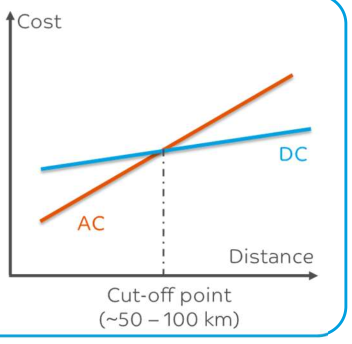
In-reactor polyethylene-based ionomer as recyclable alternative for high-voltage DC insulation cables

J. Vachon,[a] S. D'Auria,[a,b] P. Neuteboom,[a] R. Pinalli,[b] E. Dalcanale,[b] C. Müller,[c]

[a] SABIC, T&I STC Geleen, Netherlands
[b] Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Italy
[c] Chalmers University of Technology, Göteborg, Sweden

Energy transition(1)

- Transition from fossil to renewable sources of energy
- Power transmission system needs to follow such transition
- HVAC dominating electric power transmission: low installation cost, low transmission loss (good for short distances)
- Solar, wind, hydropower mostly far away from urban area (contrary to fossil fuel power plants)
- HVDC allows efficient energy transport over 100s-1000s km
- At cut-off point ~50–100 km, cost of HVDC transmission is lower



HVDC cables(2)

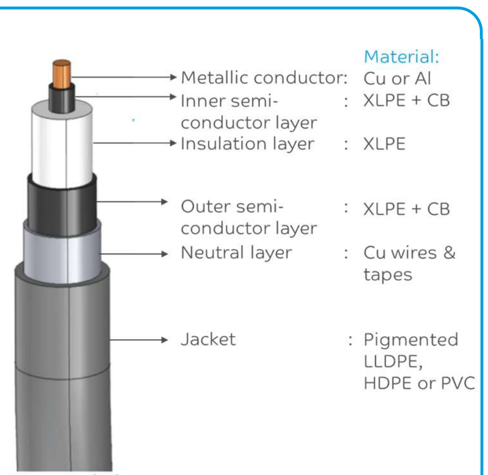
Advantages XLPE

- Good electrical insulating performance: low σ_{DC} (elec.) and high κ (thermal) conductivities
- Dimensional stability above T_m of PE (~110 °C)

Disadvantages XLPE

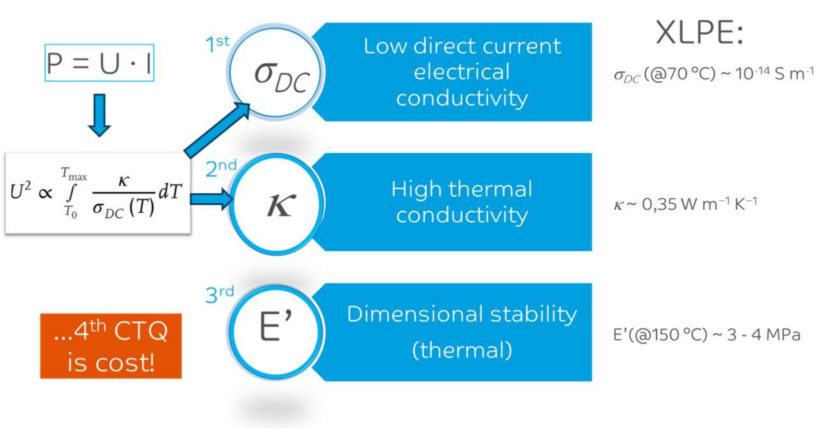
- Byproducts from peroxide crosslinking: health hazard, premature aging of dielectrics
- Degassing step: time and energy intensive
- Permanent crosslinks: not reprocessable

Need of a polyolefin recyclable alternative as insulation material with thermomechanical and dielectric properties similar to XLPE



HV extruded dielectric cable

Primary CTQs



P = U · I

$$U^2 \propto \int_{T_0}^{T_{max}} \frac{\kappa}{\sigma_{DC}(T)}\, dT$$

1st σ_{DC} Low direct current electrical conductivity

2nd κ High thermal conductivity

3rd E' Dimensional stability (thermal)

...4th CTQ is cost!

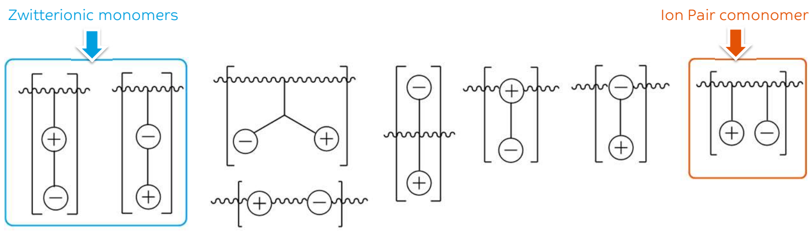
XLPE:

σ_{DC} (@70 °C) ~ 10^{-14} S m^{-1}

κ ~ 0,35 W m^{-1} K^{-1}

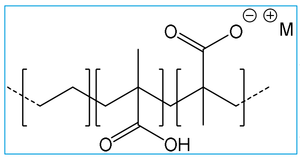
E'(@150 °C) ~ 3 - 4 MPa

Topology(3)



- Typically based on polystryrenics & polyacrylates
- Comonomers often on small scale / expensive
- Only explored via solution copol. (ATRP, RAFT)

Poly-zwitterions mostly an academic curiosity(3a)

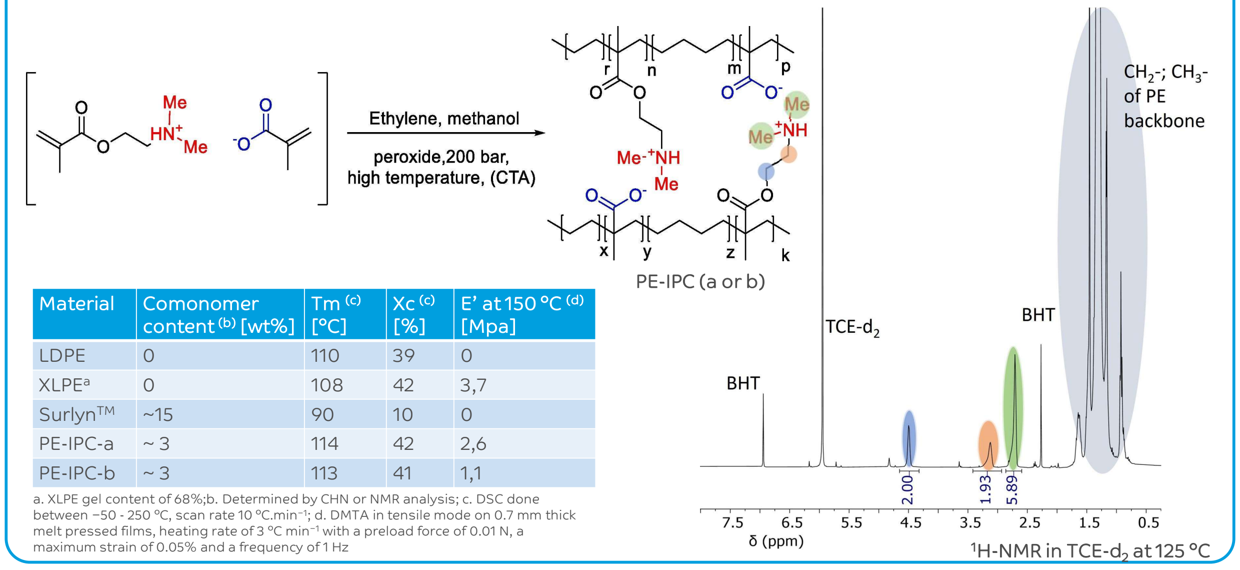


Surlyn^{TM} ionomer: Discovered in the 60's by Richard W. Rees from DuPont while working on new ways to chemically crosslink PE

Ionomer = Polymer based on macromolecules in which a significant proportion of the constitutional units has ionic or ionizable groups, or both(3b)

Our concept: In-reactor PE based ionomer (4)

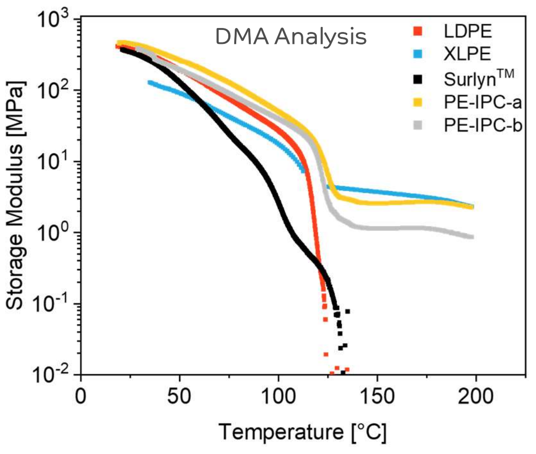
Ionic pair comonomer (IPC) was synthetized by an acid-base reaction, while the "PE-IPC" ionomer was synthetized through a free radical copolymerization reaction between ethylene and IPC in a high-pressure autoclave.

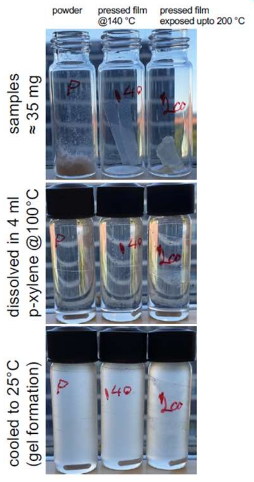


Material	Comonomer content (b) [wt%]	Tm (c) [°C]	Xc (c) [%]	E' at 150 °C (d) [Mpa]
LDPE	0	110	39	0
XLPE[a]	0	108	42	3,7
Surlyn^{TM}	~15	90	10	0
PE-IPC-a	~ 3	114	42	2,6
PE-IPC-b	~ 3	113	41	1,1

a. XLPE gel content of 68%;b. Determined by CHN or NMR analysis; c. DSC done between −50 - 250 °C, scan rate 10 °C.min^{-1}; d. DMTA in tensile mode on 0.7 mm thick melt pressed films, heating rate of 3 °C min^{-1} with a preload force of 0.01 N, a maximum strain of 0.05% and a frequency of 1 Hz

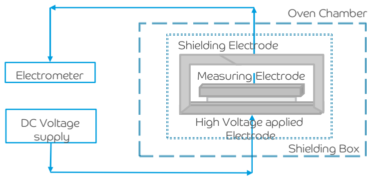
Melt strength(5)

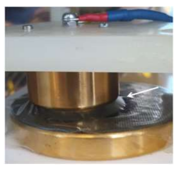




Ionic (non-permanent) crosslinks contributes to high stiffness below the melt. Rubbery plateau (T > Tm) mostly from chain entanglements

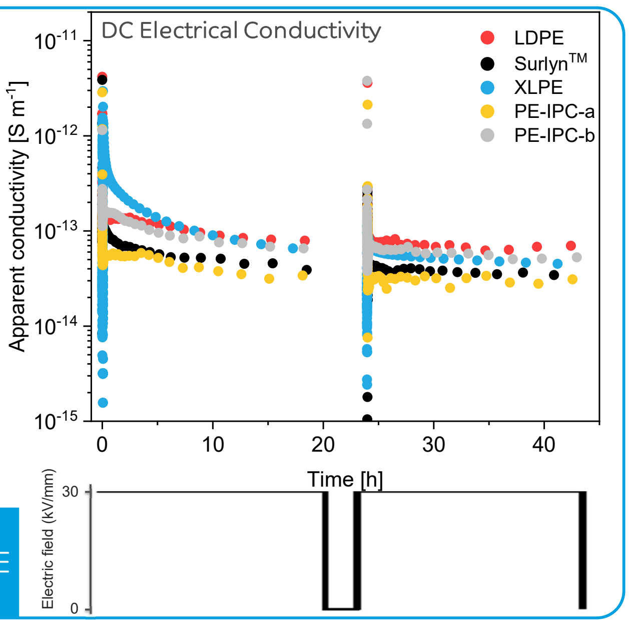
DC Conductivity(5)





Material	E' at 150 °C [Mpa]	κ at r.t. (b) [W.m^{-1}.K^{-1}]	σ_{DC} at 70 °C (c) [10^{-14} S.m^{-1}]
LDPE	0	0.41 ± 0.08	7.0 ± 2.1
XLPE[a]	3,7	0.36 ± 0.004	4.5 ± 1.4
Surlyn^{TM}	0	0.29 ± 0.002	3.4 ± 1.0
PE-IPC-a	2,6	0.37 ± 0.001	3.1 ± 0.9
PE-IPC-b	1,1	0.35 ± 0.006	5.3 ± 1.6

a. XLPE gel content of 68%; b. DC voltage applied (V = 4.2 - 4.8 kV) across ~0.15 mm films, σ_{DC} at 70 °C calculated based on charging currents obtained at the end of the second 18 h period; c. κ measured at rt with 4,6 mm thick films. 4 mW heating power applied over 2 s, resulting in a probing depth of ≈2 mm.



PE-IPC ionomers display:

- Low electrical conductivity σDC ≈ XLPE
- High thermal conductivity κ ≈ XLPE

References:
(1) a: X. Xiang et al., *CSEE J. Power Energy Syst.* **2021**, *7*, 954; b: Li et al., *High Voltage* **2022**, *7*, 610.
(2) A. Pourrahimi et al., *Adv. Mater..* **2024**, *36*, 2313508 (Chalmers, Uni. Parma)
(3) a: M. Hess et al., *Pure App. Chem.* **2006**, *78*, 2067; b: A. Laschewsky, *Polymers* **2014**, *6*, 1544
(4) J. Vachon, et al. *Copolymer of ethylene and ion pair compound,* WO2021009274A1; US 12,269,905 B2 (granted SABIC patent)
(5) S. D'Auria, et al., *Adv. Funct. Mater.* **2023**, *33*, 2301878 (SABIC, Uni. Parma, Chalmers)