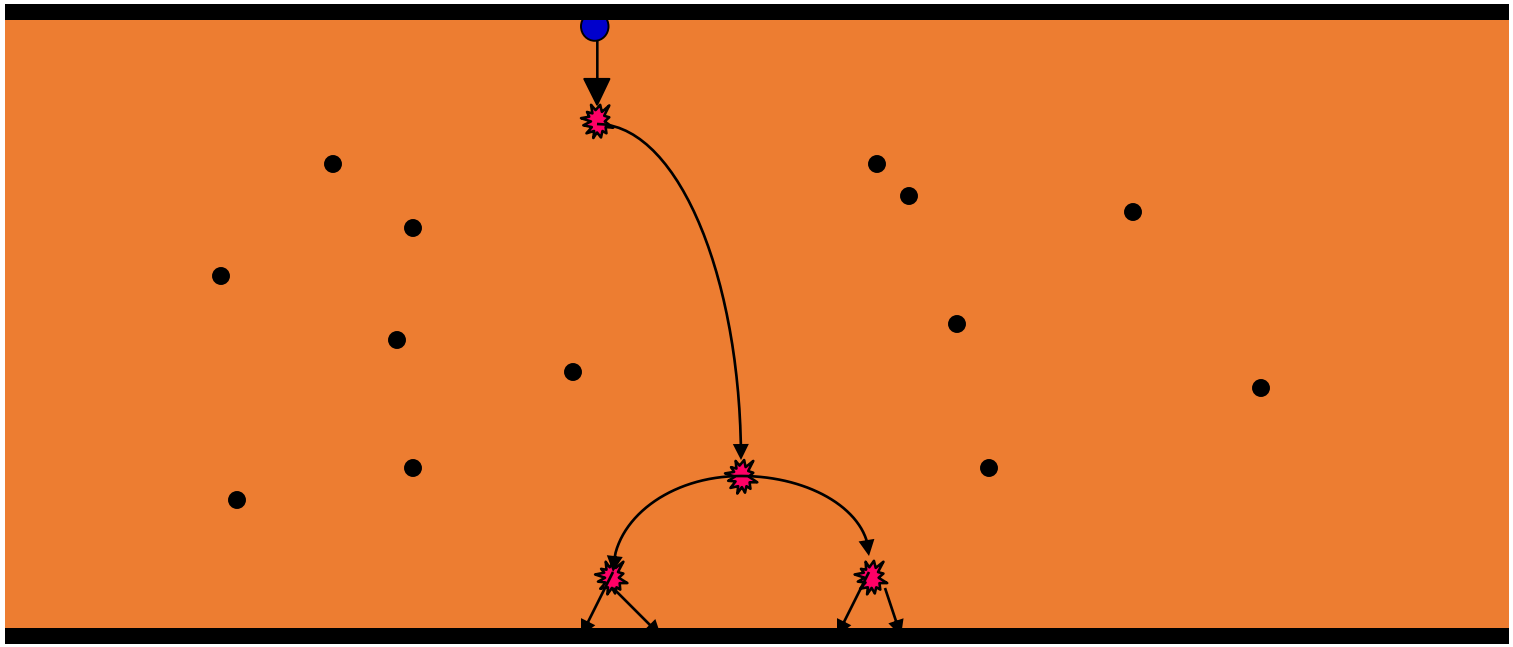
If your mountain is not steep enough …

… then your rock won't pick up enough potential energy to dislodge the next rock.

Gas Discharge

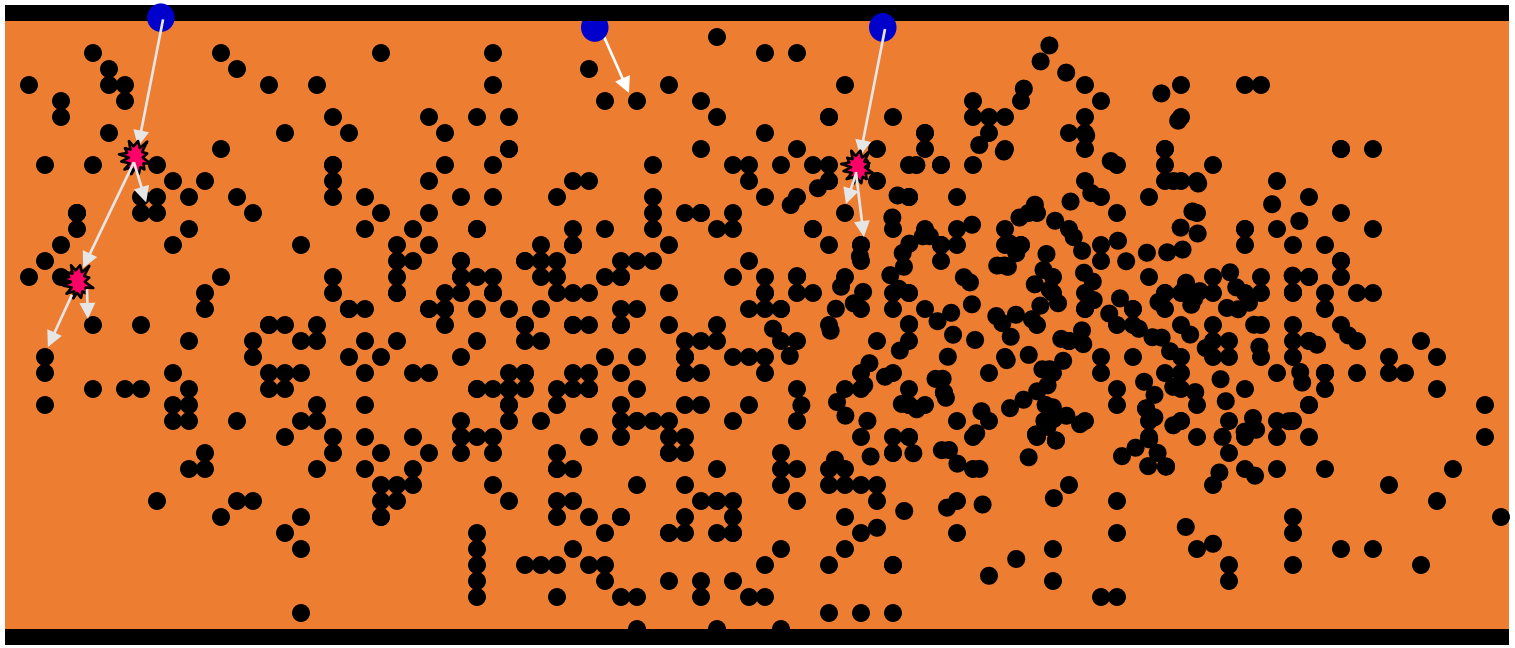


Low pressure or short gap



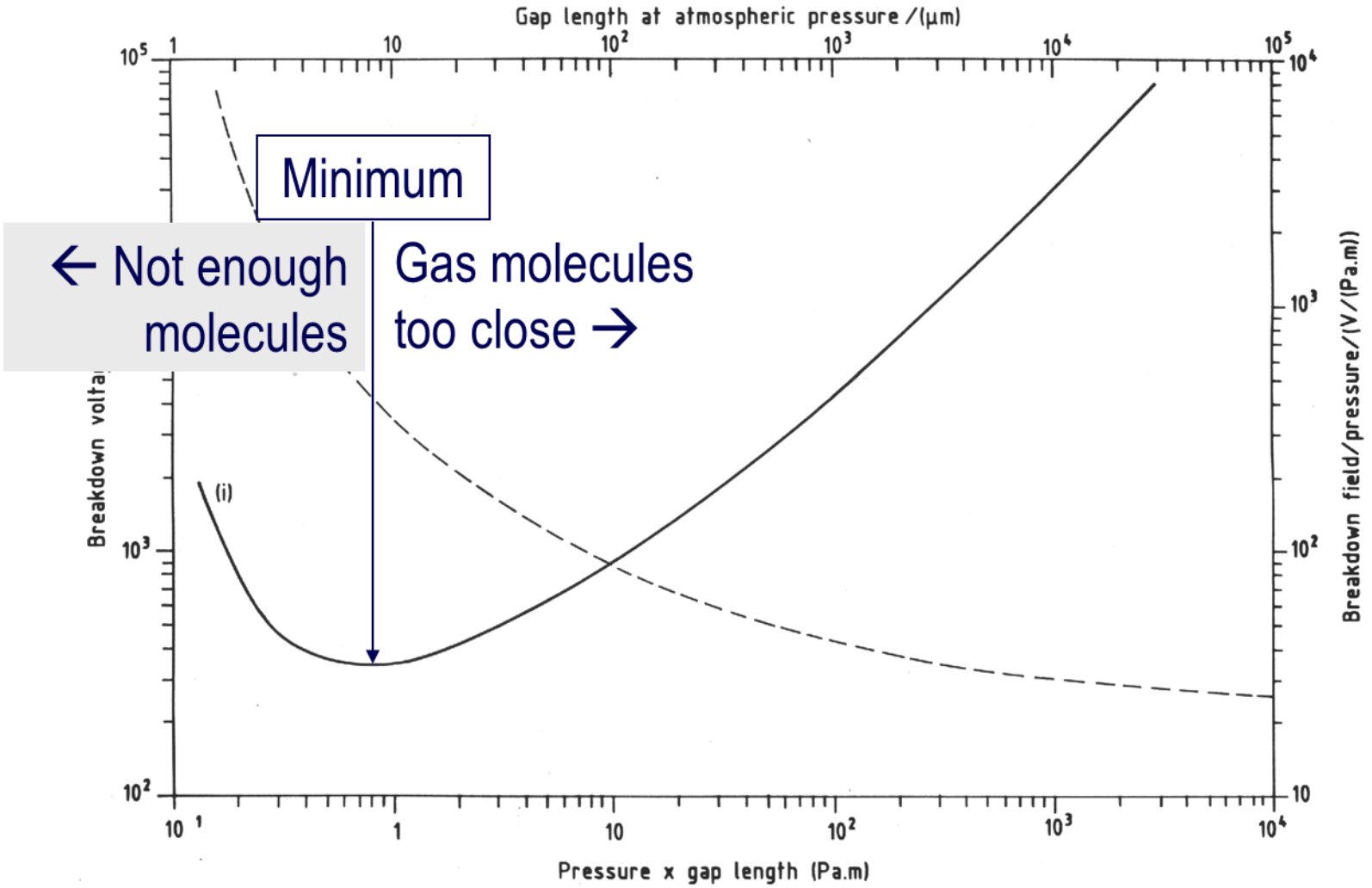
… very little carrier multiplication is produced because it is unlikely that collisions will take place.

High pressure or low voltage

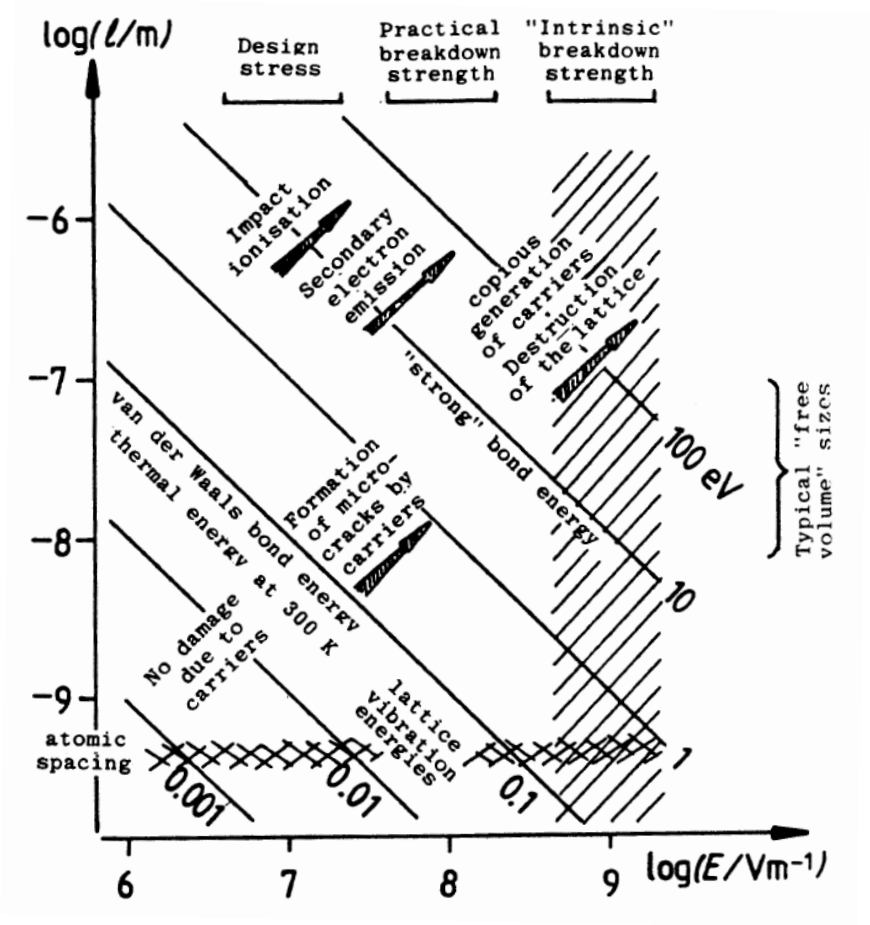


… very little carrier multiplication is produced because electrons do not gain sufficient kinetic energy between collisions.

The Paschen Curve

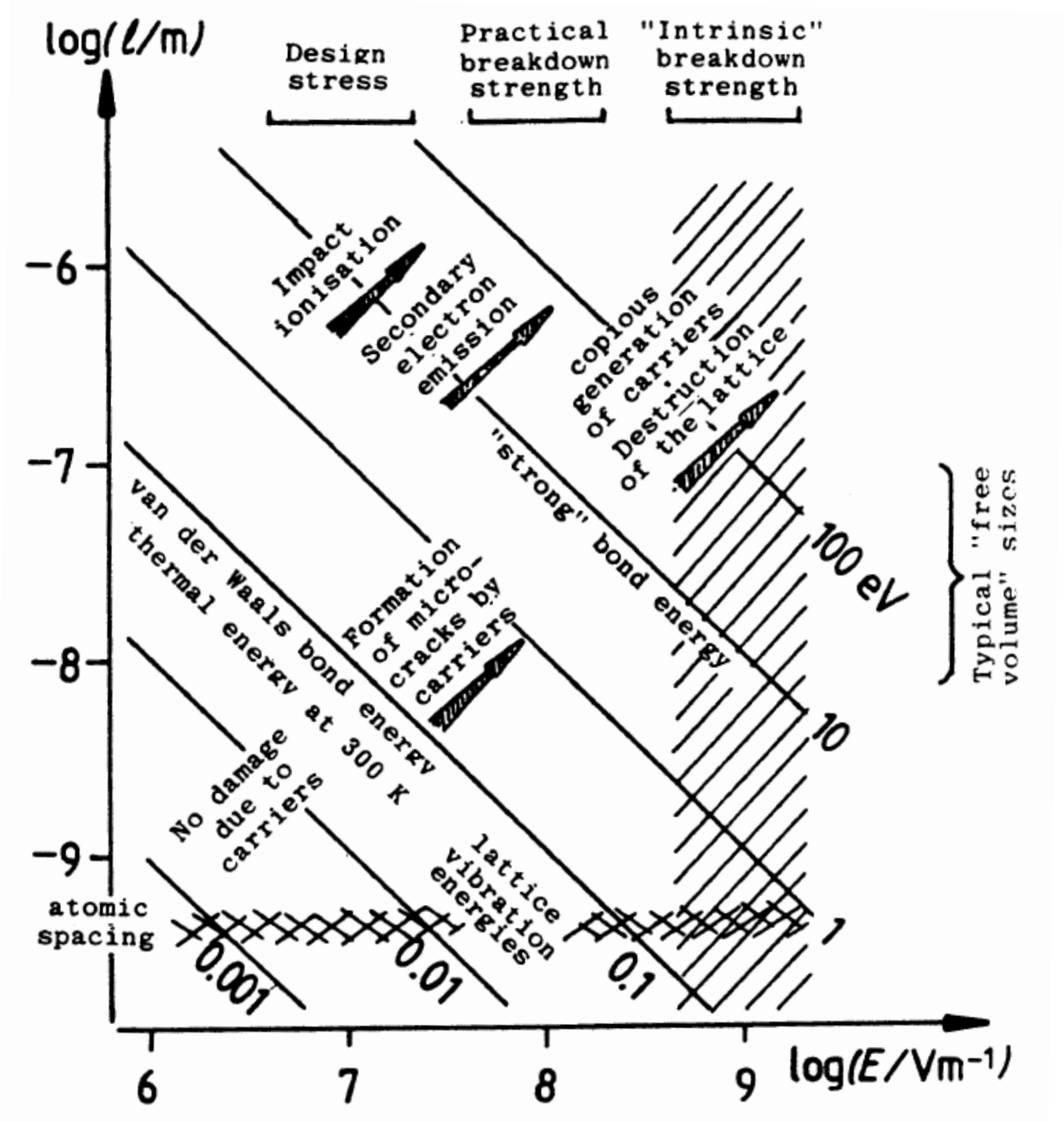


Cumulative model of dielectric breakdown



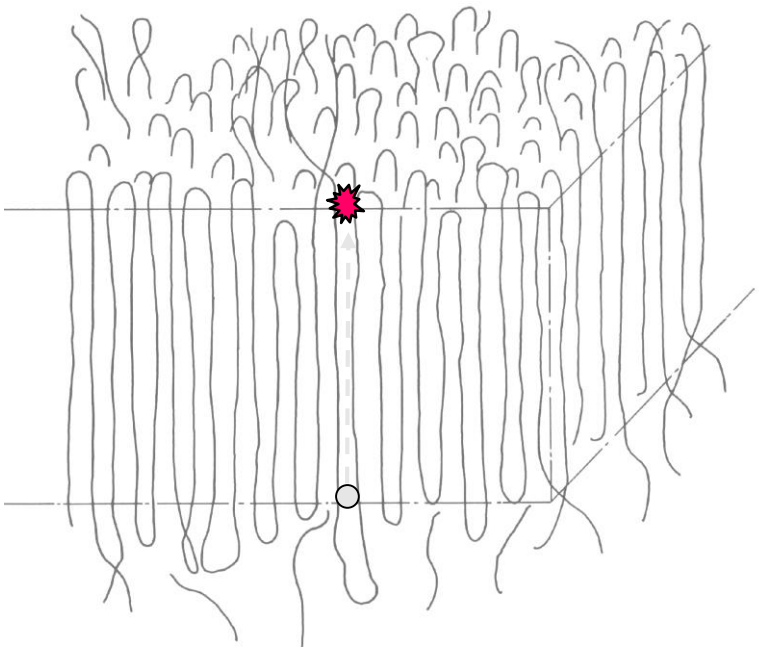
Relationship between the electric field, E, the free path of charge carriers in insulators, *l*, and the energy acquired by the carriers in a free path. Contours of constant energy are shown with the corresponding values of energy, with characteristic values of energy in solids.

A. Jonscher, R. Lacoste, *IEEE Trans. Elec. Insul*., **EI-19(6),** 567-577. (1984)


log(ℓ/m)
Design stress
Practical breakdown strength
"Intrinsic" breakdown strength
Impact ionisation
Secondary electron emission
copious generation of carriers
Destruction of the lattice
"strong" bond energy
van der Waals bond energy
thermal energy at 300 K
Formation of micro-cracks by carriers
No damage due to carriers
lattice vibration energies
100 eV
10
1
0.1
0.01
0.001
Typical "free volume" sizes
atomic spacing
−6
−7
−8
−9
6
7
8
9
log(E/Vm⁻¹)

Hot Electrons in Solids

- "Hot" electrons – those with high energies – may travel several inter-atomic distances before collision occurs – at least this may be possible for "lucky electrons"
- If they acquire sufficient kinetic energy then carrier multiplication may occur
- … or they may just lead to degradation.



“Intrinsic” breakdown

“Intrinsic” breakdown

- von Hippel and Frölich proposed “intrinsic” breakdown mechanisms based on energy balance between:
  - Rate of free electron kinetic energy gain
  - Loss due to lattice scattering

  These are unlikely to occur in polymeric insulation.
- Zener (or “field emission”) breakdown involves direct excitation from valence to conduction band.
  - This band gap is very high in insulators (>>2 eV) and is unlikely to occur in polymeric insulation.

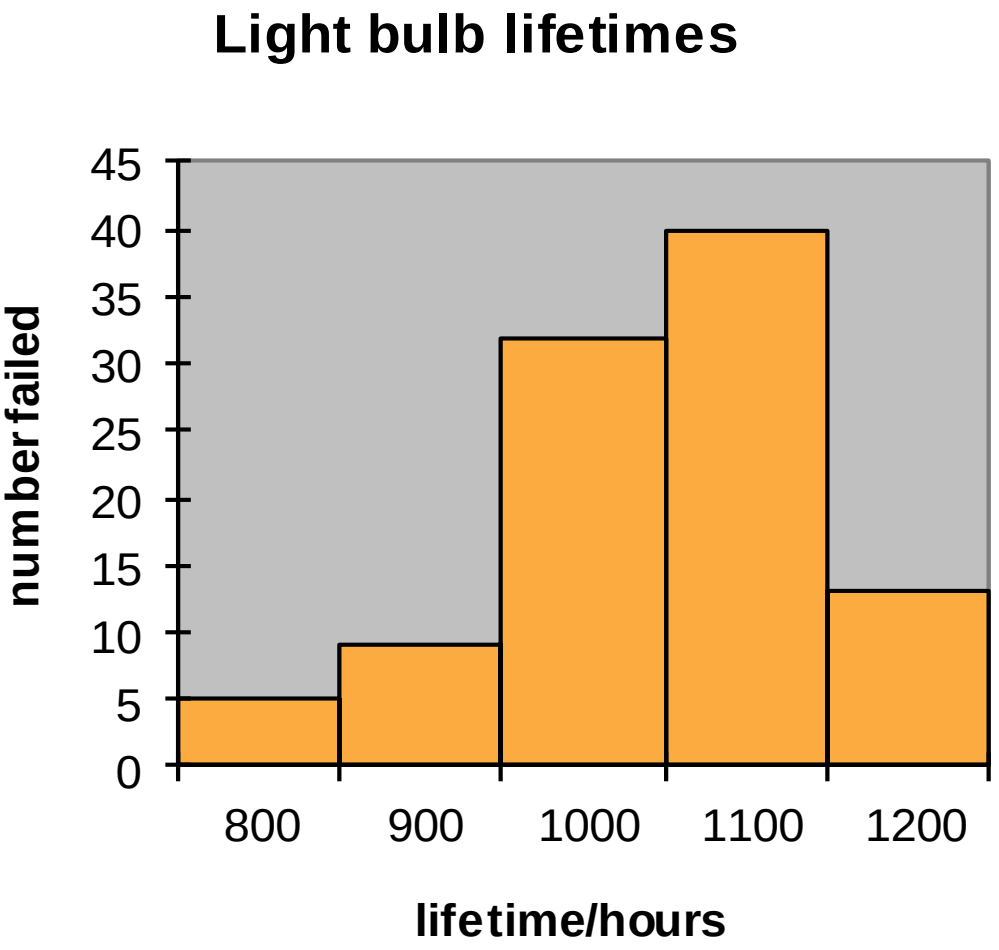
Statistics of breakdown

Two Electrical Breakdown Tests:

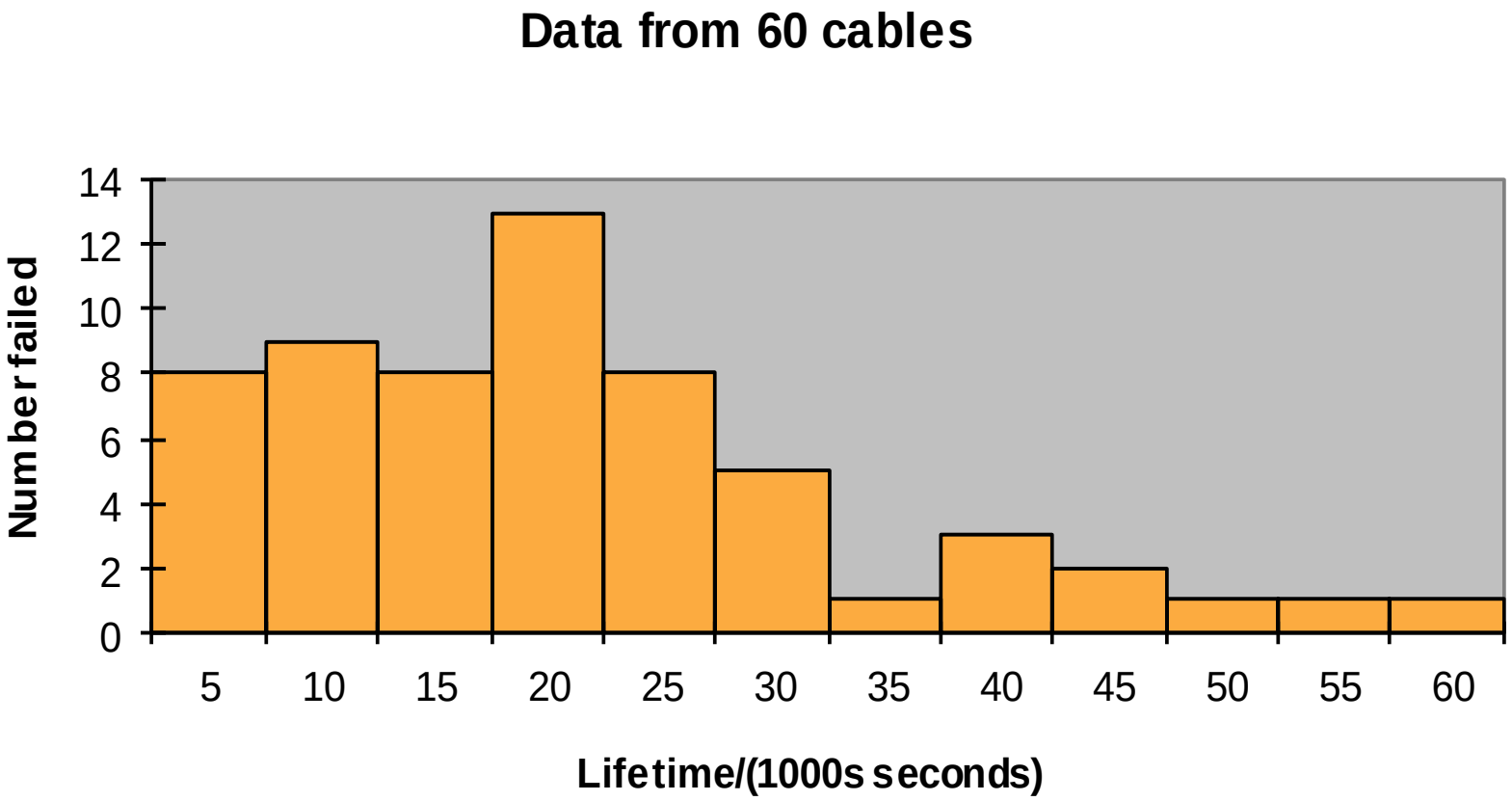
- Endurance (constant stress) tests
  - The same stress is applied to a set of items
  - The failure times form a set of data
- Ramp (progressive stress) tests
  - An increasing stress is applied to a set of items
  - The failure stresses form a set of data

Endurance Testing

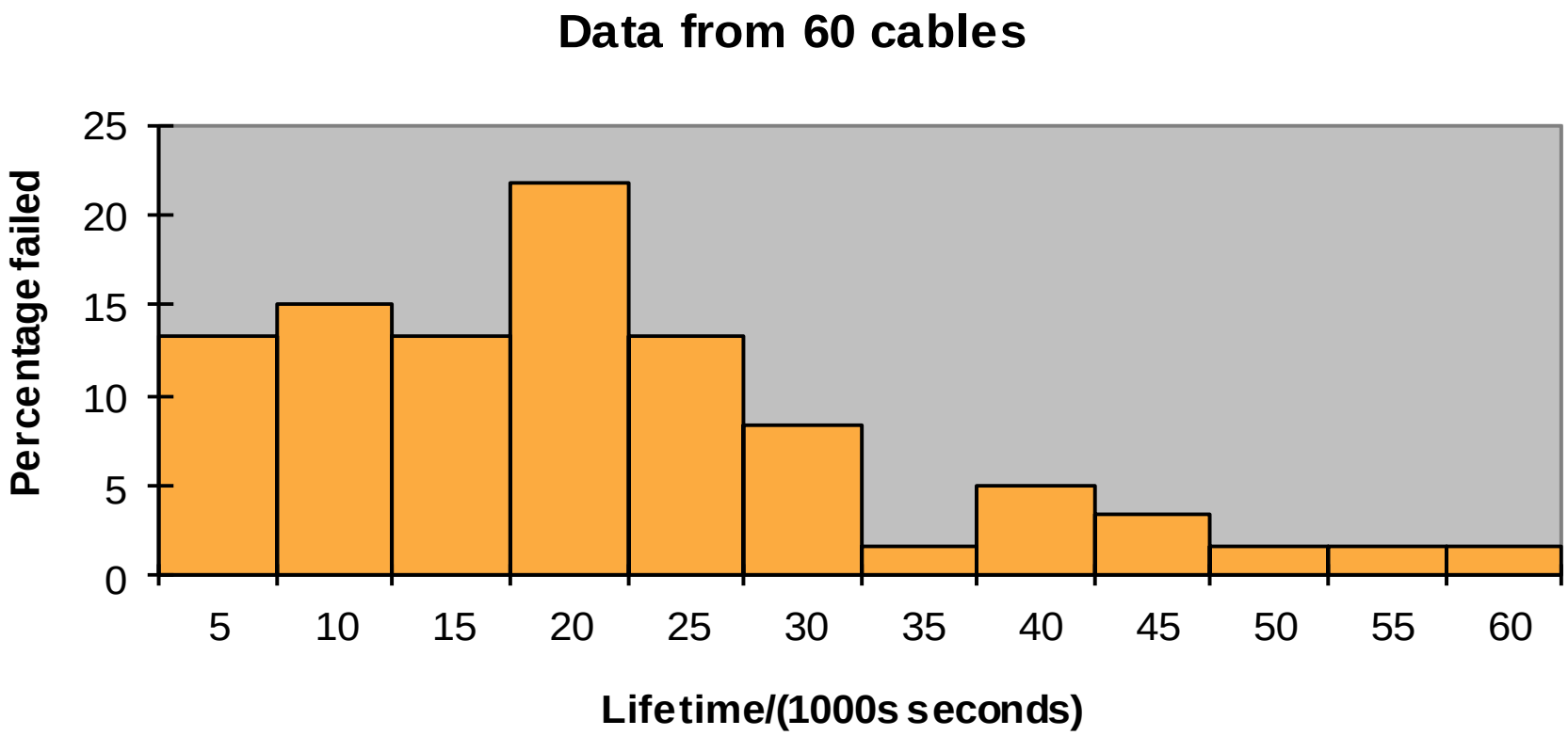
- Normal distribution
  - Chance variation in populations, errors etc.
  - Uses *mean* and *standard deviation*
- Weibull distribution
  - Failure statistics
  - Uses *characteristic life* and *shape parameter*



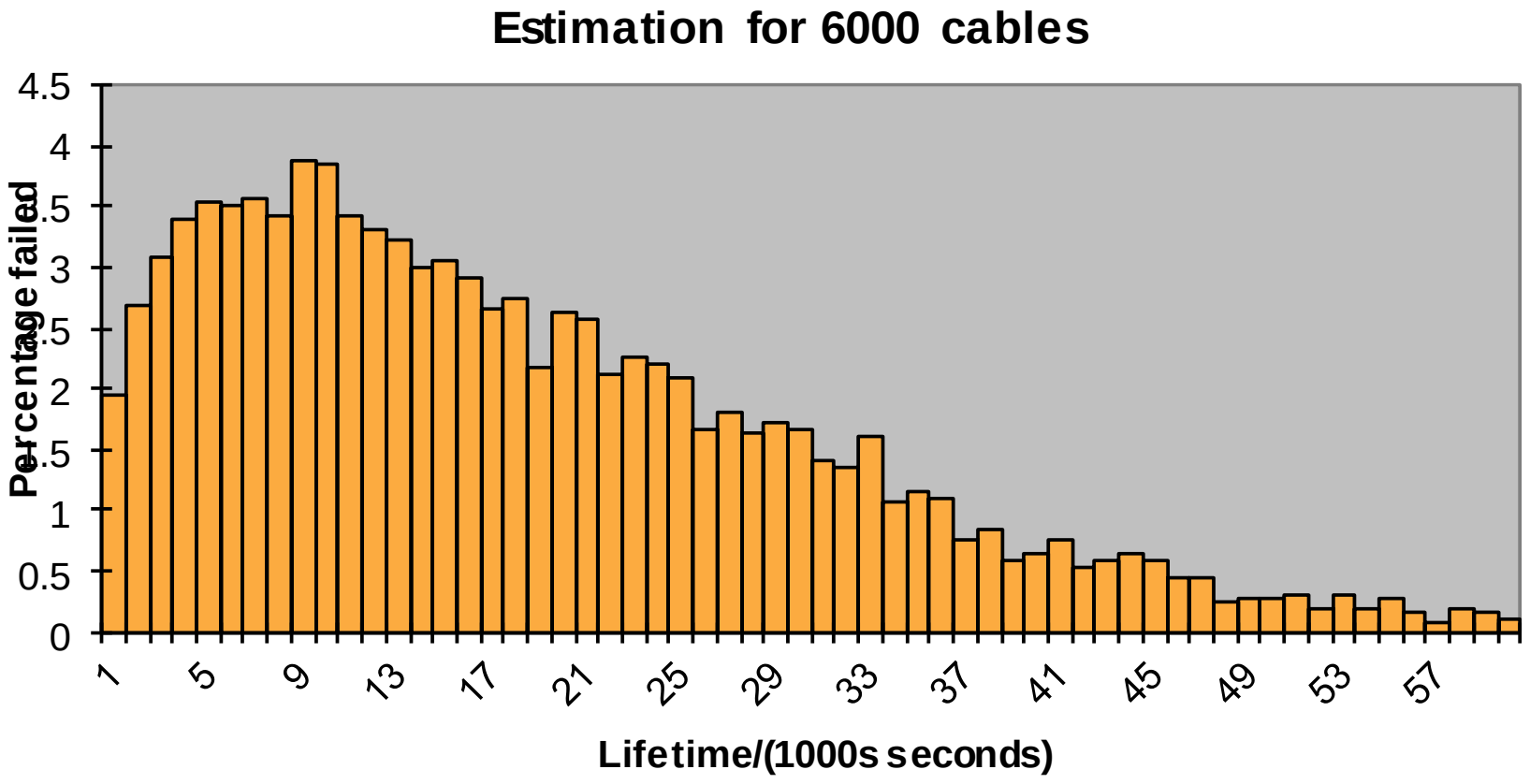
Measurements of Lifetimes of Cables Under Constant Voltage



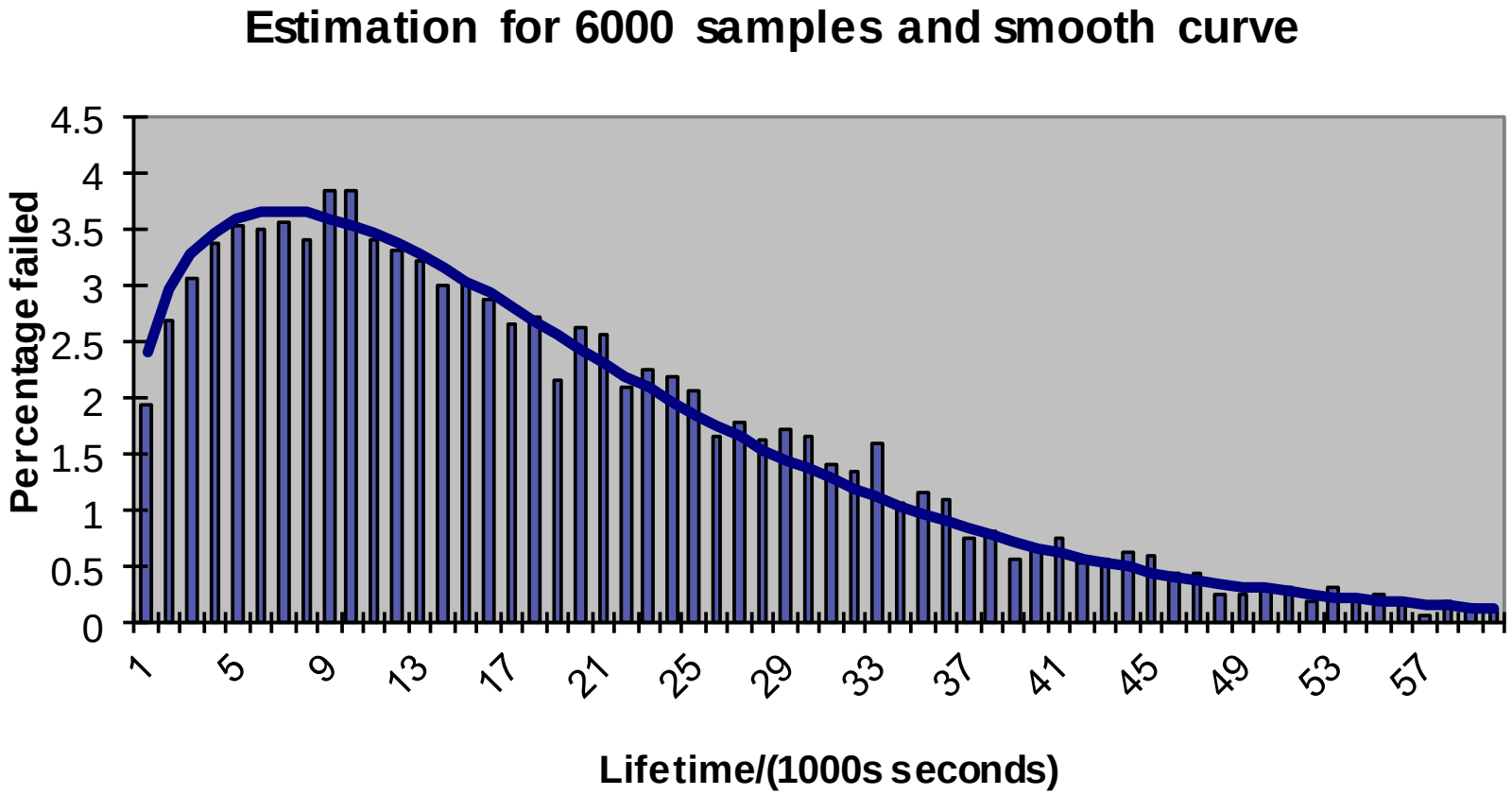
Cable Lifetime Data: Presented As a Percentage of All Samples Failed



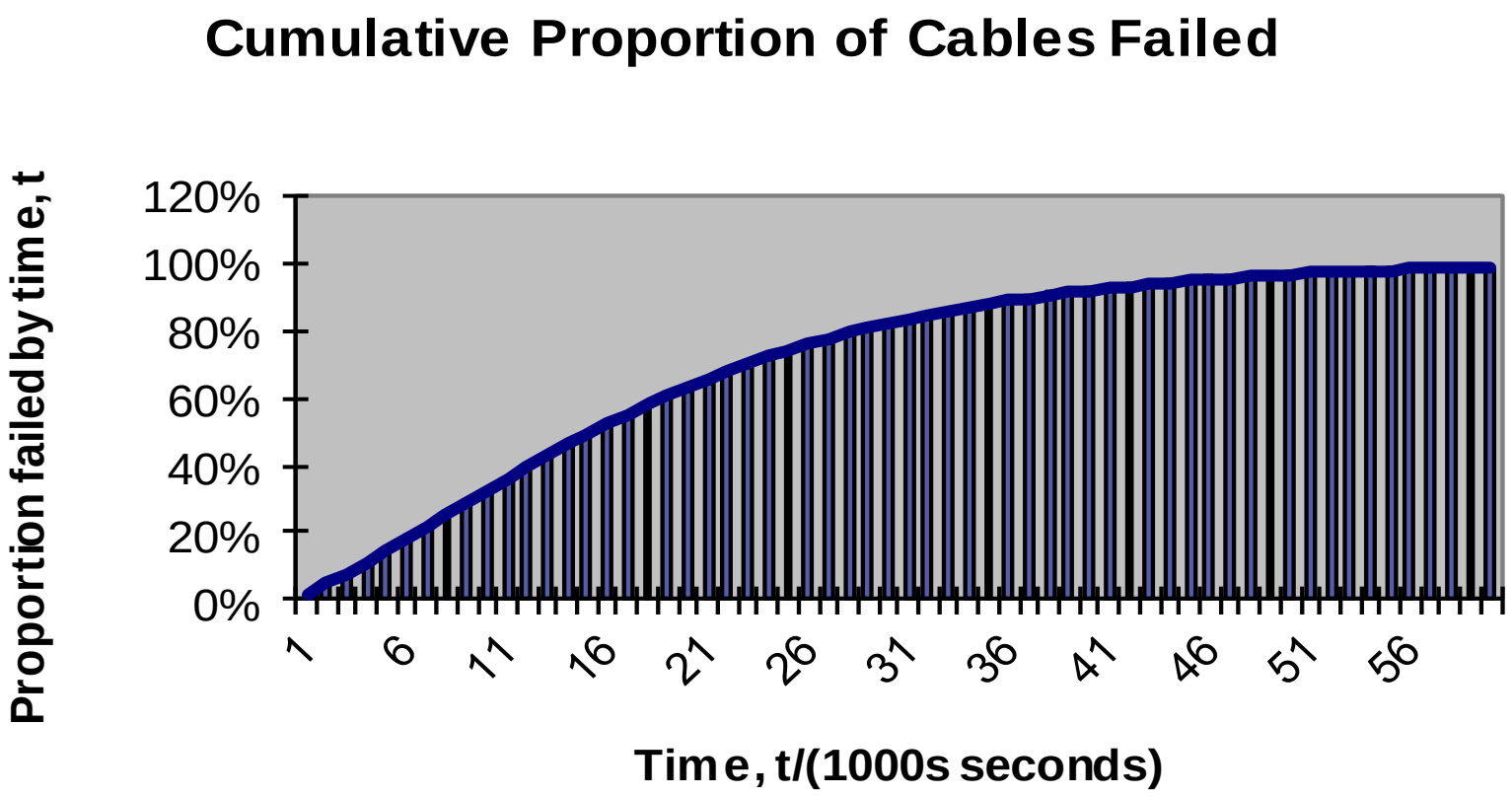
Extrapolation to a Large Number Gives a Smooth Distribution…



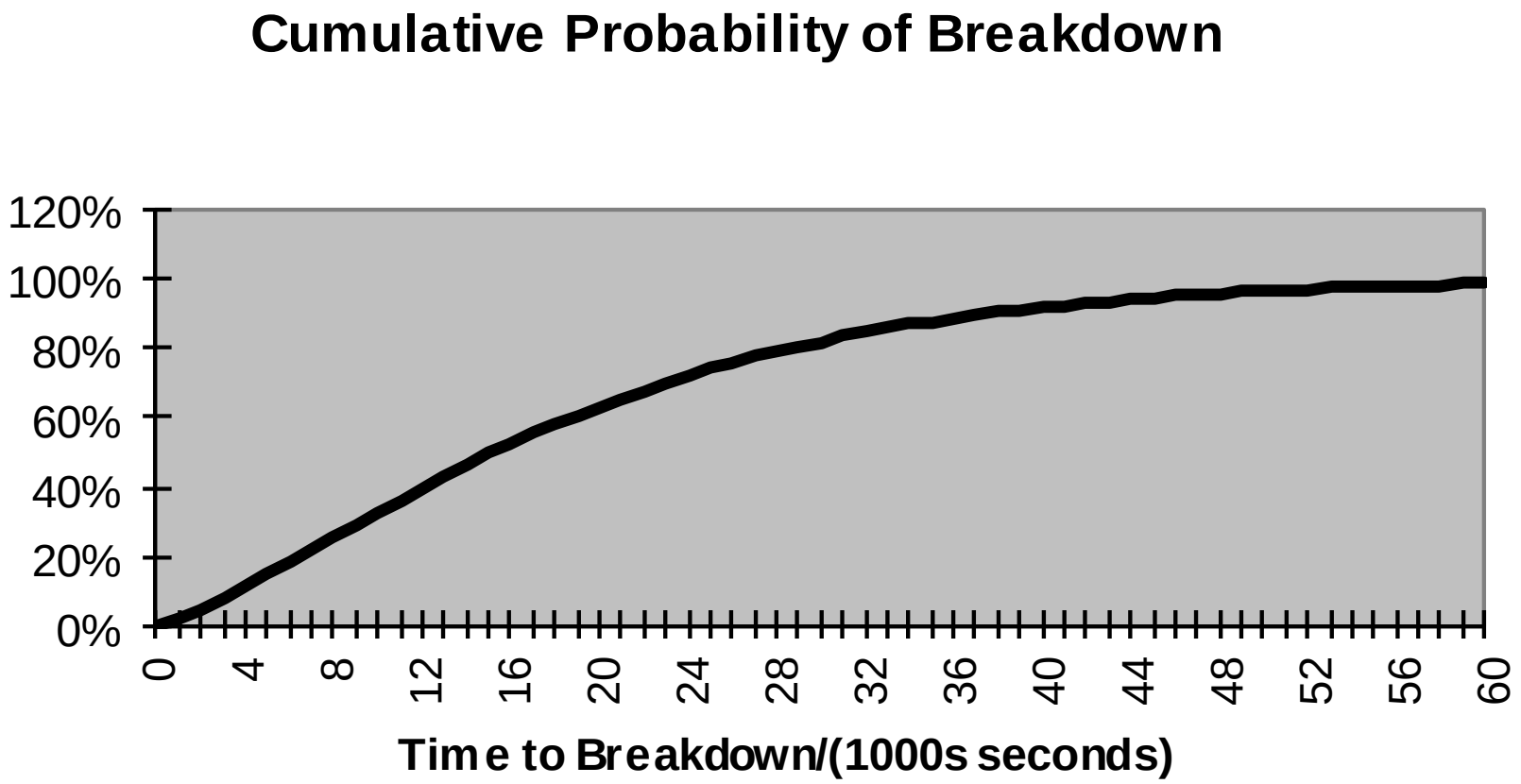
… through which a line can be drawn.



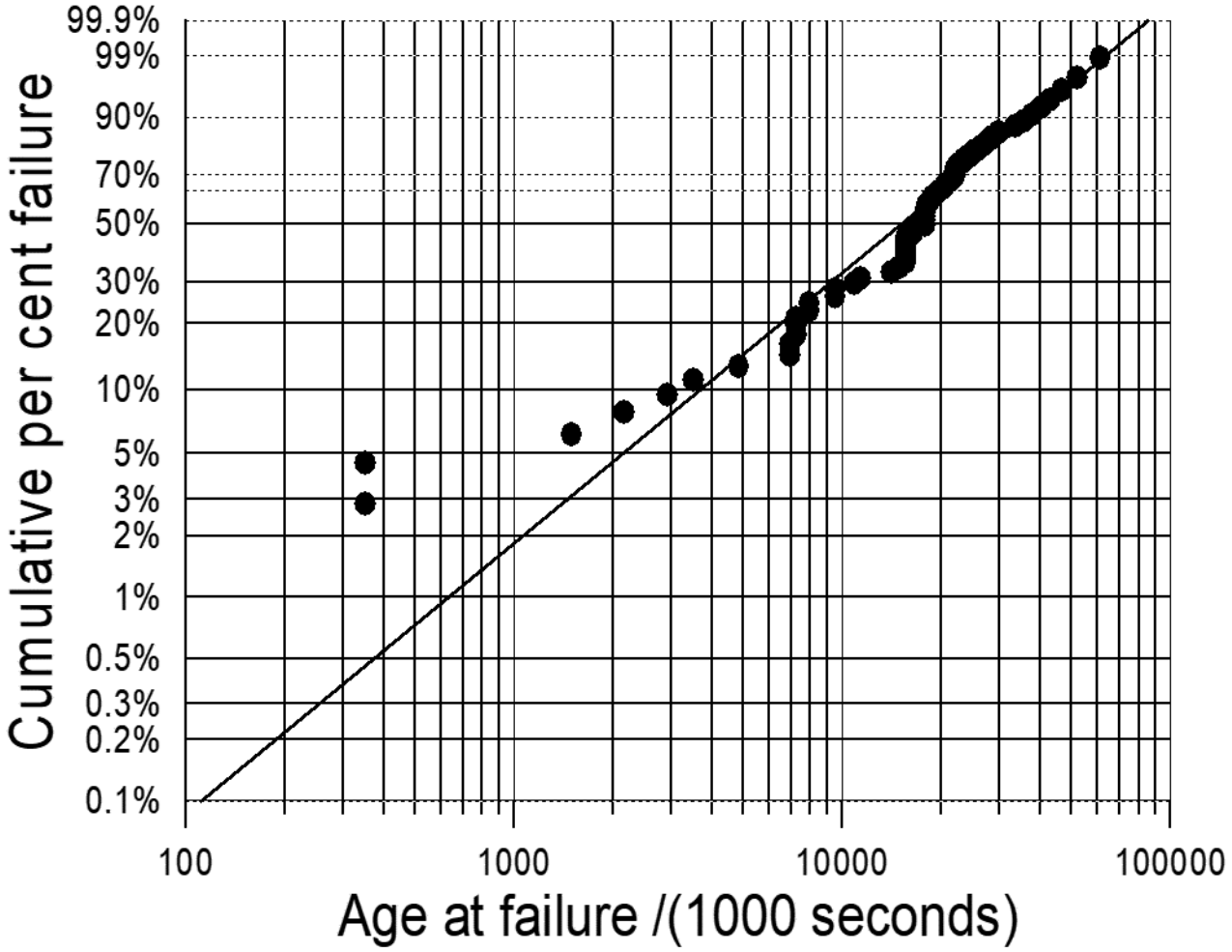
Often Useful to Plot: Proportion of Cables Failed by a Given Time



Smooth Curve Is the “Cumulative Probability of Breakdown”

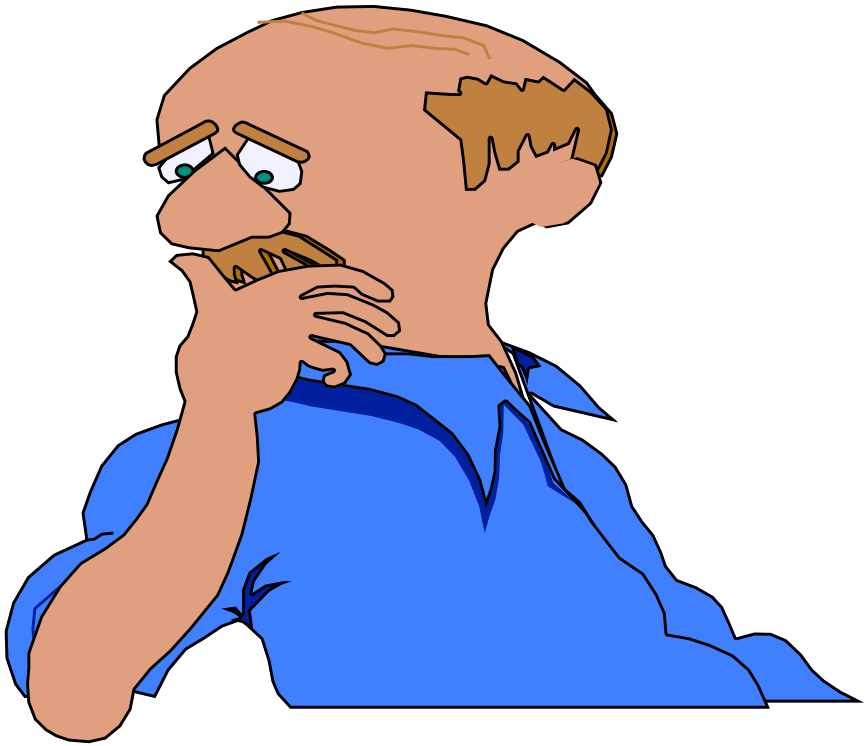


The Weibull Plot

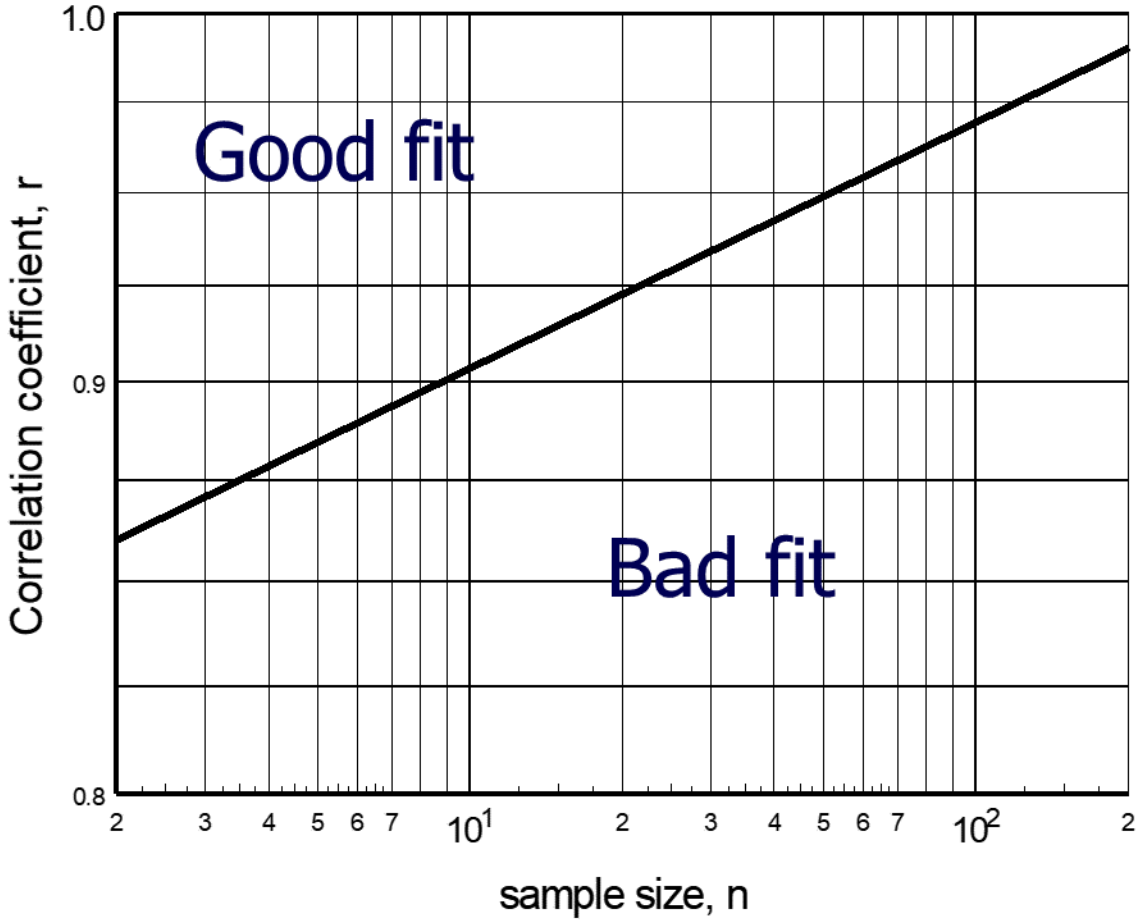


Assumptions Implicit in the Weibull Plot

- Cable lifetimes are distributed according to the Weibull distribution and not some other distribution
- The data measured is representative of the distribution



Is it a Weibull distribution?
How straight is the Weibull plot?



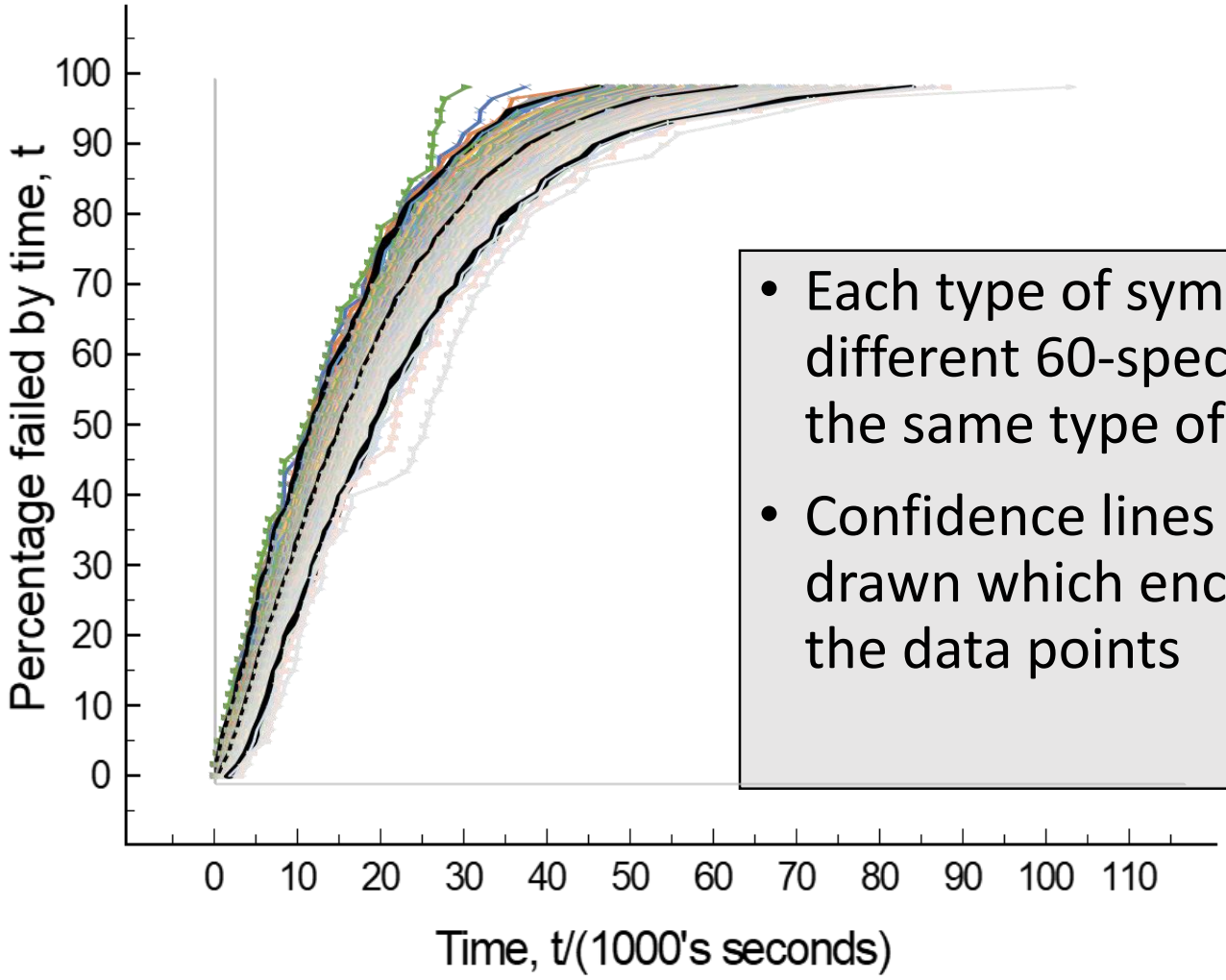
Representative Data?

Is it reasonable to extrapolate from:

- 60 measured data points to ...
- 6000 points to ...
- a smooth curve?

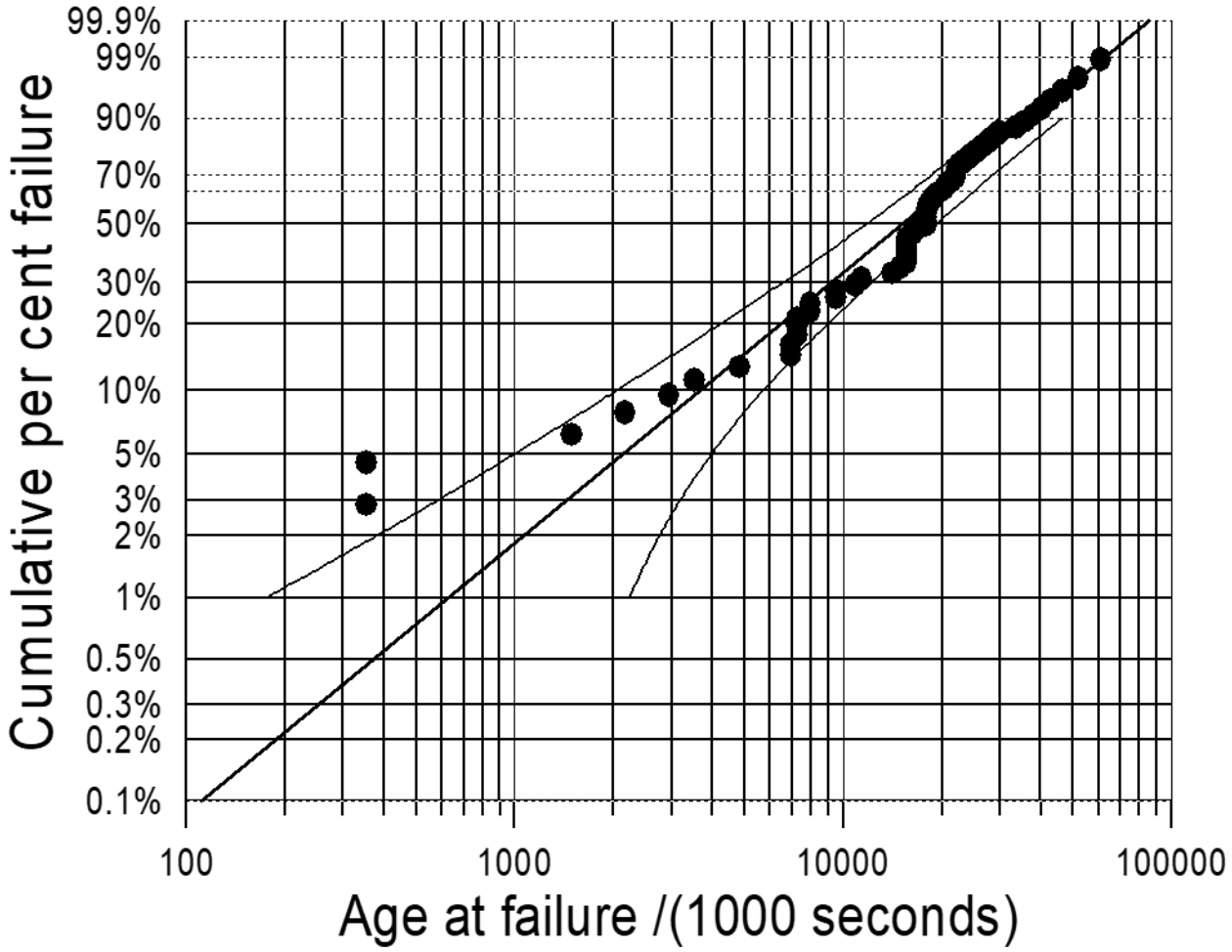
(...and yes 60 tests is a lot!)

The Endurance Test Performed a Large Number of Times



- Each type of symbol is for a different 60-specimen test on the same type of insulator
- Confidence lines could be drawn which enclose 90% of the data points

Use of Confidence Limits



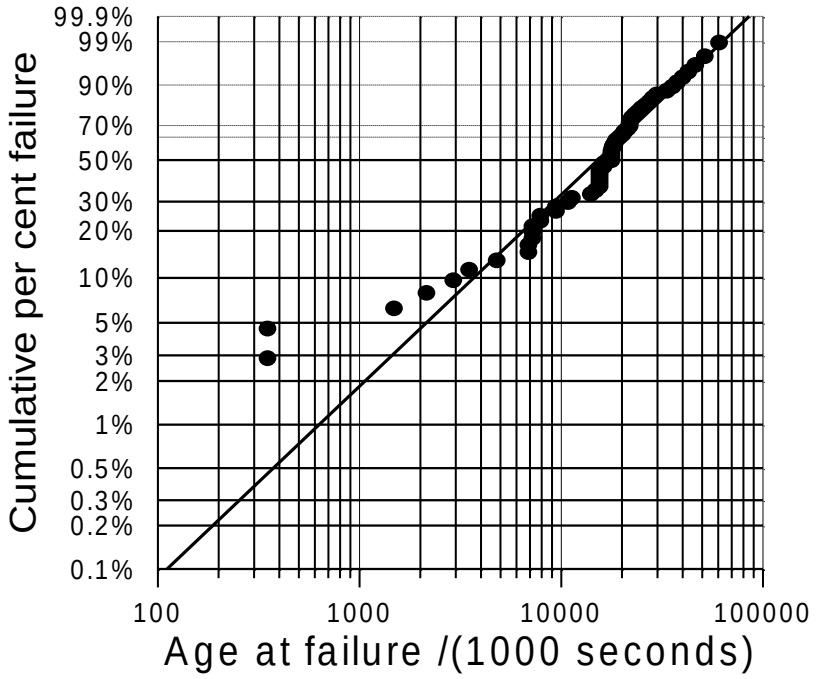
The Weibull equation

$$P(t) = 1 - \exp\left\{-\left(\frac{t}{\alpha}\right)^{\beta}\right\}$$

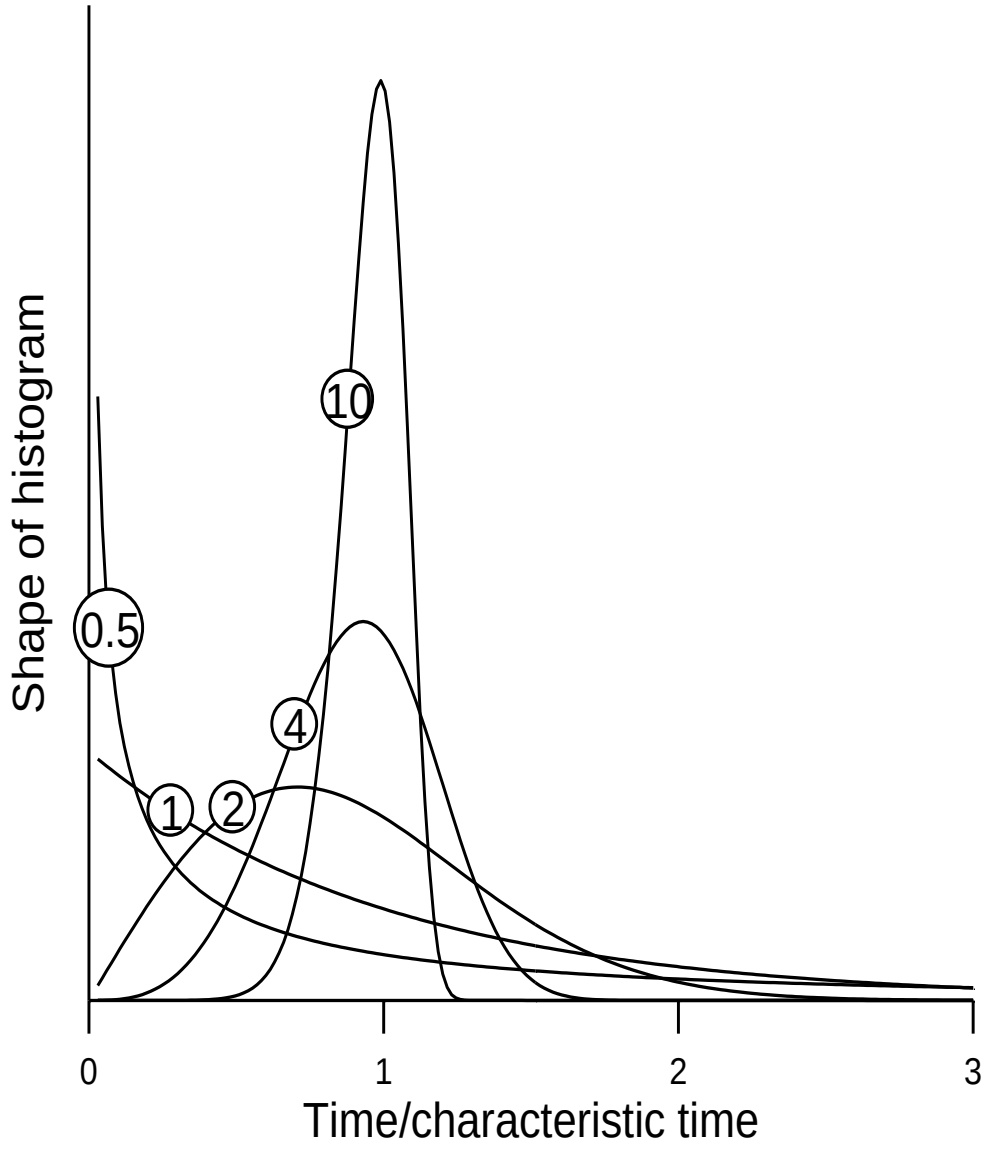
- *P(t)*= probability of failure by time *t*
- α = *characteristic time to failure*
- β = *shape parameter*

Characteristic Time to Failure, α

- Time for 63.2% of cables to have failed (or strictly cumulative probability of failure = 63.2%)
- 20,000 seconds in this example

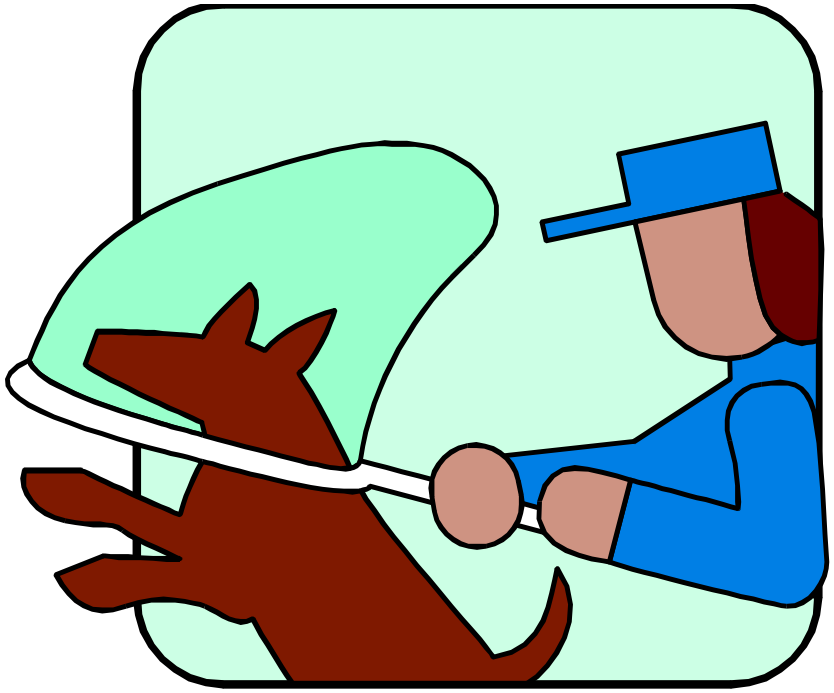


Shape parameter, β



- β = slope of plot
- β <<1 indicates infant mortality
- β >>1 failures occur at about same time
- random failures: β =1
- β =1.33 in this case

Constructing a Weibull Plot
First - Catch Your Data



Rank (i)	Time to failure (years) ranked by value
1	0.64
2	1.34
3	2.60
4	3.88
5	4.08
6	7.47
7	9.13
8	11.66
9	17.58
10	22.76

Constructing a Weibull Plot 2: Cumulative Failure Probabilities

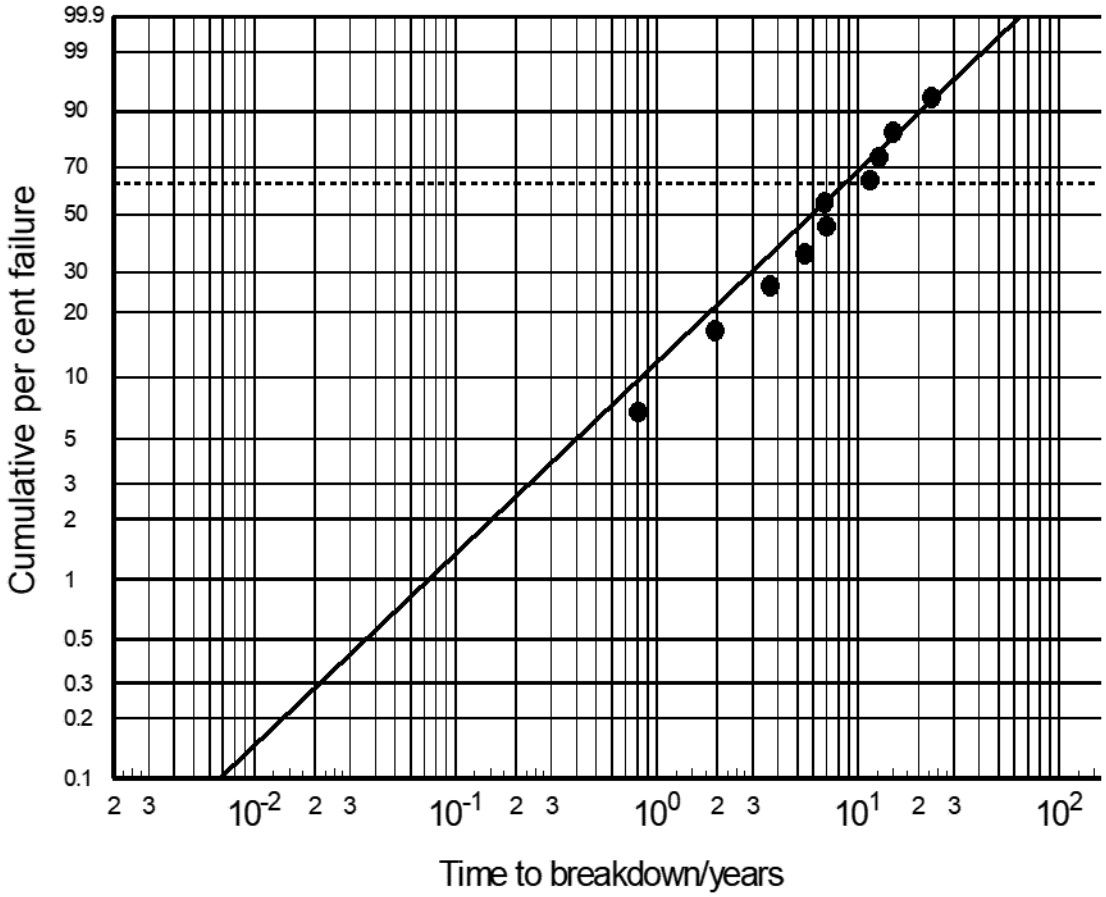
$$F(i,n) \approx \frac{i-0.3}{n+0.4}$$

$$i = \text{rank}$$

$$n = \text{sample size}$$

Rank (i)	Cumulative Probability of Failure (%)	Time to failure (years)
1	6.7	0.64
2	16.3	1.34
3	26.0	2.60
4	35.6	3.88
5	45.2	4.08
6	54.8	7.47
7	64.4	9.13
8	74.0	11.66
9	83.7	17.58
10	93.3	22.76

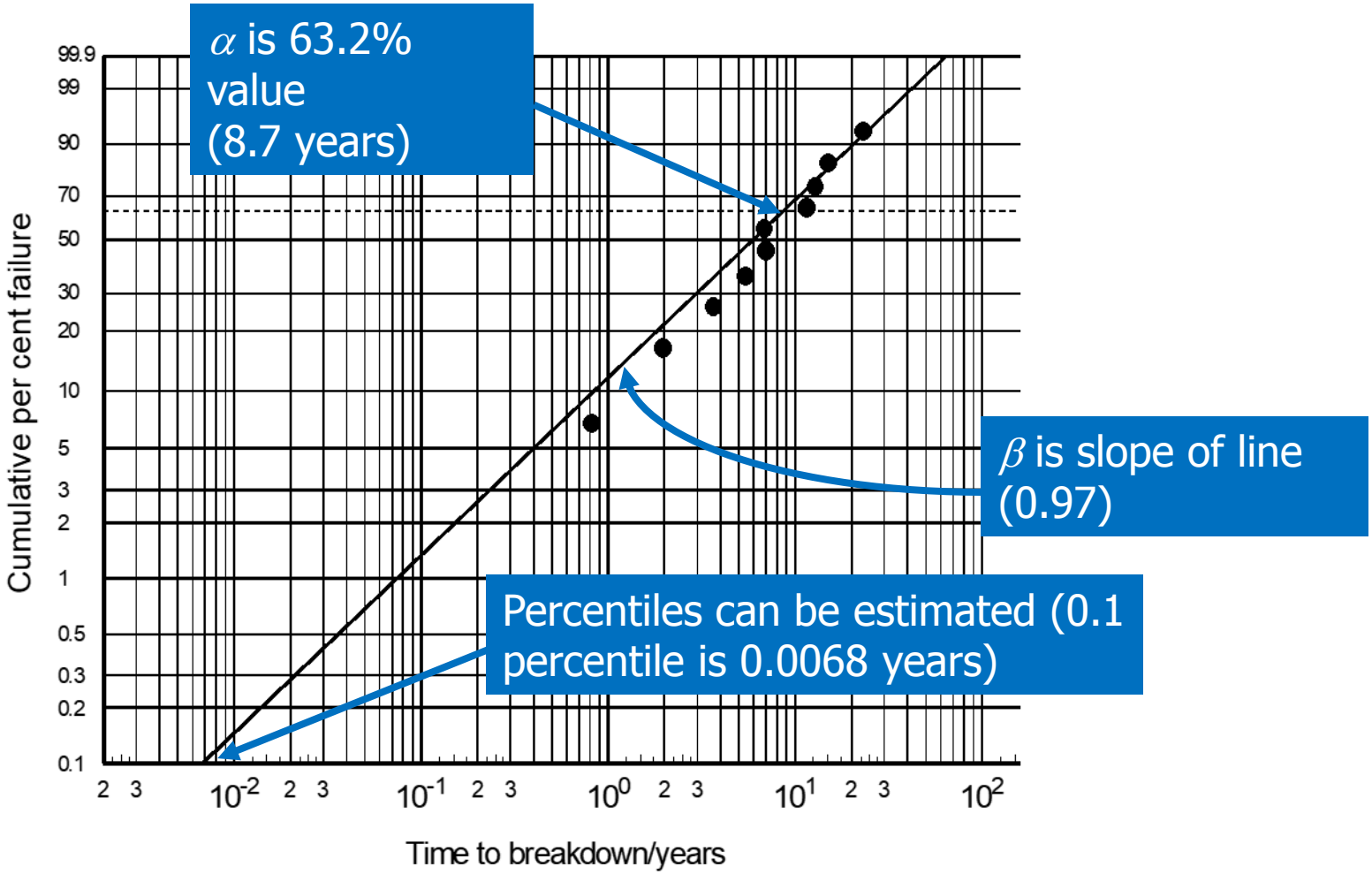
Constructing a Weibull Plot
3: Plot on Weibull Graph Paper



Fit line by eye or use mathematical technique

e.g. Montanari *et al*, IEEE Transactions on Dielectrics & Elec. Insul., **4(3)**, 306-313, 1996

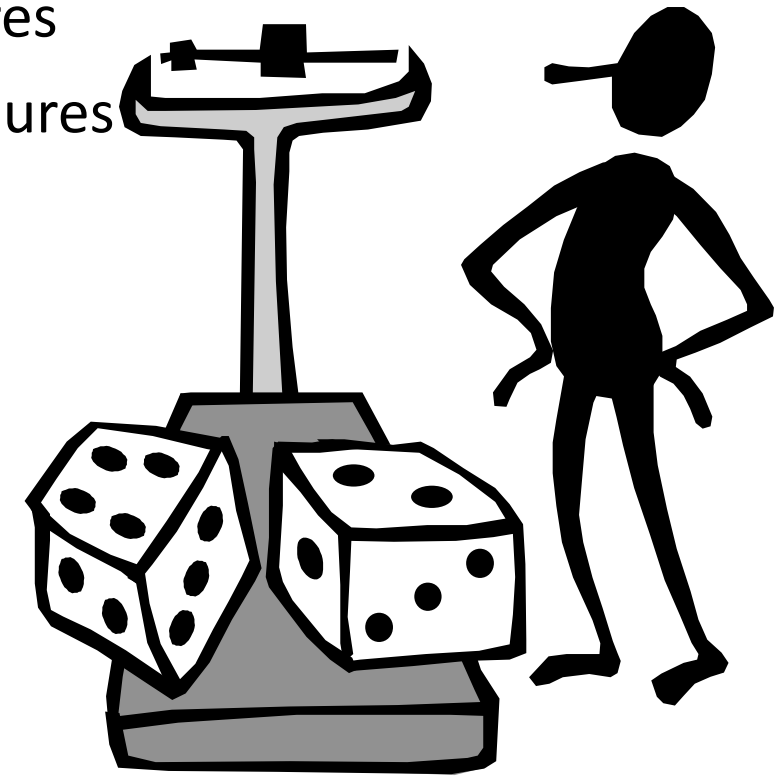
Constructing a Weibull Plot 4: Estimating Parameters



How Reliable?

Typically one may use

- 1 percentile for benign failures
- 0.1 percentile for serious failures
- 0.01 percentile for catastrophic failures

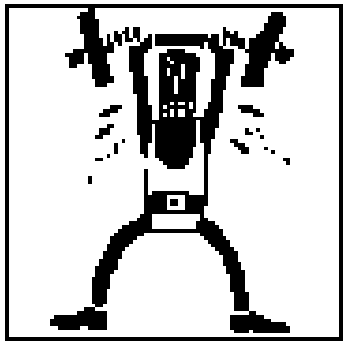


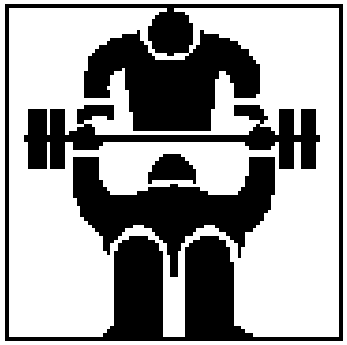
From Laboratory Specimens to Service: A Cable Example

- Cable in service is *N* times longer than lab. specimens:
- Then probability of survival in service
  = joint probability of survival of all regions
  = (probability of survival of laboratory specimen)^{N}
- e.g.: Service reliability required=90%, *N*=100
  $\therefore$ Probability of survival of specimen=$0.9^{1/100}$»99.9%
  $\therefore$ require that cumulative probability of failure at service life of specimen to be 0.1%

Ramp (Progressive Stress) Testing

- Failure *voltages* (instead of *times*) may conform to Weibull distribution
- Shape parameter, β, is much higher (~10) than for endurance tests
- Characteristic breakdown voltage may depend on ramp rate
  - slower ramp rate →
  - item must withstand voltage for longer →
  - Breakdown may occur at lower voltage)





Weibull *Versus* Normal

- Normal distribution ≈ Weibull with β=3.4
- Very unusual for endurance data ($\beta < 2$)
- Weibull has some theoretical basis (weakest link)
- Normal parameters (mean and standard deviation are easy to estimate)

Weibull Versus Log-normal

- Log-normal generally fits data better than normal but not as well as Weibull
- No theoretical basis for log-normal
- Log-normal parameters are easy to estimate
- “Tails” of distributions are different and critical for extrapolation to service conditions.

Estimating Lifetime

- Can one estimate service life from measurements in the laboratory at higher stresses and different temperatures?
- A knowledge of the ageing mechanism is required.

Use of other statistical distributions

2002 Annual Report Conference on Electrical Insulation and Dielectric Phenomena

PREDICTING ELECTRICAL BREAKDOWN IN POLYMERIC INSULATORS: *FROM DETERMINISTIC MECHANISMS TO FAILURE STATISTICS*

L.A.Dissado
Department of Engineering, The University of Leicester, Leicester, UK

(Whitehead memorial lecture, Pages: 1 - 18)

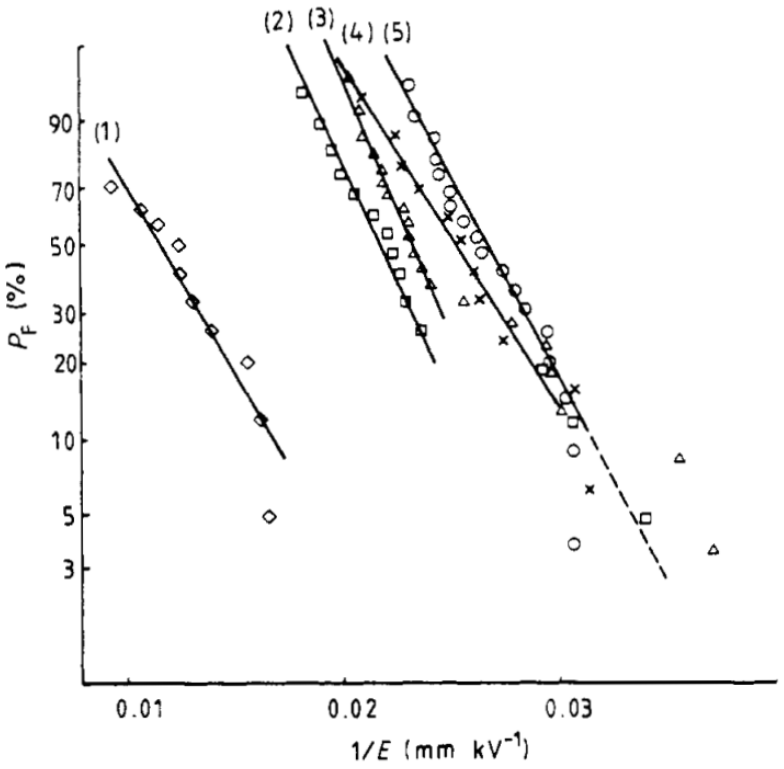
"The use of failure statistics to predict electrical breakdown can at worst become an exercise in mathematical manipulation with parameters to which no physical meaning can be assigned and who values are imprecisely known."

For some breakdown mechanisms other functions may be more applicable

In ramp tests, where breakdowns are initiated by features such as field enhancing defects or discharges in voids, the Gumbel function rather than the Weibull function may be more applicable.

$$P_F(x) = 1 - \exp\left\{-\exp\left[\frac{x - x_l}{x_s}\right]\right\}$$

Where x_l is the location parameter (i.e. characteristic value) and x_s is a scale parameter

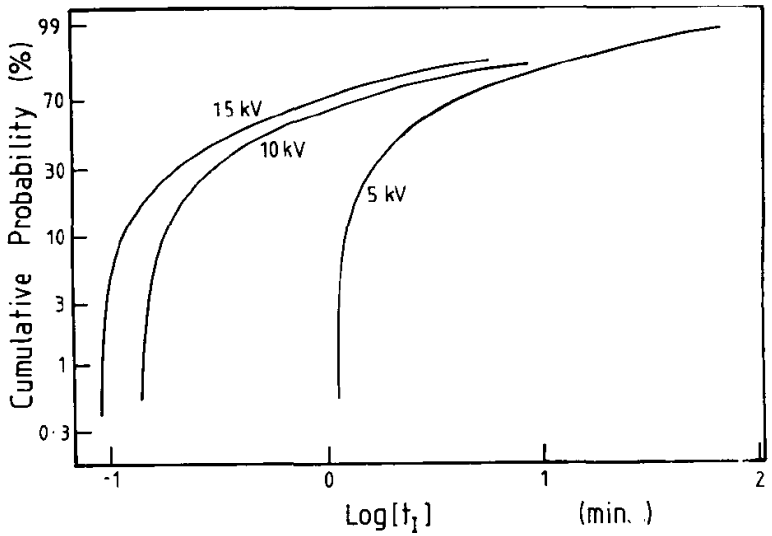


Gumbel plot for superclean and aluminium loaded polyethylene plaques

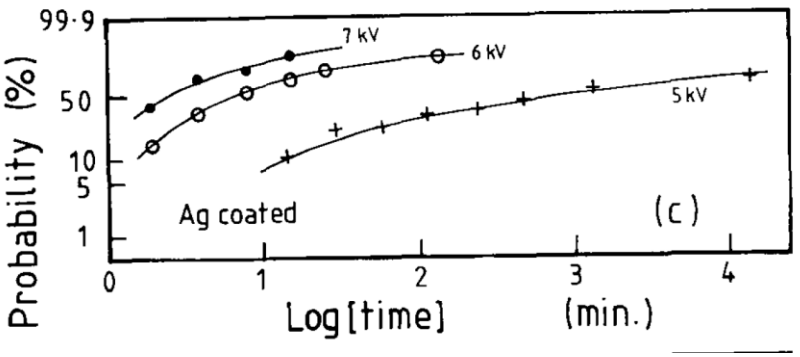
R W Coppard *et al* 1990 *J. Phys. D: Appl. Phys.* **23** 1554

There may be a basis for a 3-dimensional Weibull analysis, which includes a threshold before which degradation does not occur.

Calculated inception statistics for electrical trees



Example of experimental data



L. A. Dissado; R. M. Hill, IEEE Trans Electr. Insul, **25(4)** 660 - 666 (1990)

Summary

- Try to understand what breakdown mechanism is operative – if possible do experiments that will reject other breakdown mechanisms
- Be careful applying statistical techniques – although data may be sparse – a knowledge of the breakdown mechanism will support the use of a given statistical distribution