Electrical Breakdown Testing of Materials Intended for use in PV Modules

IEC Standard Development and Progress

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Keep Discovering

Acknowledgement

– We are grateful to 3M and Isovoltaic who are member of the ongoing DC breakdown round robin testing within IEC TC 82 WG2 and already have contributed with data of which some is used in this presentation

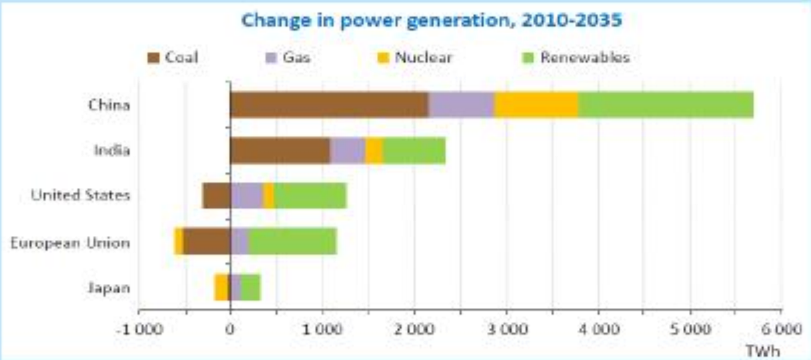
– We also thank Toray, NREL and Isovoltaic for contributing with material for the ongoing tests

Content

1. **Breakdown Fundamentals**
2. Test Method and Variables
3. Impact of Environmental Parameters

Renewables - increasing need to transport energy over longer distances – DC transmission

Renewable energy deployment



Source: EIA 2012

Bigger power stations

Solar energy for Europe

Within 6 hours deserts receive more energy from the sun than humankind consumes within a year

Source : Desertec

Increase energy trading

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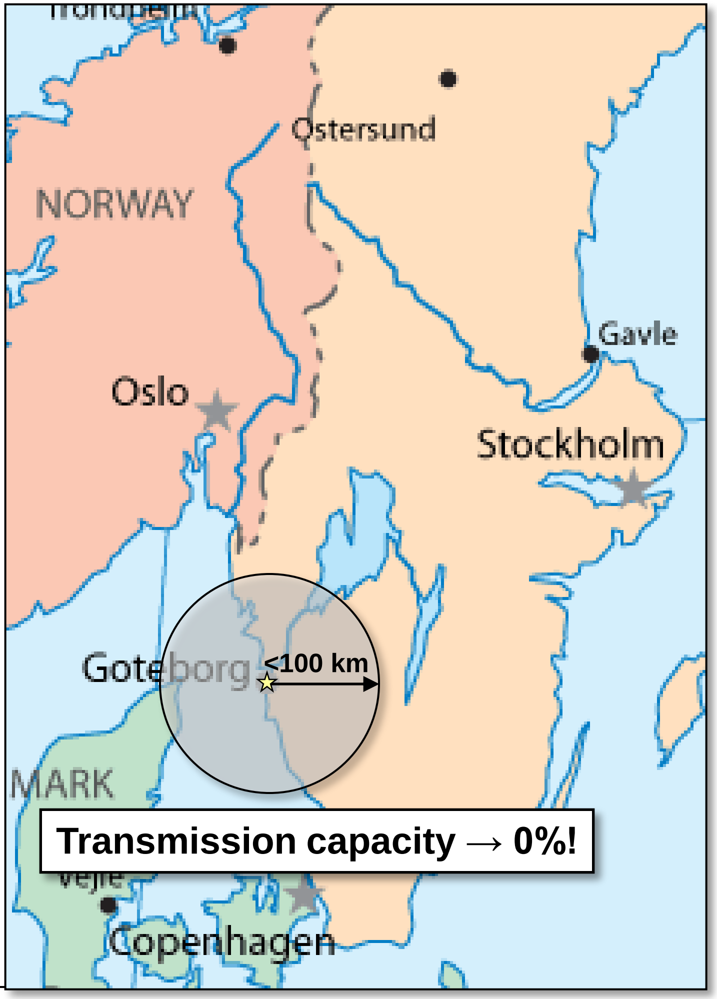
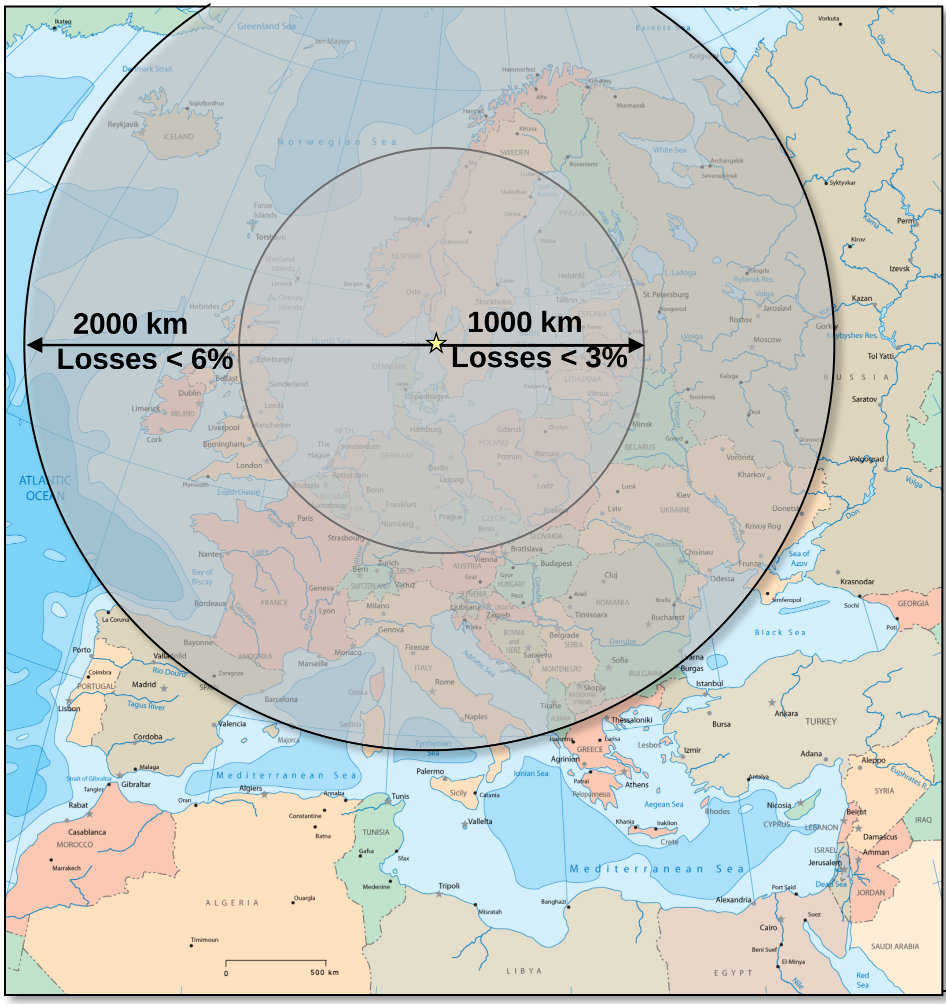
Why HVDC cables?

Maximum transmission distance:

HVAC power cables



HVDC power cables



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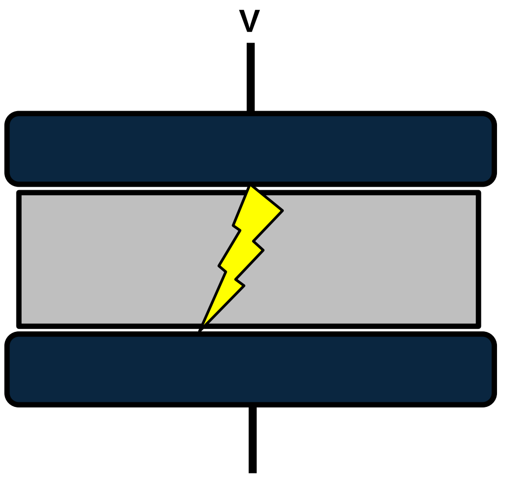
What is an electrical breakdown?

- If the voltage is steadily increased over a sample it comes to a point where the dielectric insulating barrier properties are exceeded. A short-circuited breakdown channel is formed.
- Common names: (Dielectric) breakdown strength, withstand voltage
- Maximum electric field stress (kV/mm) a dielectric material can withstand without breakdown
- Several mechanisms can cause electrical breakdown (BD)



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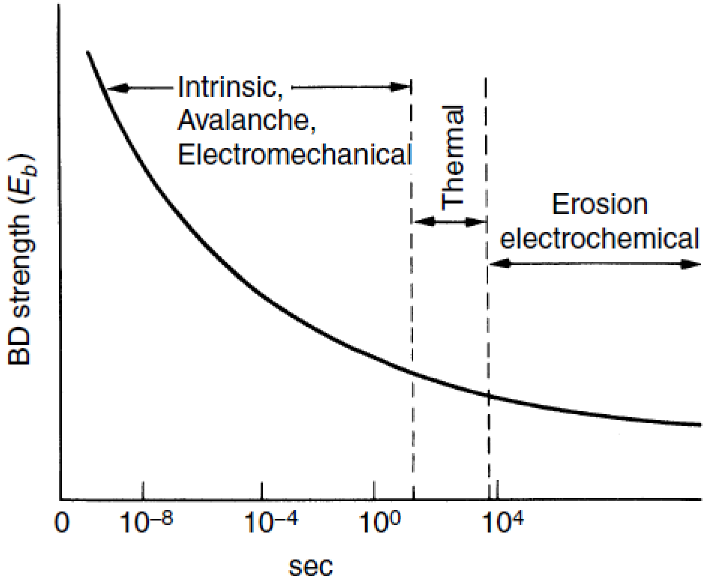
Breakdown (E_b) mechanisms

Short term mechanisms

- Intrinsic breakdown
- Thermal breakdown
- Electro mechanical

Long term mechanisms

- Breakdown caused by partial discharge activity
- Breakdown caused by inclusions of foreign particles
- Electrical treeing
- Water treeing



- The cause of E_b is usually defined by some **localized imperfection** or non-uniformity in the material or its surrounding test environment
- **BDs are stochastic in nature**, depending critically on the **statistical variation** of the composition and structure

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Intrinsic breakdown

- The breakdown strength of the material itself and not influenced by defects or environmental circumstances(Material property).
- Short time to breakdown ~10 ns and up to **1000 kV/mm**, which is far above levels where materials fails in practice.
- Believed to occur from a single electron avalanche exceeding a critical size and forms a conductive channel.
- High electric field induces large electrostatic pressures $P= \varepsilon_0 \varepsilon E^2$

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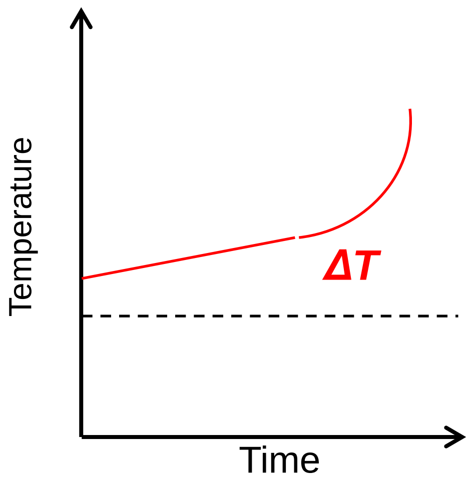
Thermal breakdown

- Caused by excessive dielectric heating from;
  - Dielectric losses during AC-voltages:
    - $W = U^2 \omega C \tan\delta = U^2 2\pi f \varepsilon' \tan\delta (A/d)$
  - Conductive losses during DC-voltages:
    - $W = E^2 / \rho$
    - Increased temperature cause higher losses which further heat the material
- Is dependent on heat generation and removal

Thermal runaway



E= Electric Field V/m

ρ= Resistivity, Ωm

U=Voltage, V

ω= Angular frequency

C=Capacitance

tanδ=Dissipation factor, loss angle

ε'=Dielectric constant, permittivity

A=area

d=thickness

The most common breakdown mechanism: Electrical treeing

- Electrical trees are tree- or bush-shaped structures consisting of hollow channels.
- Initiated at defects such as contaminants, voids and soldering points
- The tree grows by electrical discharges inside the channels
- Can propagate fast and lead to dielectric failure

DC Electrical properties

In the quest for DC insulation materials for higher voltages the electrical properties are crucial, in particular:

- Impulse and DC breakdown strength
- Low space charge accumulation
- Low conductivity=High volume resistivity

To meet these demands it is essential to have:

- **Physical cleanliness**
- **Chemical cleanliness**

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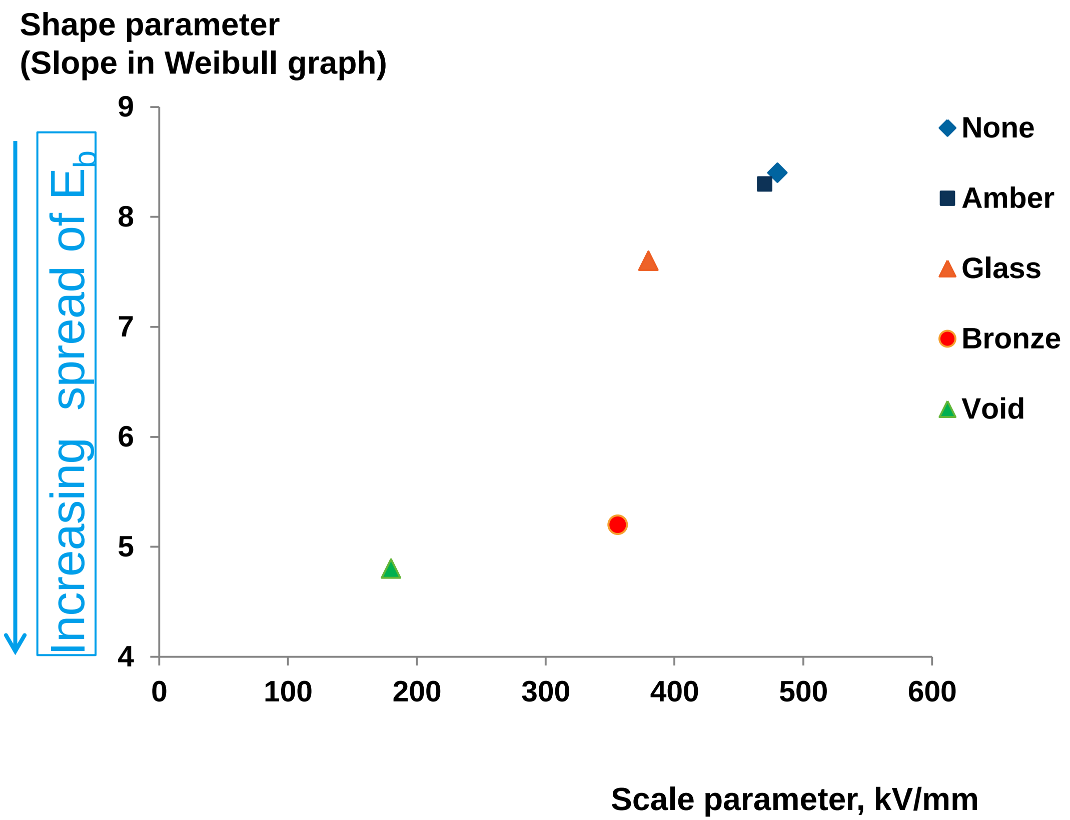
Breakdown strength and physical cleanliness

The effect of added contaminants (50 – 60 μm) on the Weibull breakdown parameters of LDPE discs with a Rogowski profile and tested under DC.



Important aspects:

- Size and shape
- Dielectric properties
- Matrix contact

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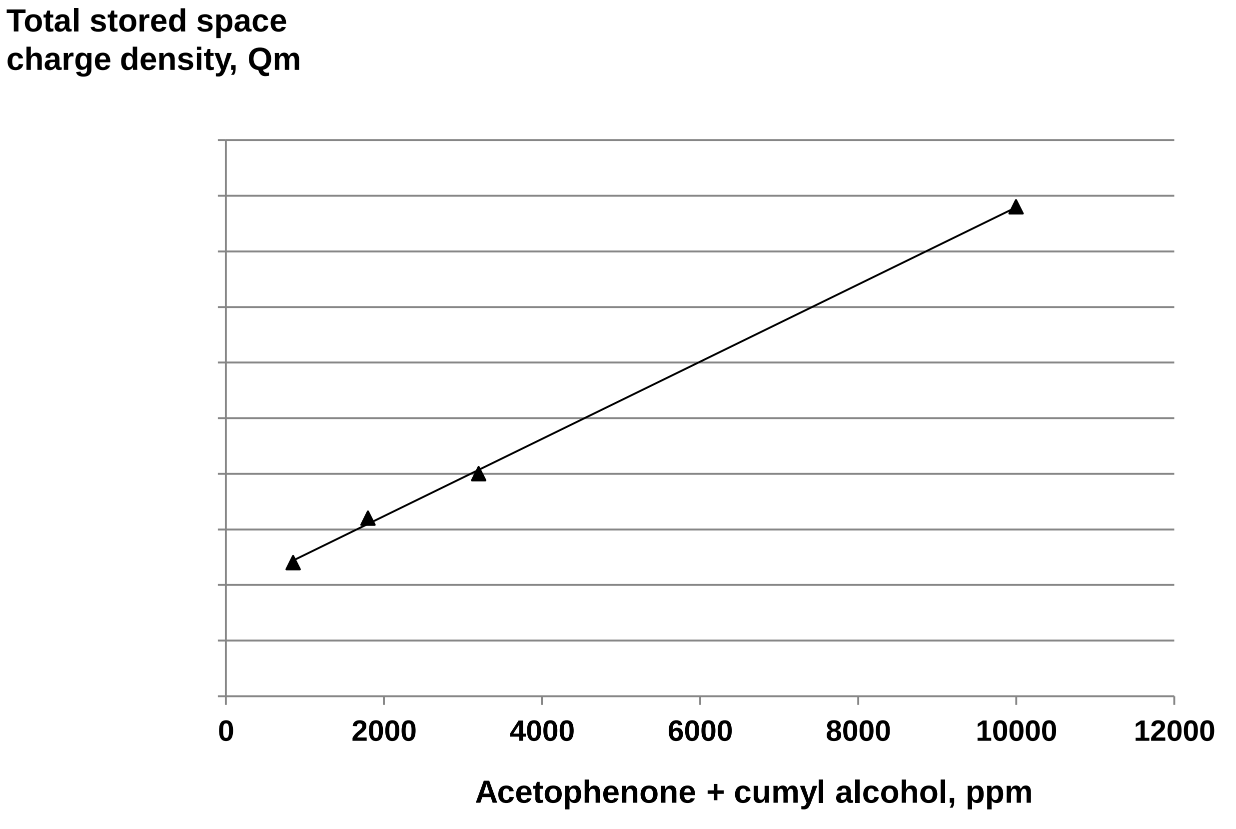
Chemical cleanliness and space charges

The effect of the decomposition products from Dicumyl-peroxide on the accumulation of space charges.



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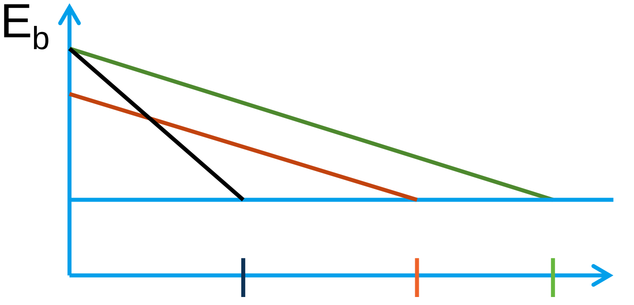
The reasons for electrical breakdown testing of materials used for electrical installations

- ❑ High initial breakdown strength essential as E_b normally is decreasing with time in use due to;
  - ❑ Electrical degradation phenomena
  - ❑ Chemical degradation phenomena e.g. oxidation, UV etc.
  - ❑ Introduction of contaminants e.g. water, salts etc.
  - ❑ Mechanical deformation
  - ❑ To have margins for “sunny days”; Normally lower breakdowns at high temperature running conditions
  - ❑ Delamination

- ❑ Powerful tool for life time predictions



Life time material a, b and c

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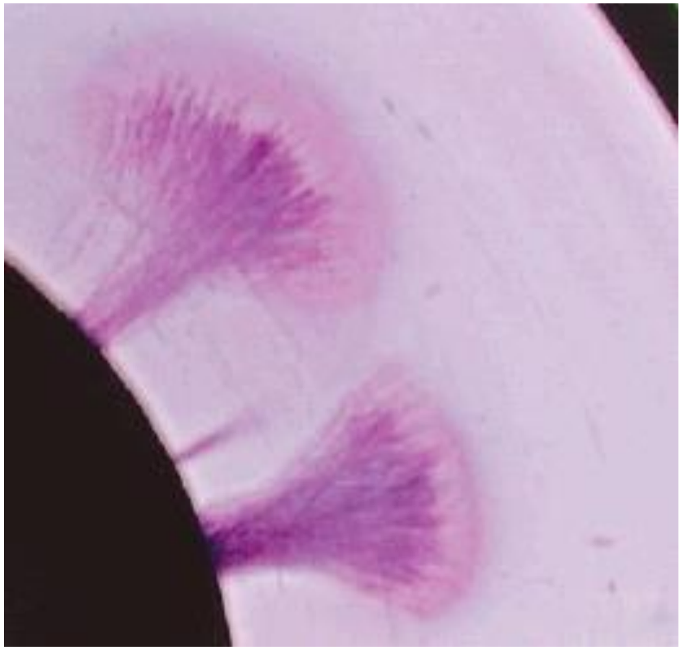


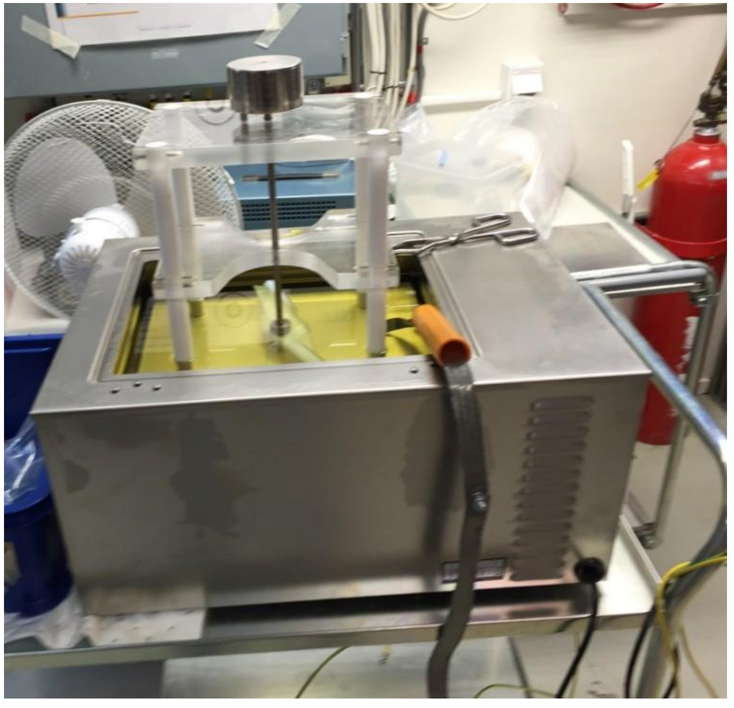
Background IEC TC 82 E_b test development

- Test method to be based on IEC 60243-1 and IEC 60243-2;
  - " Electrical strength of insulating materials – Test methods"
    - These standards very broad and a separate standard for solar applications needed.

- Primary targets:
  - The E_b method included in IEC 62788-2 "measurement procedures used for frontsheets and backsheets"
    - Secure that the materials fulfill the relied upon insulation criteria of IEC 61730
    - Data-sheet values
    - Influence of environmental parameters
    - Diagnostic tool for different electrical and non electrical ageing phenomena

- Secondary targets
  - Investigate what E_b testing can bring for other PV related polymeric materials e.g. encapsulants
  - Investigate the need for electrical endurance testing

Example of E_b Test set-up

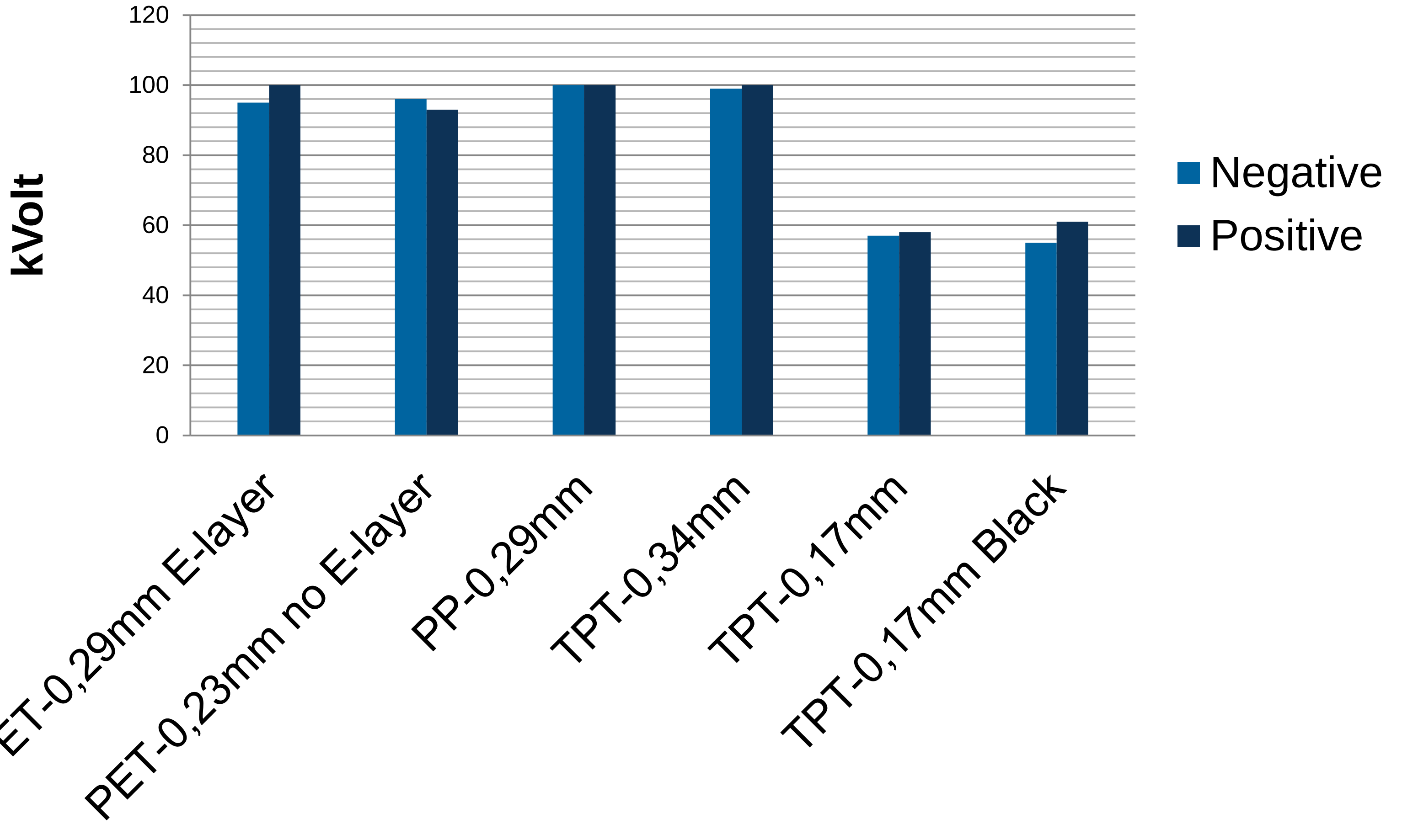


- Heatable oil bath allowing measurements also at elevated temperatures
- Fixed Equal sized diameter electrode
  - IEC 60243 section 4.1.1.2: Stainless steel, diameter 25 mm, curvature 3mm
- DC and AC testing possible in the same set-up

E_b testing in accordance with IEC60243 – Variables

	Test conditions	Comments
Preconditioning	Min 24 hours, 23ºC, 50% rel. humidity	Unless other conditions agreed upon
Ramping speed	2 kV/s if post 10s, otherwise change to 1, 0,5, 0,2 or 0,1 kV/S until E_b occurs after 10 s.	For molded materials
Surrounding media	-Air (Only possible for materials having low E_b values due to flash over) **-Transformer oil (mineral oil) IEC60296** -Silicone fluid according to IEC60836 ester fluid according to IEC61099	"Select a medium which has min deleterious effect on the material. In most cases transformer oil is the most suitable medium."
Electrodes	Equal 25/25 mm or Unequal 75/25 mm	Important to use rounded edges giving a diameter of 3mm
Temperature	23ºC	Unless other conditions agreed upon
Polarity	Negative or Positive?	No guidance given
Thickness	Fixed for back-sheets as being laminates	For non-laminates e.g. encapsulants pressing for adjusting to available voltage source possible

Back-sheets - Influence of polarity on E_b



➢ The polarity has negligible impact on E_b

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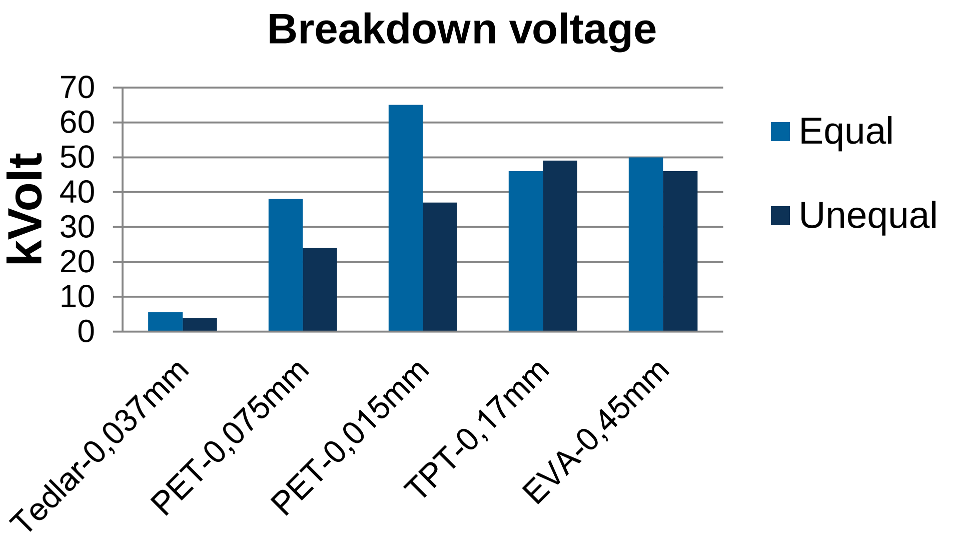
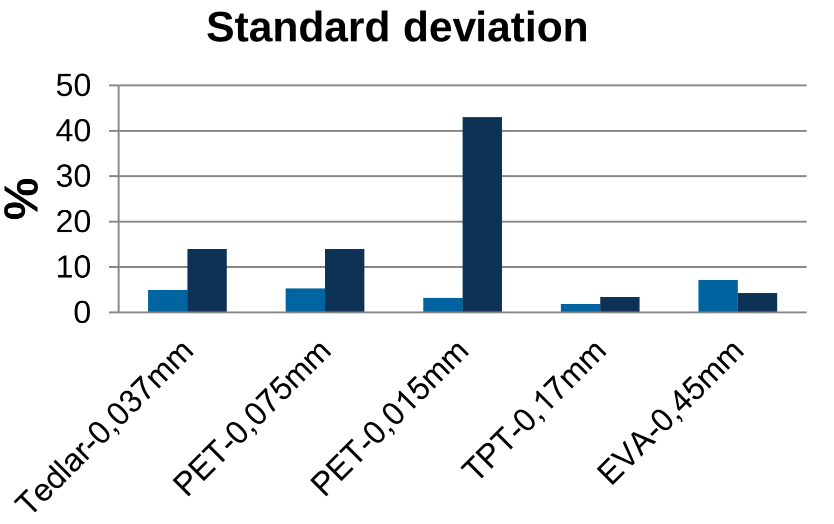
Influence of electrode type on E_b





- Large impact - Commonly lower breakdown and higher spreading for the unequal electrodes
- Less edge field enhancement for equal sized electrodes (C. Chauvet and C Laurent, IEEE Transactions on Electrical Insulation Vol. 28, No 1, February 1993)

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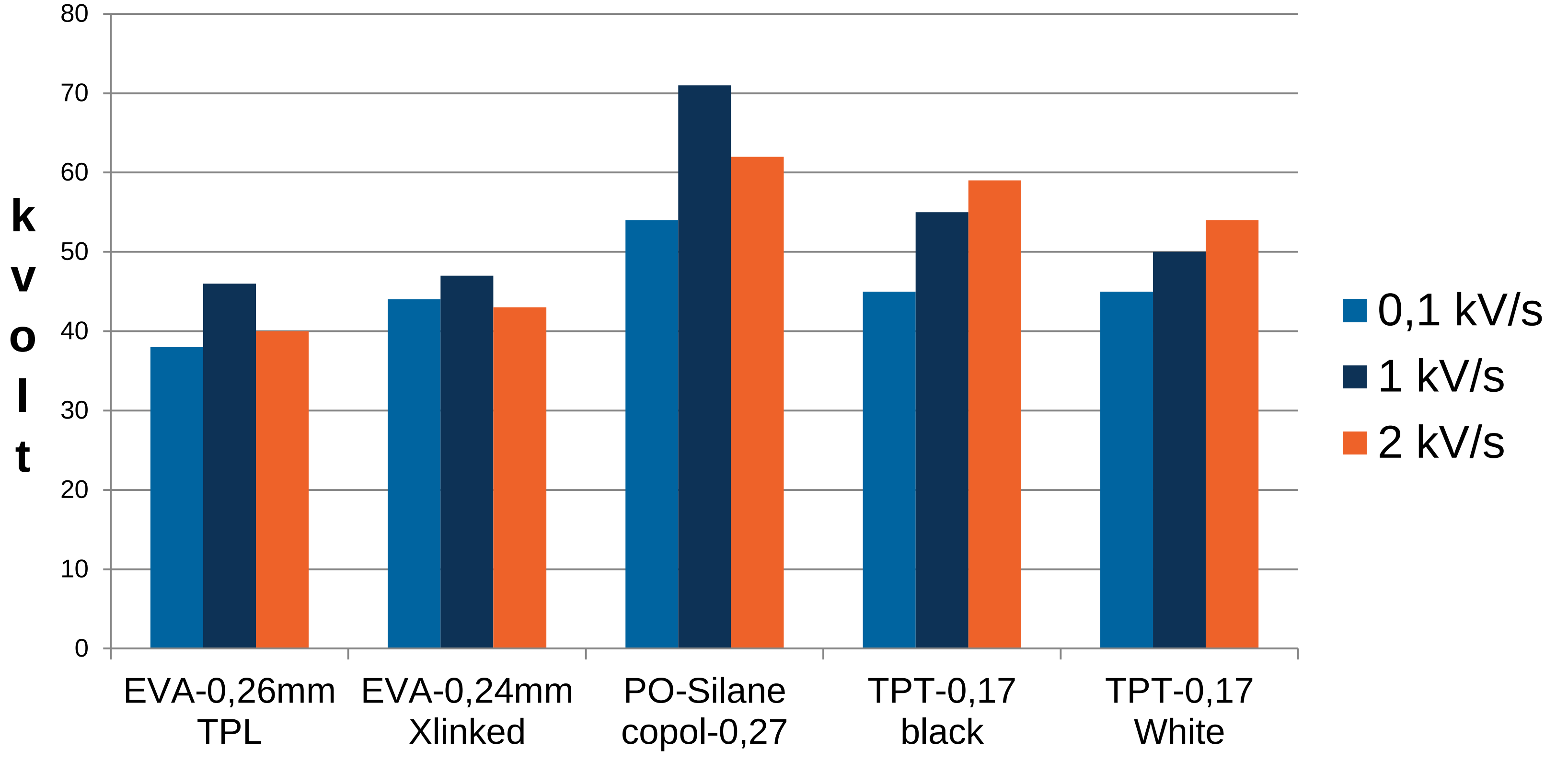
Influence of ramping speed



- The E_b has a tendency to increase with increasing ramping speed, especially when high E_b's is reached

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Influence of Surrounding media on DC-E_b

Options	Standard	Permittivity, ε	E_b, LDPE, kV/mm	E_b, PET, kV/mm
Mineral oils	IEC60296	2,06	376	558
Silicon fluids	IEC60836	2,53	373	631
Ester fluids	IEC61099	2,95	375	665
LDPE		2,21		
PET		2,95		

- Recent publication[1] recommend to use oil of equal of higher permittivity of the sample to be tested
- When low permittivity oil was used for the PET the field was significantly enhanced in the oil immediately adjacent to the sample-electrode interface explaining the lower values for low perm. oils
- [1] Hosier, Vaughan, Chippendale, "Permittivity mismatch and its influence on ramp breakdown performance", IEEE International Conference on Solid Dielectrics, Bologna, Italy, June 30- July 4, 2013

Testing parameters impact on DC E_b testing

Parameter	Impact	Recommendations for PV applications
Polarity	Low	No restriction, but polarity to be reported
Current limit	Low	No restriction.
Electrode types, equal or unequal	High	Equal electrodes recommended
Type of oil	High	"Select a medium which has min deleterious effect on the material under test (IEC60243-1) among; **-Transformer oil (mineral oil) IEC60296** -Silicone fluid according to IEC60836 -Ester fluid according to IEC61099
Ramping speed	Moderate	Fixed. 2kV/s if breakdown post 10 s. Otherwise change to 1, 0,5, 0,2 or 0,1 kV/S until E_b occurs after 10 s.
Water content (Preconditioning)	High	Standard preconditioning: Min 24 hours, 23ºC, 50% rel. humidity.
Temperature	High	Standard test conditions 23°C.
Sample thickness	High	Multilayer constructions (e.g. back-sheets) to be tested as is. For non laminates reporting in kV/mm suggested and pressing to suitable thickness.

Influence of DC and AC on E_b

Material	DC kV/mm	AC kV/mm	DC/AC ratio	Vol. res. Ωm
Back-sheet				
PET-0,29 w. E-layer	>331	67	>4,9	$2,6x10^{18}$
PET-0,23 wo. E-layer	>305	62	>4,9	$2,6x10^{17}$
PP-0,29	>342	108	>3,2	$9x10^{17}$
TPT-0,34	>287	70	>4,1	-
TPT-0,17 black	341	139	2,5	$1,3x10^{17}$
TPT-0,17 White	320	81	4,0	$7,5x10^{17}$
Encapsulant				
EVA Tpl	155	48	3,2	10^{13}-10^{14}
EVA Xlinked	178	36	4,9	10^{13}-10^{14}
PVB	215	-	-	10^{16}
PO Si-Copolymer	229	48	4,8	10^{16}

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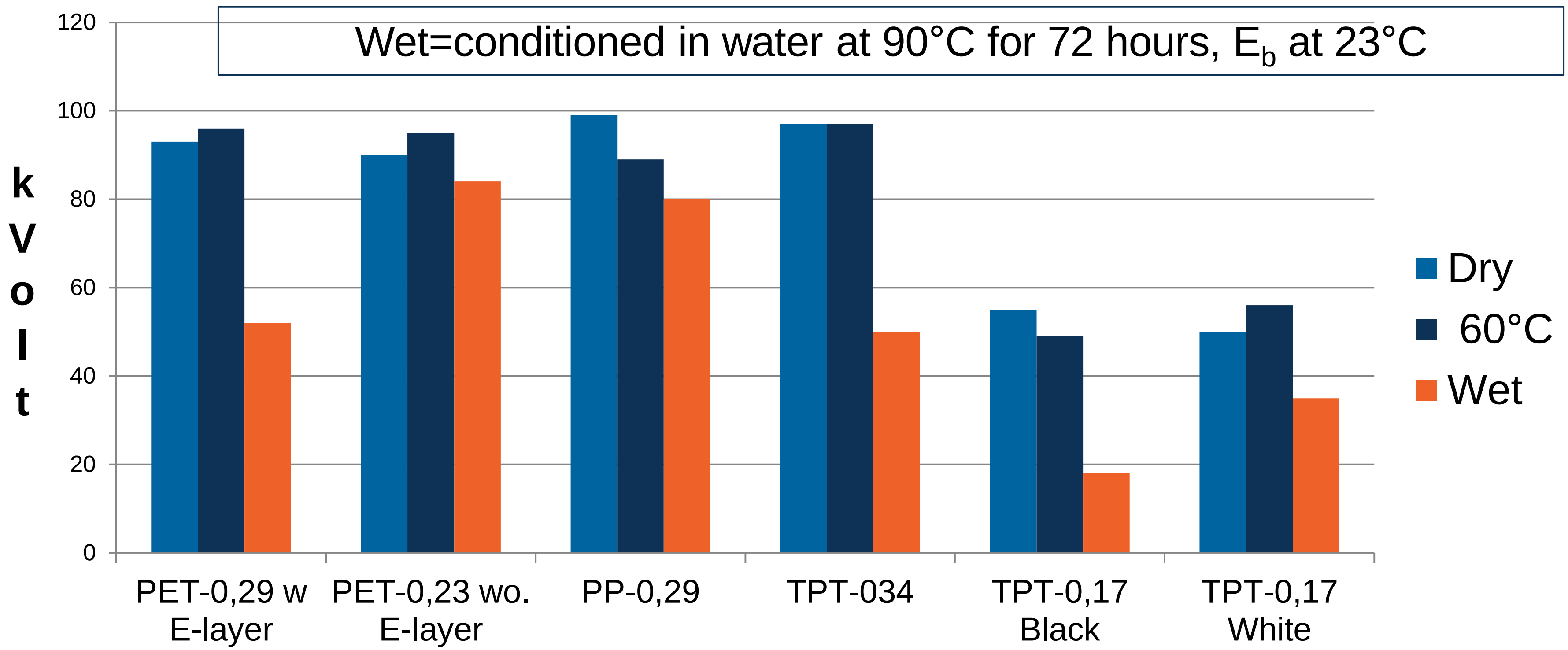
Back-sheets - Influence of temperature and water on DC-E_b



- Water preconditioning largely reduces E_b for a majority of the back-sheets containing polar polymers.
  - Addition of carbon black leads to a further reduction in E_b
- All back-sheets withstand 60°C

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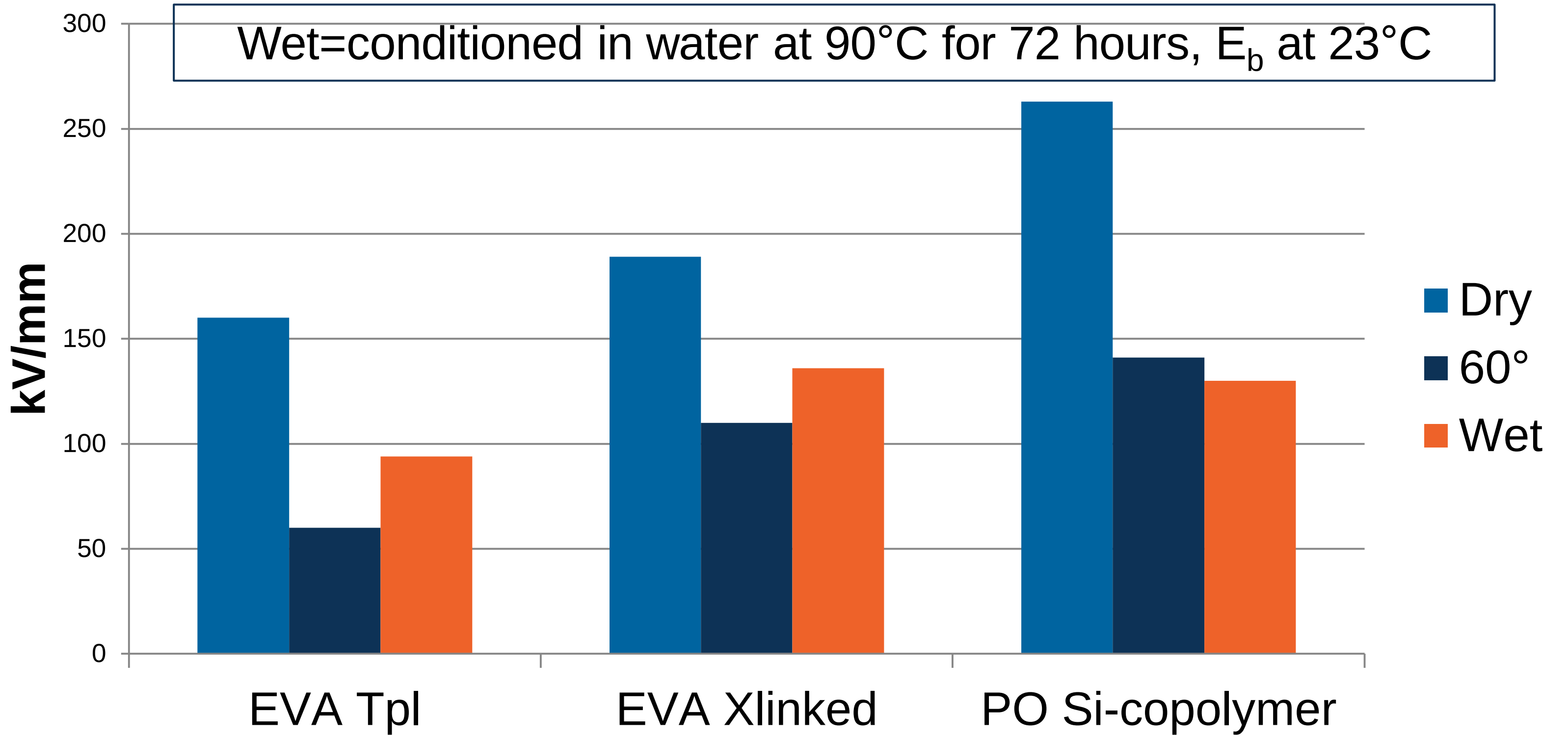
Encapsulants - Influence of water and temperature on DC-E_b



- Moderate temperature increase and water preconditioning reduces largely E_b
- X-linking improves the breakdown strength at all conditions
- PO Si-copolymer shows higher initial and 60°C E_b's and similar to Xlinked EVA post water treatment

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Conclusions

1. Within IEC TC 82 WG2 a test method measuring DC breakdown strength is being established
   a. Quick and easy to perform over a wide temperature range
   b. Round robin test ongoing involving common back-sheets and encapsulants
2. DC current gives 2,5-5 times higher breakdown strength vs. AC for investigated PV materials.
3. Investigated back-sheet materials show all very high DC breakdown strength (~300 kV/mm) probably due to they all show very high volume resistivity.
4. The investigated encapsulants show lower volume resistivity and breakdown strength (150-250 kV/mm)
5. Moderate temperature increase (60°C) shows negligible effect on E_b for the back-sheets, but large reduction (~50%) for the encapsulants.
6. Conditioning in water has very big impact on most polar back-sheets and the encapsulants

Thank you