Specific Considerations for Extruded HVDC Cable Insulation Evaluation under Temperature Gradient

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Changes in energy structure,
Development of urbanization
Economic activity

- HVAC cables (large capacity, big length)
- HVDC cables (space charge、temperature stability)
- Nuclear power cables (high reliability, retarding, radiation resistance)
- Submarine cables (large water area , deep sea)
- PV Station & Connection cables (extreme weather)

Trends of network structure

- More HV power cables will be in operation (several 500kV XLPE land cable systems in service in Beijing, Shanghai in China) ；
- Bigger share of power transmission will be through cable network；
- Extruded cable will be dominating (e.g. CSG has 2285 cable lines of 110kV and above, length 5042km, annual increase 15%, 20km/500kV XLPE cable system is under construction) ；
- Large cable network will be constructed which will be a heavy asset of electric power utility.

Trends of technical requirements

- Large ampacity, higher operation temperature and high reliability;
- Improved mechanical performance, in particular for deep sea cables and testing techniques;
- Environmentally friendly and recyclable cable insulations;
- New cable design and installation method to reduce environment impact;
- Advanced modeling and calculation method to improve cable system performance, e.g. thermal bottleneck identification and dynamic rating calculation;
- New standards and testing techniques, e.g. standards for HVDC cables, testing and evaluation of HVDC cable systems.

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Examples of VSC-HVDC Projects

Project name	Location	Record	Insulation type	Converter type	Voltage/Power	Time
NorNed	Norway-Netherland	Longest:580km	MI	LCC	±450kV/700MW	2008
SA. PE. I HVDC Link	Italy-Sardinia	Deepest:~1650 m	MI	LCC	±500kV/1000MW	2010
Western HVDC Link	Scotland-England	Highest Voltage:±600kV	PPLP-MI	LCC	±600kV/2200MW	2016
Kii Channel HVDC Link	Shikoku-Kihoku, Japan	Highest Power:2800MW	SCOF	LCC	±250kV/2800MW	2000
DolWin1	Germany	Highest Voltage with XLPE: ±320kV	XLPE	VSC	±320kV/800MW	2015

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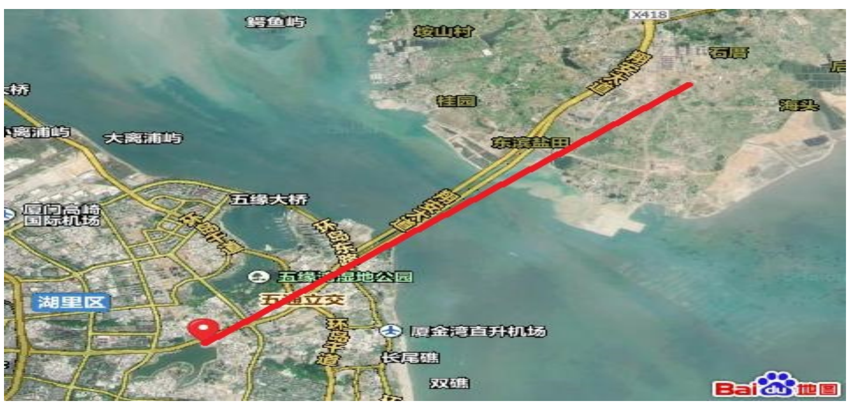
VSC-HVDC Projects in China

Nan’ ao ±160kV, 200MW 3-terminal VSC project, cable length 35km, Commissioned in Dec. 2013

Zhoushan ±200kV/400MW 5-terminal VSC project, cable length294km, commissioned in Jun 2014



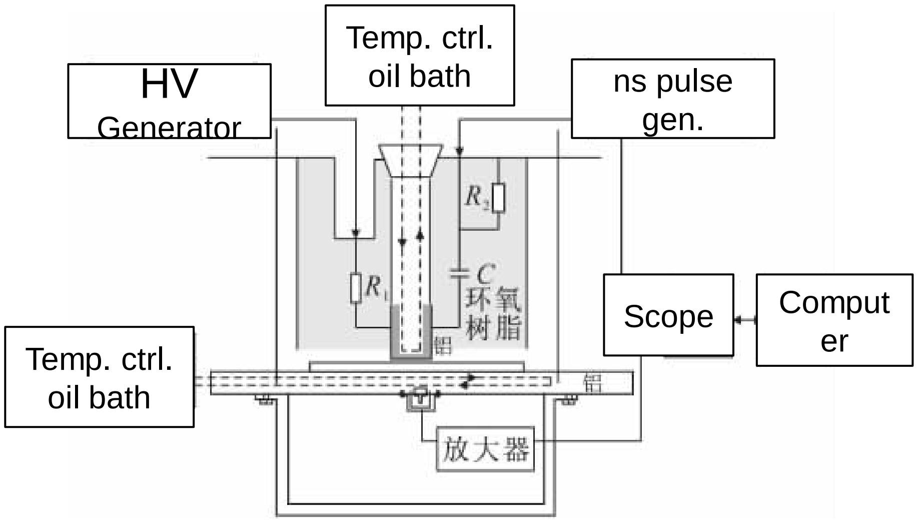
Xiamen ±320kV/1000MW VSC project, cable length 21km, commissioned in Dec. 2015

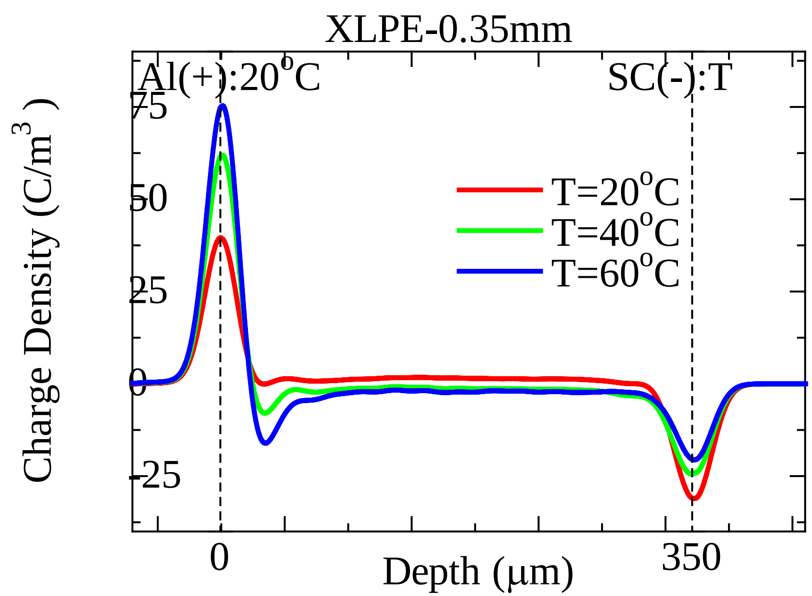
Planned Zhangbei ±500kV/3000MW 4-terminal VSC projects, 500km OHL, 4x500m trial cables, project for 2022 Beijing Winter Olympic.

Concerns over extruded HVDC cables from utilities

- Does space charge evaluation on film or thin plate samples reflect space charge behavior in real cable?
  - Much higher stressing field than designed values ;
  - Weight between interfacial and bulk effects;
  - Surface condition between insulation and metal/semi-con electrode, e.g PEA.
- Apart from the correlations insulation’s conductivity and temperature, how to evaluate space charge activity under temperature gradient?
- Concerning long term performance, does space charge measurement has to be involved in PQ-tests, and how?
- What ‘s the precise life exponent of DC insulation(e.g n=10 or 16)? Can the value achieved under uniform temperature be used for cable life expectancy design?
- What’s the biggest danger of HVDC cable fault? Their mechanism, progression and failure.

Space charge accumulation under temperature gradients





- Upper electrode (SC) controlled at 20ºC, 40ºC & 60ºC, i.e. ΔT=0ºC, 20ºC,40ºC
- More hetero-charge accumulated next to anode electrode (lower temp.,) and the charge density is proportional to temperature difference across over the sample thickness;

PEA measurement with temperature difference

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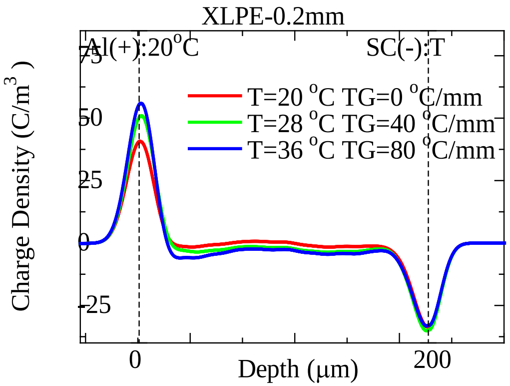
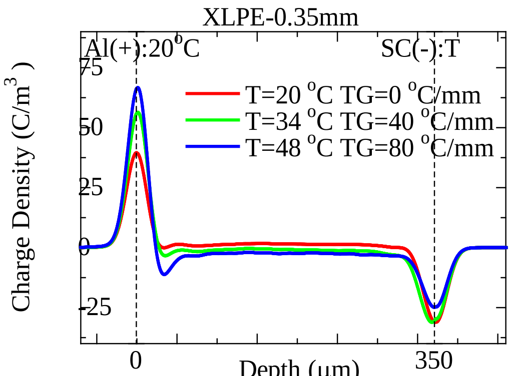
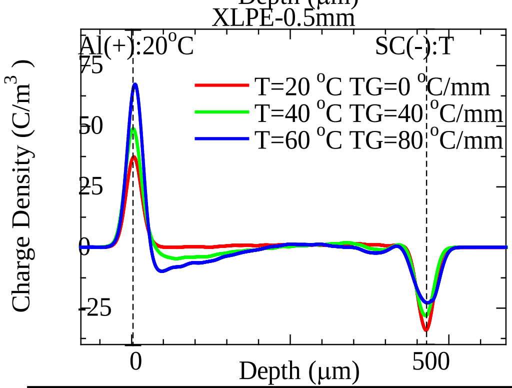
Space charge under different temperature difference but the same temperature gradient *(E=50kV/mm)*







- Samples' thickness are 0,2mm, 0.35mm and 0,5mm;
- To maintain the temperature gradient at 0^{o}C, 40^{o}C & 80^{o}C/mm, the upper electrode temp has to be 0^{o}C 20^{o}C, 28^{o}C, 34^{o}C 40^{o}C, 48^{o}C & 60^{o}C,;
- Comparing the space charge profiles of upper electrode at T=36^{o}C, 48^{o}C & 60^{o}C, the highest charge density appears when ΔT=40^{o}C

Space charge under the same temperature difference but different temperature gradient *(E=50kV/mm)*

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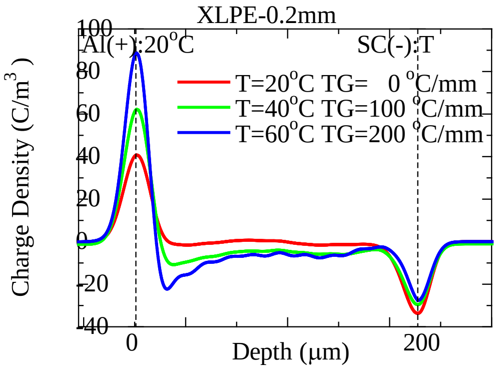

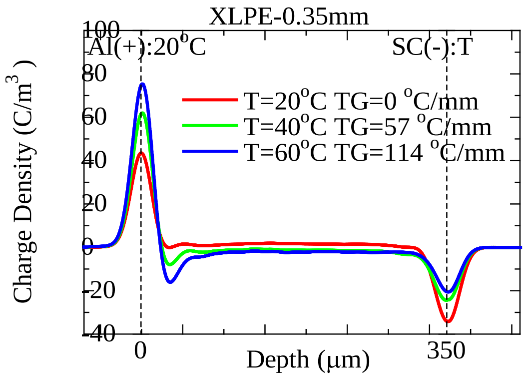

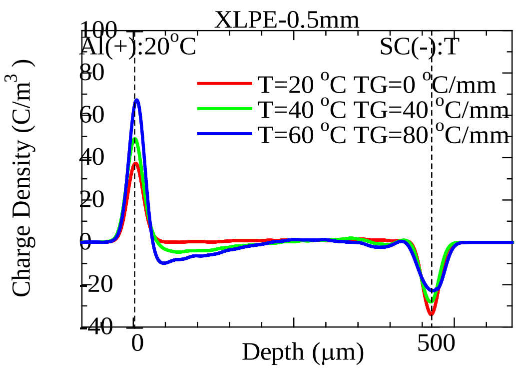

- Samples' thickness are 0,2mm, 0.35mm and 0,5mm;
- For the same the temperature difference, the highest temperature gradients achieved within the thinner sample 0.2mm are 100°C/mm & 200°C/mm;
- The highest hetero-charge accumulation appeared next to anode with lower electrode.

Conclusions:

- Same temp. difference, different temp. gradient, thinner sample accumulated more hetero-charge;
- Same temp. gradient, different temp. difference, thicker sample accumulated more hetero-charge. **Similar situation of full sized HVDC cables;**
- Temperature dependent interfacial injection, residues ionization and charge migration with bulk.

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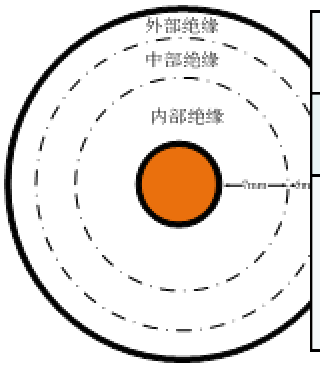
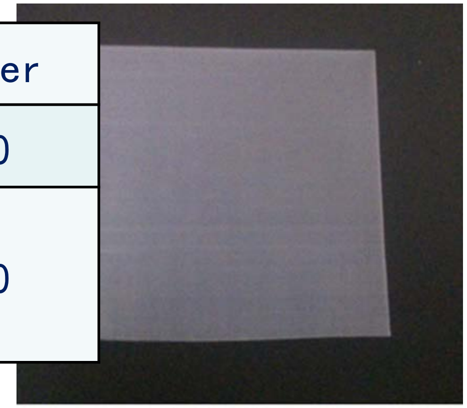
Voltage endurance for cable insulation materials

- Experimental setups and details

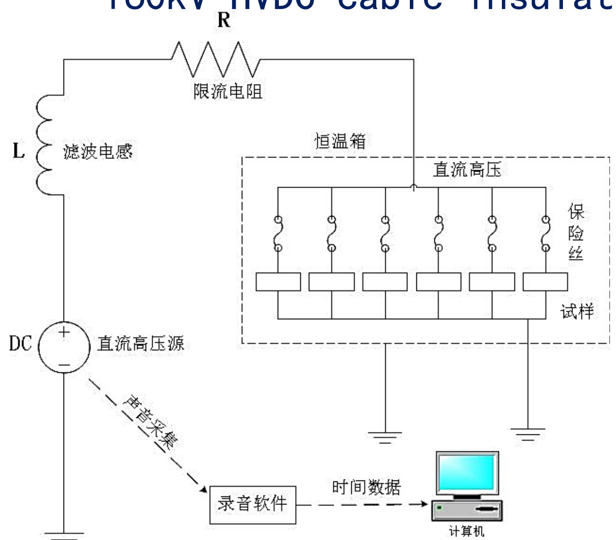


Position	Inner	middle	outer
Virgin	10	10	10
After PQT	10	10	10

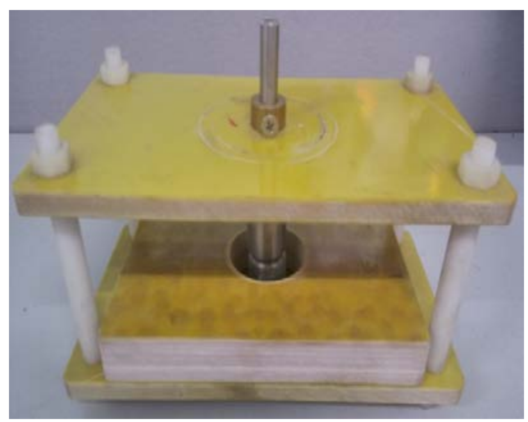


处理后试样图

160kV HVDC cable insulation material(peeled from cable)



DC breakdown and *V-t* test

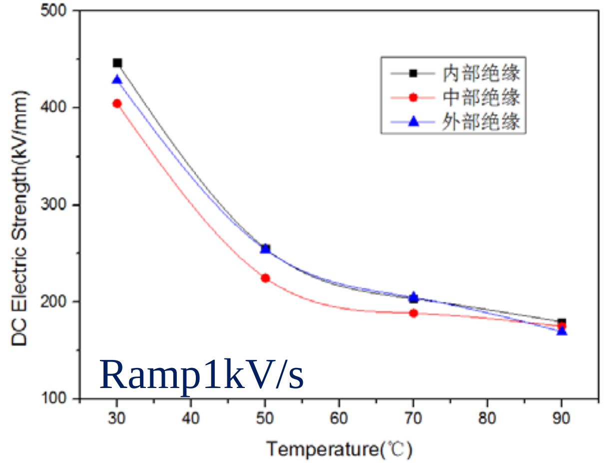


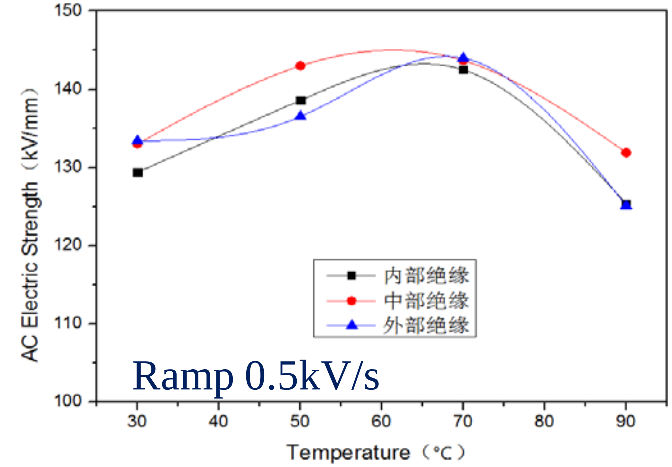
Electrodes

Voltage endurance for cable insulation materials

- Change of electric strength for specimens(d=0.2mm) with temperature

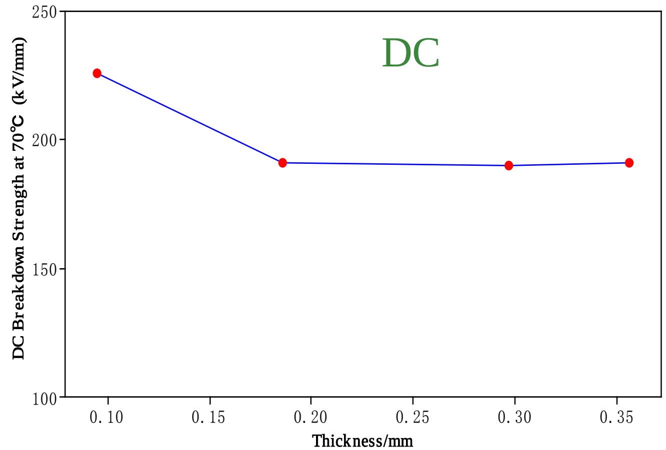
➢ DC E_b decreases exponentially with temperature; AC Eb increases and then decreases with the rise of temperature.

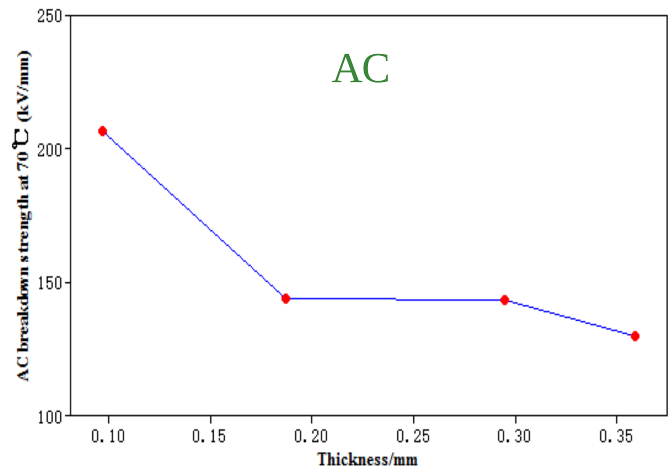




- Thickness dependence of specimens with different thickness

➢ In the range of 0.2-0.35mm specimen, thickness effect is not obvious





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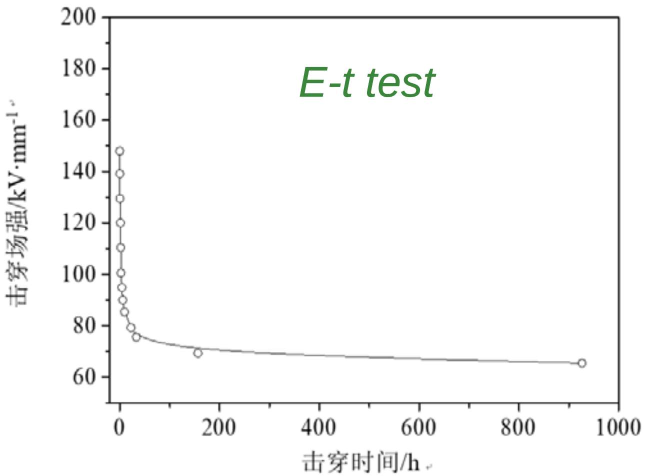
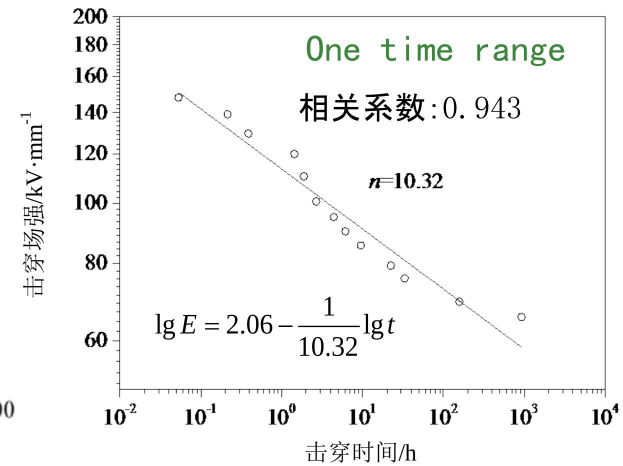
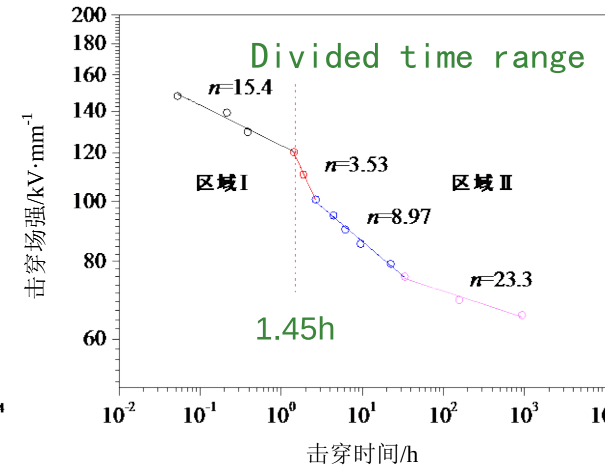
Voltage endurance for cable insulation materials

■ *E-t Characteristics (DC)*

➢ *E-t test* at 70℃ with sample thickness of 0.2mm







	One time range	Divided time range
Life exponential n	10.32	20.19
30 y lifetime	E=34.3kV/mm	E=47.8kV/mm
40y lifetime	E=33.3kV/mm	E=46.7kV/mm

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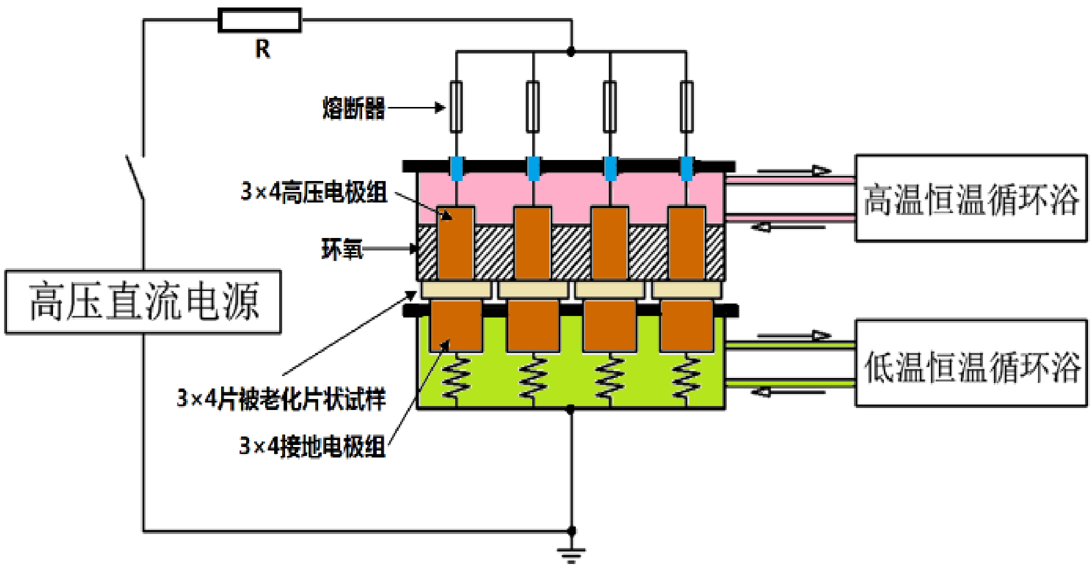
Thermoelectric ageing at temperature gradient



E=-40kV/mm

△T=40℃

T_h=60 ℃

Thermoelectric ageing at temperature gradient (PEA)

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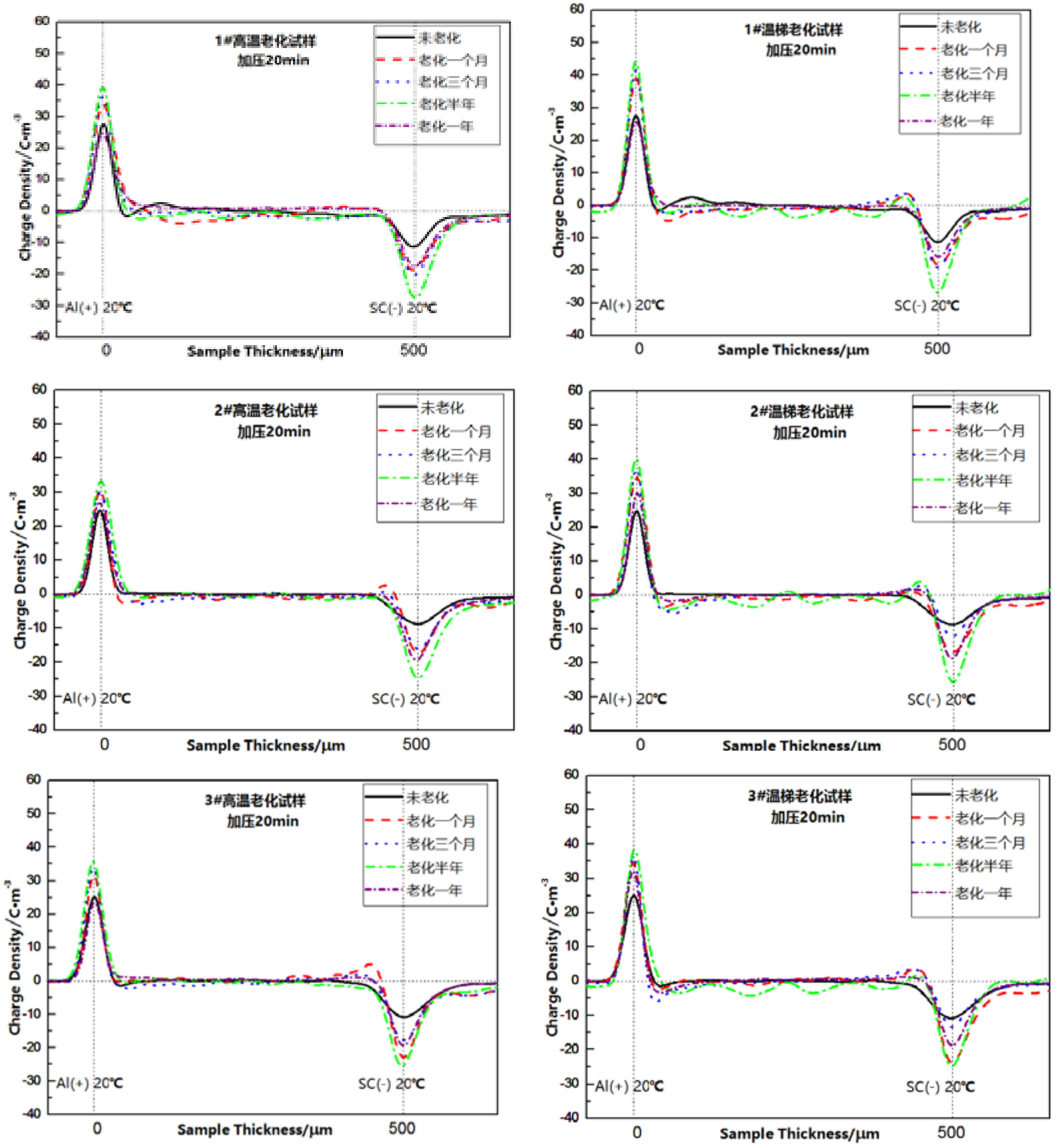
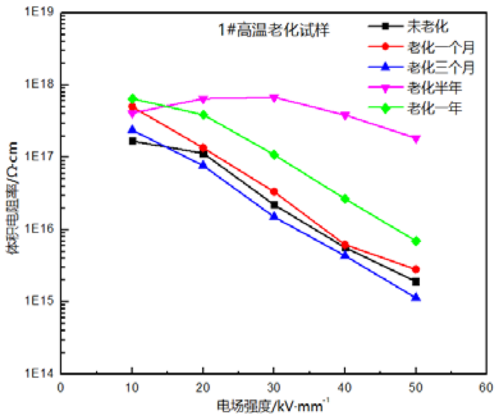
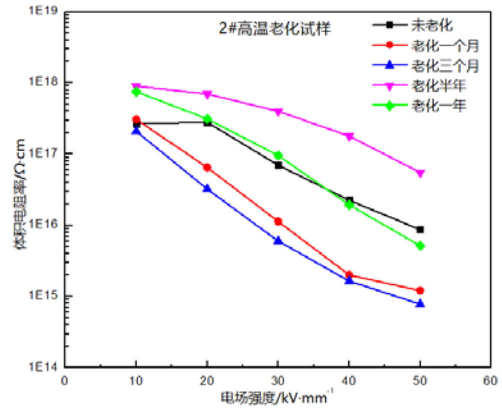
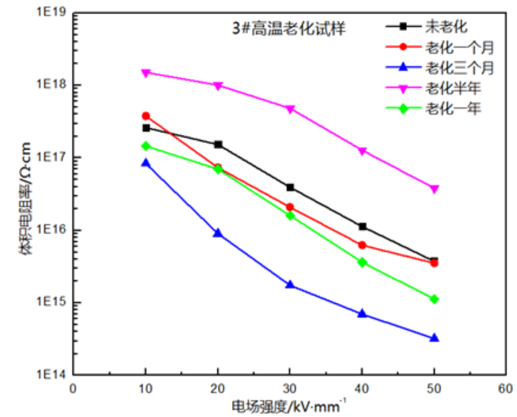
High temperature ageing | Temperature gradient ageing

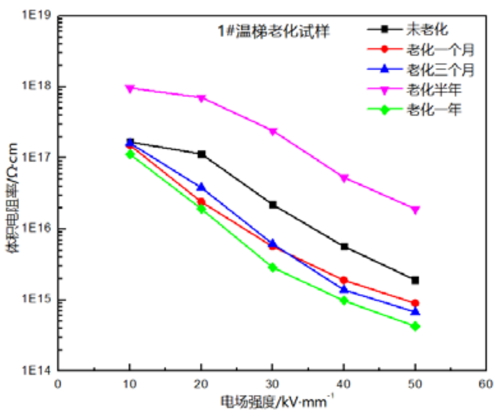


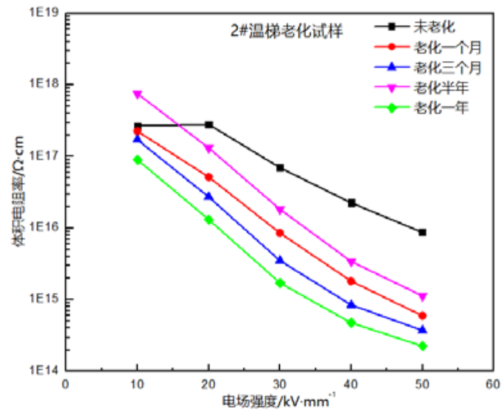
Thermoelectric ageing at temperature gradient (DC Resistivity)

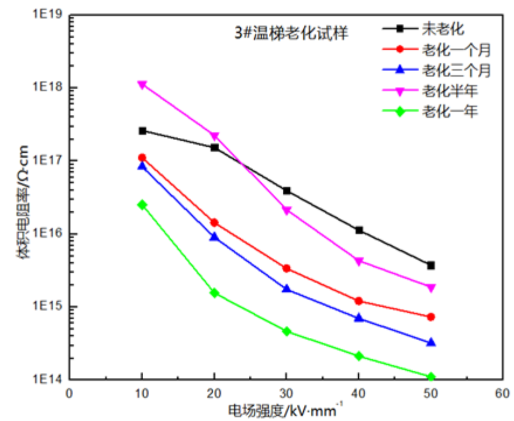












Thermoelectric ageing at temperature gradient (permittivity)

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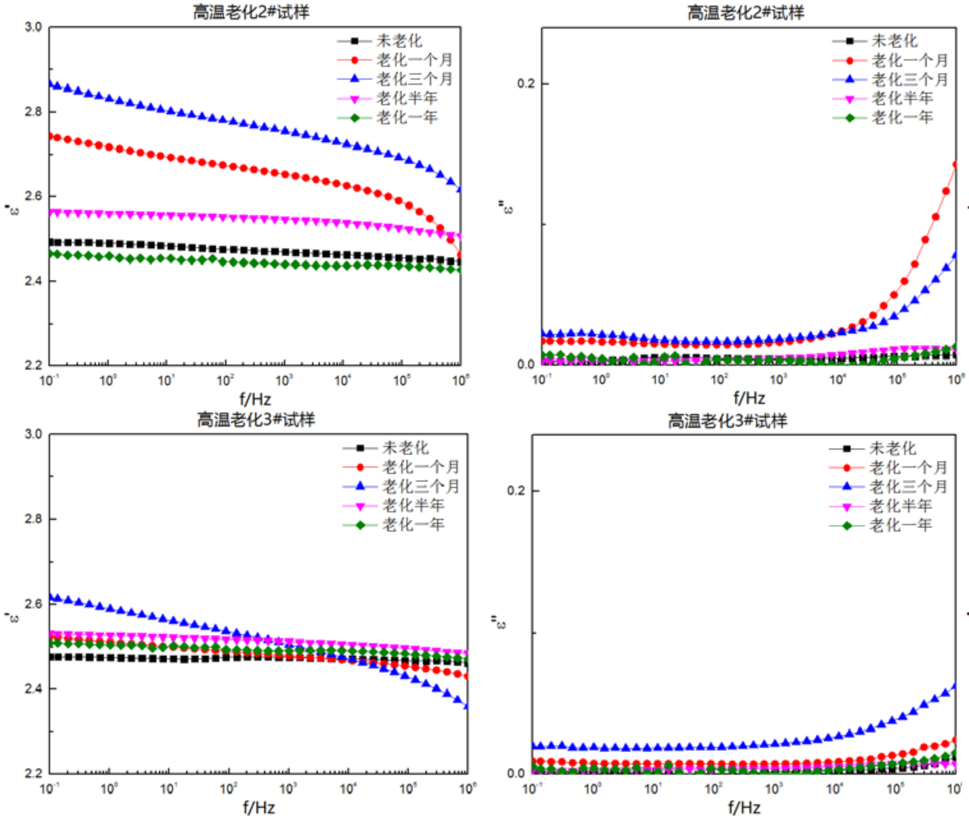
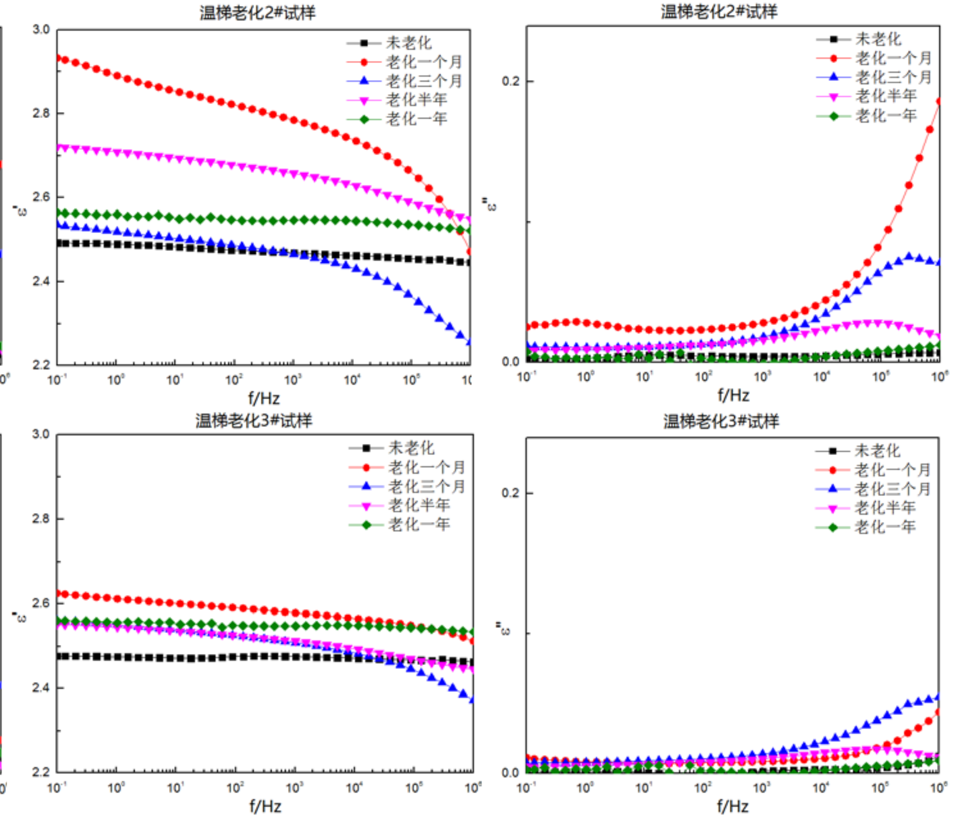
High temperature ageing



Temperature gradient ageing



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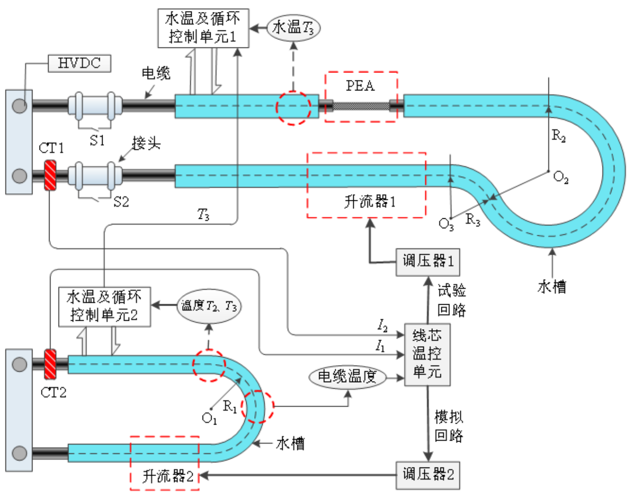
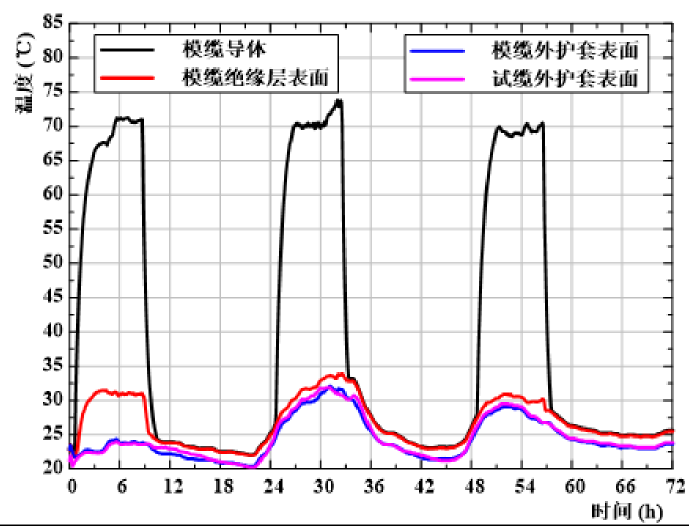
HVDC cable long-term evaluation and space charge measurement under operation condition with temperature difference



- DC Electric field distribution controlled by insulation conductivity, temperature and local field itself;
- Space charge initiation, migration and accumulation relevant to temperature, temperature gradient and interfacial condition, which can be fully reflected in full-sized cables;
- Space charge measurement at film or thin plaque sample cannot represent temperature gradient, interfacial and bulk effects;
- Operation conditions: controlled loading, temperature difference and gradients.



Space charge measurement on full size cable with temperature difference

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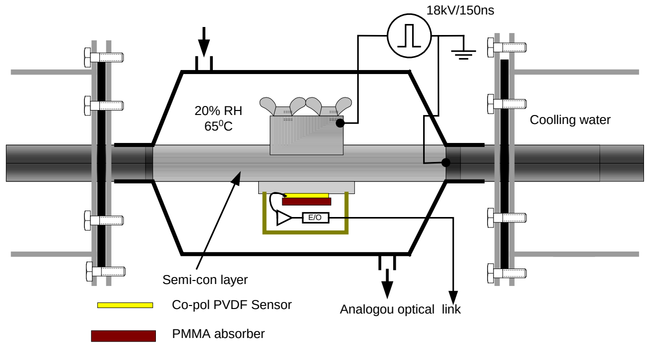

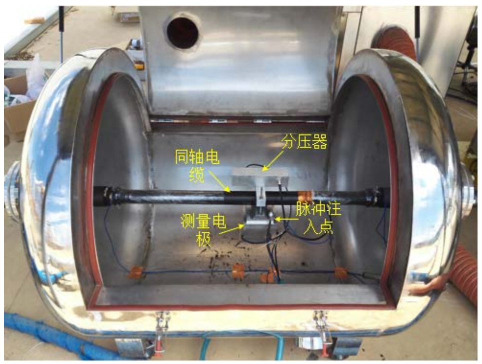

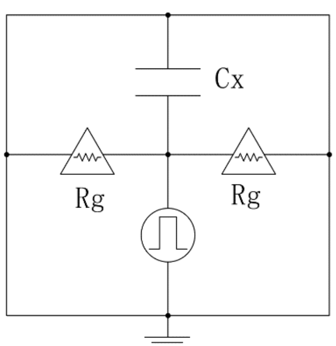

- Duo to strong signal attenuation, PEA measurement has to remove outer sheaths of cable;
- Outer semi-conductive lay needs to be kept in dry condition；
- A small temperature and humidity controlled chamber houses PEA system;
- Impulse voltage injected from PEA measuring point to solve the difficulty of attenuation if it's injected from the terminal i

Max Temp.	60^{o}C
Impulse generator	Up to 30kV, 200ns
Charge density resolution	20mC/cm^{3}
Position resolution	600mm
Max measuring thickness	20mm

Space charge measurement on full size cable with temperature difference

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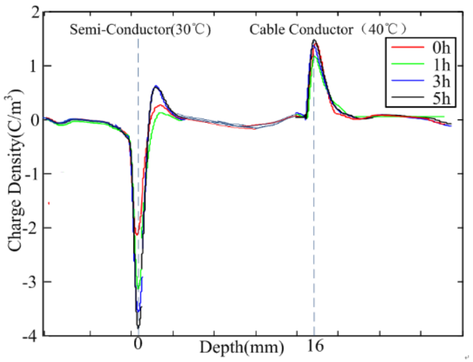
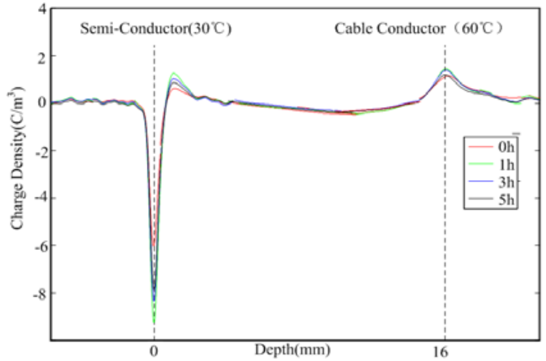
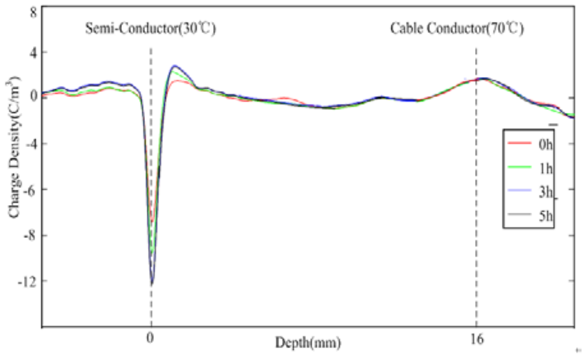


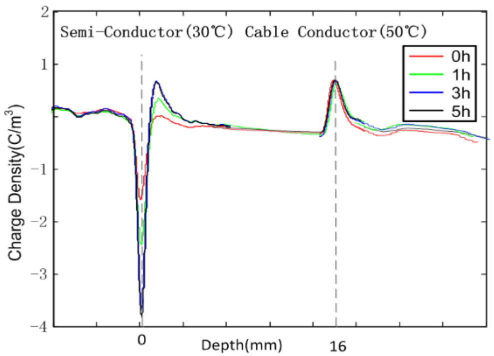
ΔT=10ºC



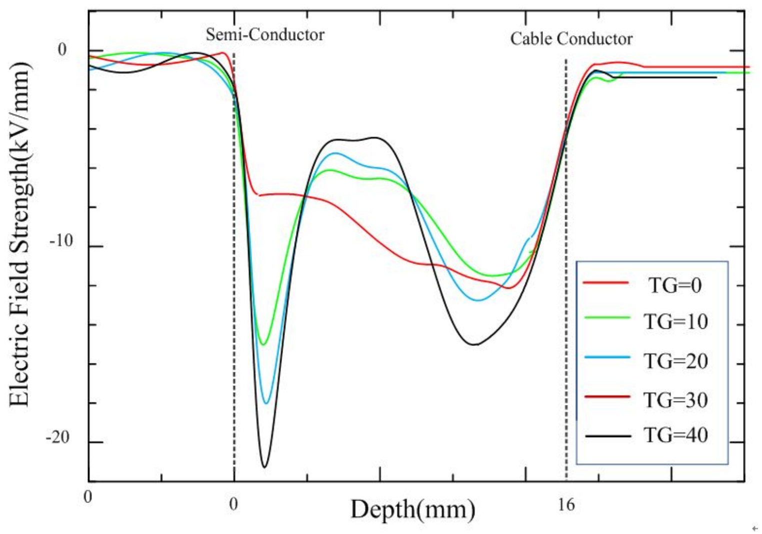
ΔT=30ºC



ΔT=40ºC



ΔT=20ºC



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