

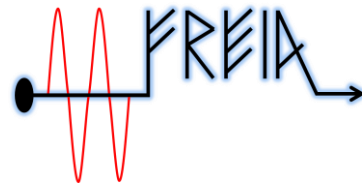


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Green alternatives to transformer mineral oils

Piotr Szaniawski



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Outline

1. Reasons for replacing mineral oil
2. Oil types
3. Tested oil selection
4. Experimental setups
5. Measurement methodology
6. Breakdown results
7. Dielectric probe results
8. Conclusions and final remarks





General reasons for replacing mineral oil

Oil spills

- All oil spills, not just from mineral oil, can be hazardous to animal and plant life
- Most happen during extraction and transport, alongside constant spillage from the marine and forestry industries

Potential toxicity

- Some mineral oils contain toxic additives
- Can be avoided by choosing non-toxic product varieties

Poor biodegradability

- Longer-term detrimental effects of spills on the environment
- Decommissioning can be complicated and expensive

Non-renewable sources

- Fossil fuels will eventually run out

Fire safety

- Mineral oils have relatively low flash points





Mineral oils

Mixtures of different **hydrocarbons**

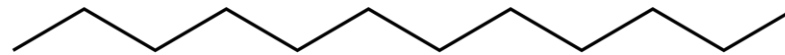
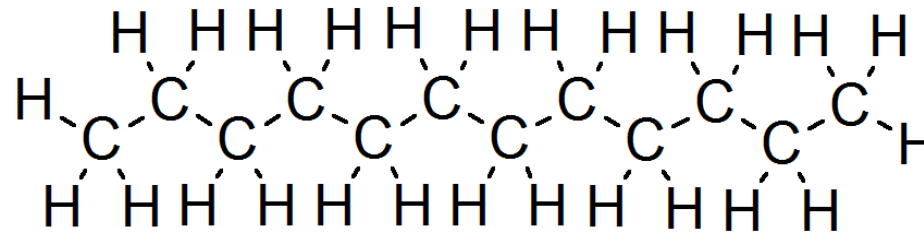


Image source: Wikipedia

Refined

- Produced by refinement of crude oil
- Poor biodegradability, <35%
- Often contain undesirable impurities
- Very sensitive to moisture
- Various additives, some toxic, are used to improve chosen properties

Synthetic

- Based on chemical synthesis of modified crude oil components or natural gas
- Higher purity than refined mineral oils
- Biodegradability potentially up to "readily biodegradable", ≤60%
- Also contain potentially toxic additives





Ester oils

Esters – compounds typically formed from **acids** and **alcohols**

Natural

- Mixtures of triglycerides – compounds of glycerol and fatty acids
- Very high biodegradability, ~99%
- Properties and chemical stability depend on the saturation of contained acids
- Additives are necessary to improve certain properties, e.g. oxidation resistance
- Often not recommended for breathing transformers

Synthetic

- Synthesized from organic acids and alcohols
- Lower biodegradability, >60%
- Properties tunable based on chosen reactants
- Also might contain additives

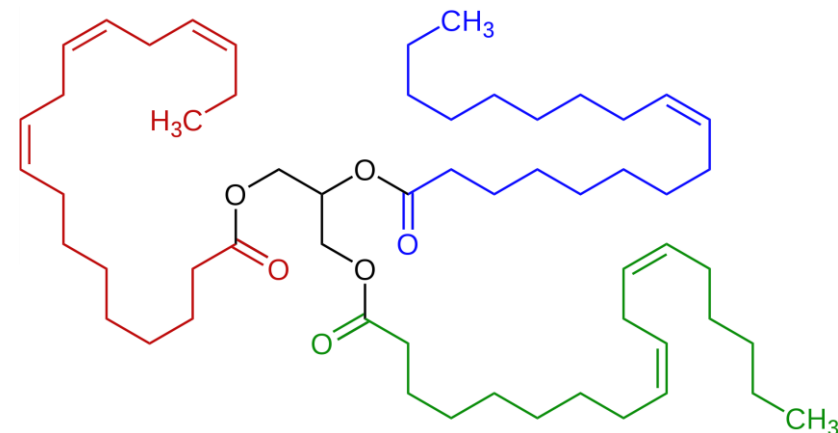


Image source: Wikipedia



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Tested oil selection

For preliminary testing

- Olive oil
- Rapeseed oil

Mineral oils

- Nynas Nytro 10XN (refined)
- Shell Diala S4 ZX-IG (synthetic, gas-to-liquid from natural gas)
- Shell Diala S5 BD (synthetic, gas-to-liquid from natural gas)

Ester oils

- Cargill Envirotemp 360 (synthetic)
- Cargill Envirotemp FR3 (natural)
- MIDEL 7131 (synthetic)
- PFAE – palm fatty acid ester (synthetic, monoester)
- Shell Naturelle S4 I (synthetic)



Megger OTS100AF

- Automatic testing according to IEC 60156-95
 - 400 ml oil vessel
 - 6 measurements per test
 - 2.5 mm distance between mushroom-shaped electrodes
 - 100 kV rms (AC) maximum voltage
 - 2.0 kV/s voltage ramp-up rate
 - Actively stirred with magnetic pill
- Measurement resolution and accuracy
 - 0.1 kV +/- 1% +/-2 digits
- From the user guide:
 - "Allow the sample to stand for a few minutes before testing to allow air bubbles to clear. However, it is important not to leave the sample to stand for longer than absolutely necessary as it may absorb water from the air in the headspace above it, again reducing the breakdown voltage."





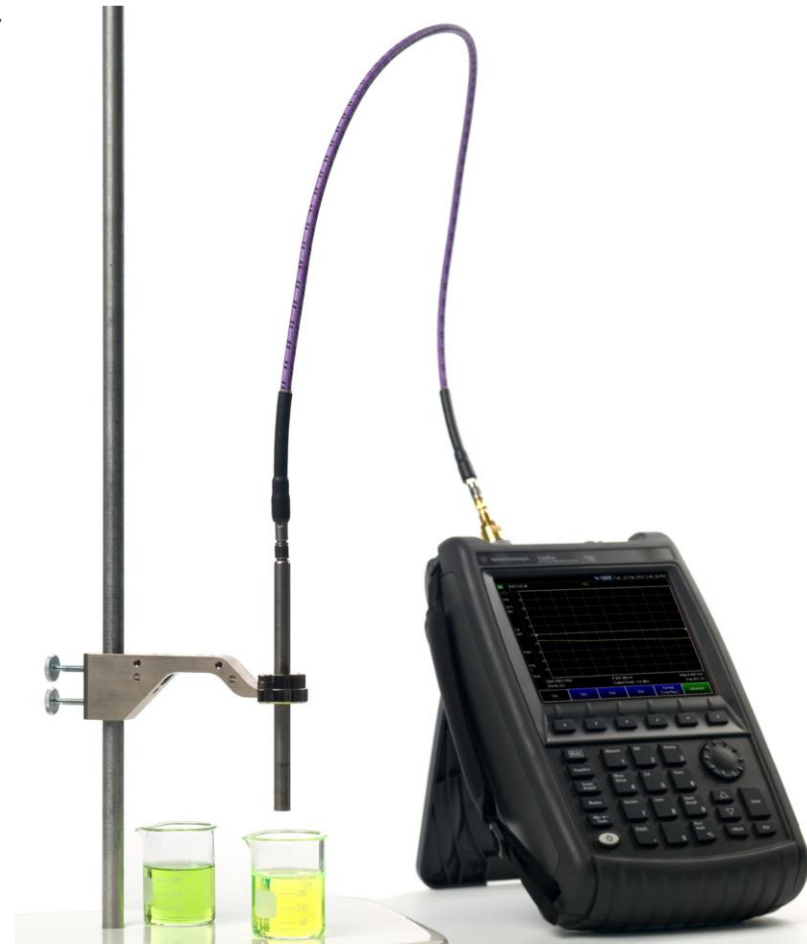
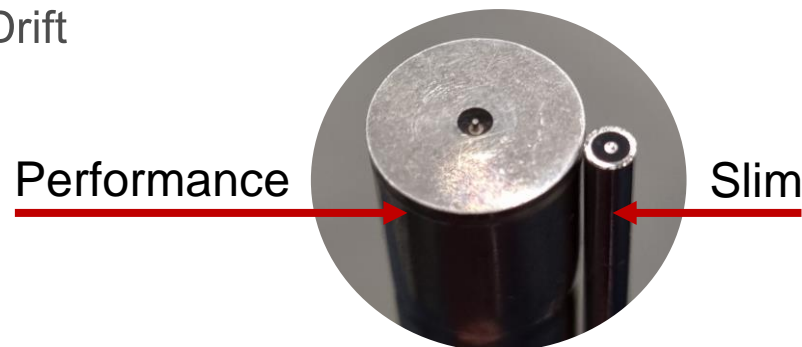
85070E Dielectric Probe Kit

Idea: monitoring of water content through permittivity measurements

- Used in tandem with a Keysight FieldFox network analyzer
- Performance and slim probes
- Calibration by short circuit, air, and water
- Measurement range: 200 MHz – 4 GHz

Issues

- Inaccurate results with the slim probe
- Inconsistent results with the performance probe
- Poor calibration reproducibility
- Drift



Vacuum "oven"





Oil treatments – 4 states

Fresh

- Untreated oil, measured soon after container opening

Cooked

- 4h with heater at 50W and static starting vacuum of ~1 mbar
- Final temperature ~120-130°C
- Cooled overnight

Filtered and cooked

- Oil filtered through 200 nm SFCA membrane
- Following procedure identical to **Cooked** state

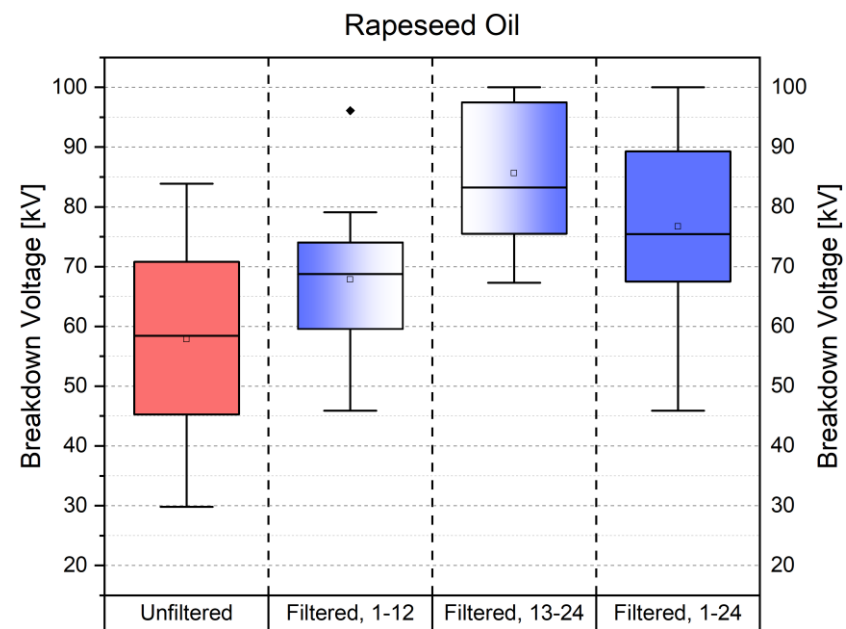
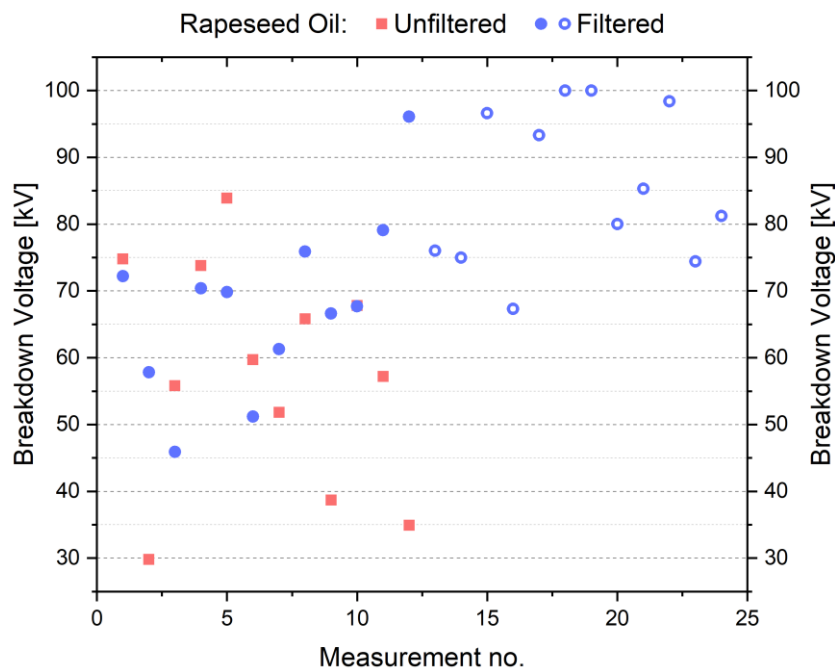
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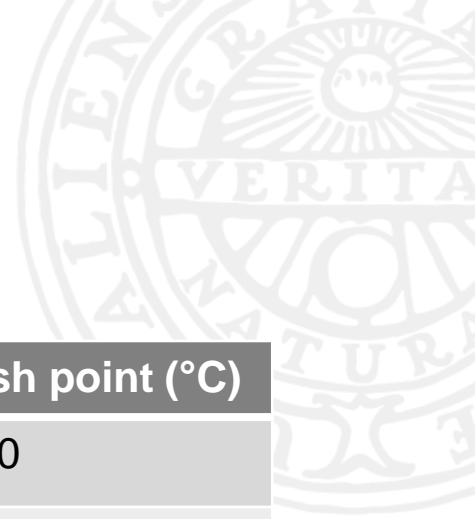
- ~115h with heater at 32W, sealed chamber, starting at atmospheric pressure
- Beaker with 80 ml of water in the chamber
- Final temperature ~80°C – below the boiling point of water
- Cooled overnight



Comments on filtering

- Several articles have shown that **filtering has a positive effect on breakdown voltage** due to removal of contaminating particles
- Filtering was done using Thermo Fisher Nalgene Rapid Flow Filter Units, which utilize **vacuum to facilitate fluid flow** through the filter membrane
- The “vacuum-compatible” bottles shouldn’t be actively pumped, since they **break** quite easily
- Preliminary testing with off-the-shelf rapeseed oil **showed a positive effect of filtering** on breakdown voltage:



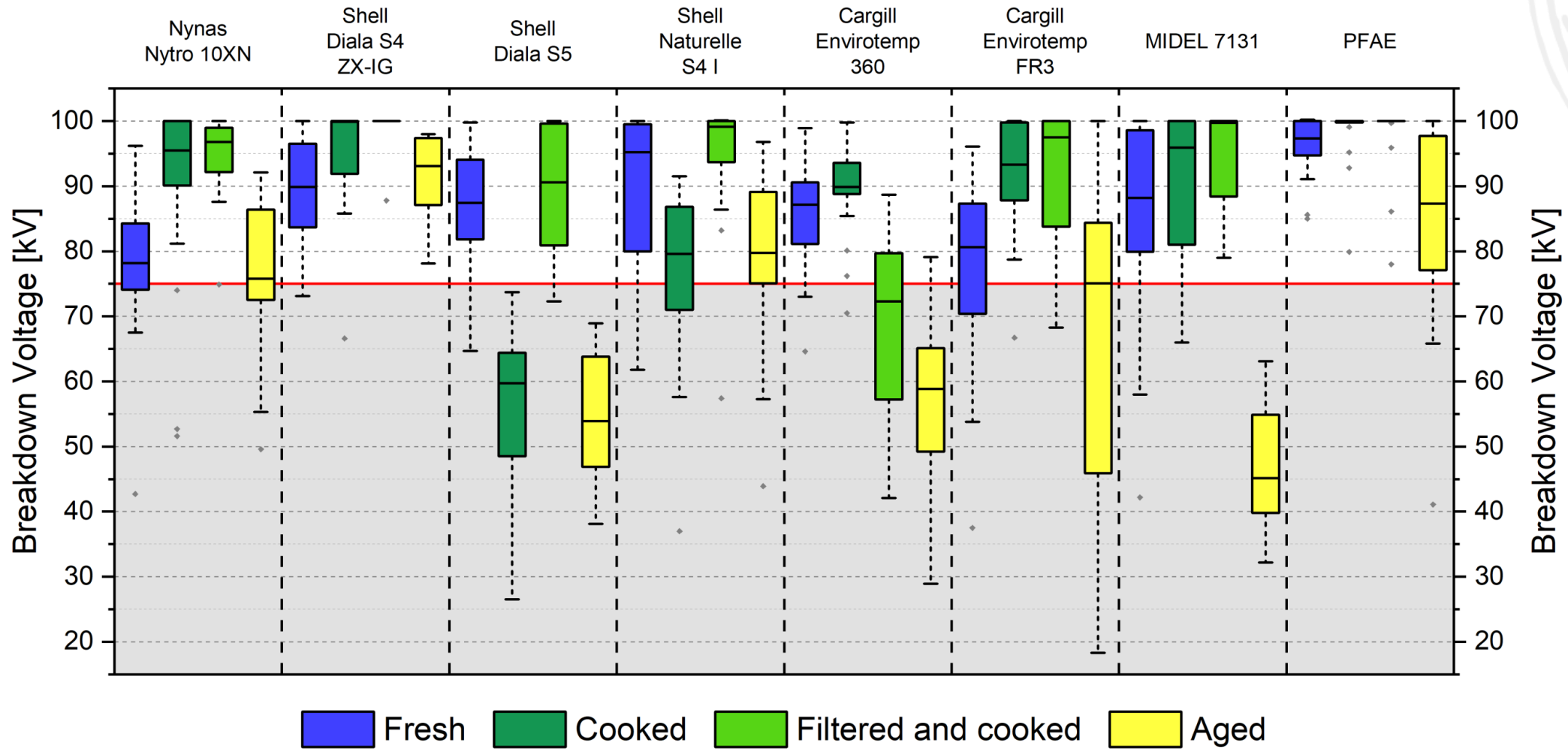


Tested oil selection – summary of important properties

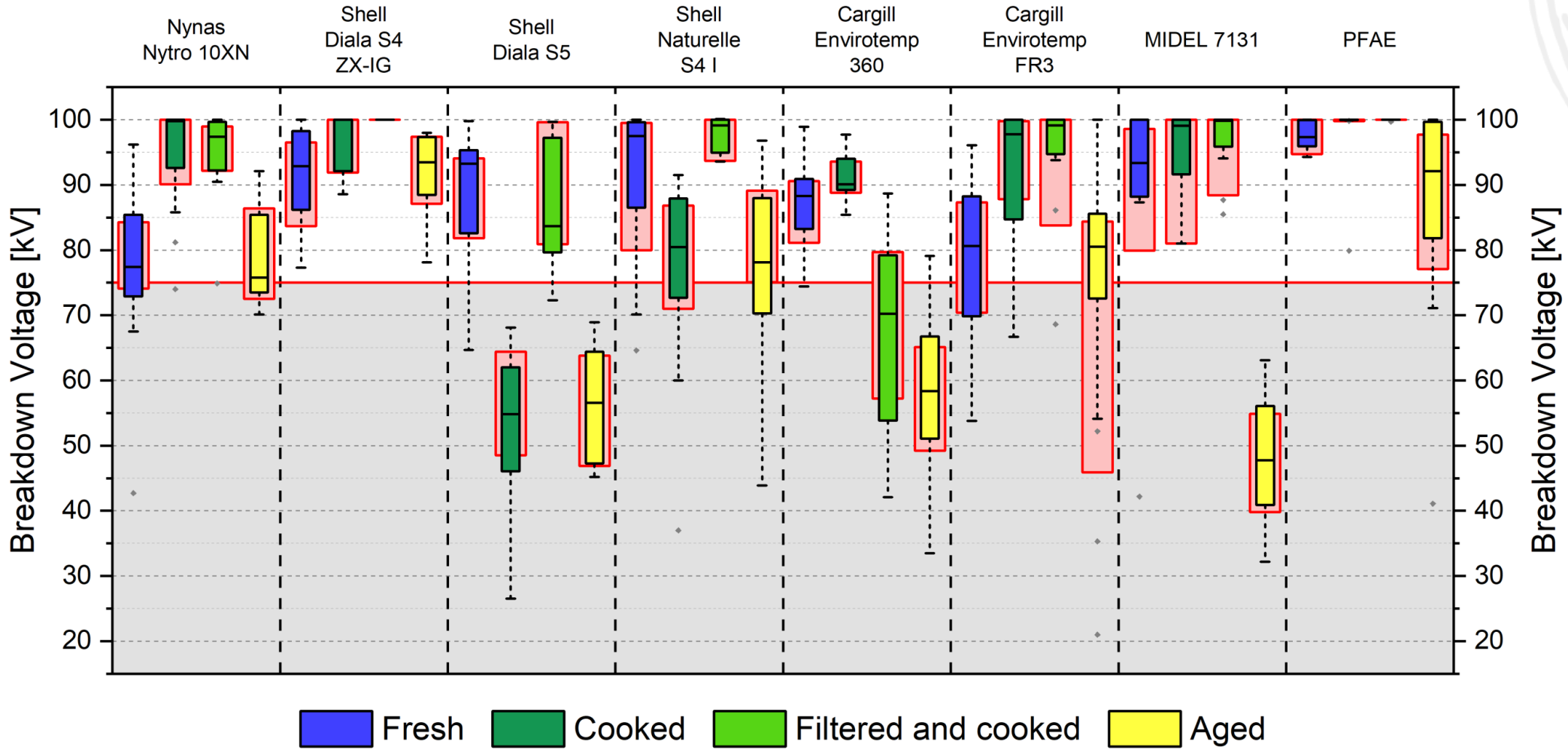
Oil	Type	Source	Biodegradability	Toxicity	Viscosity (cSt)	Flash point (°C)
Nytro 10XN	Mineral	Refined	Inherent / 4.5%	Harmful	7,6	≥140
Diala S4 ZX-IG	Mineral	Synthetic	Inherent / ?	No*	9,4	≥145
Diala S5 BD	Mineral	Synthetic	Readily (≥60%)	No*	7,4	≥135
Envirotemp 360	Ester	Synthetic	Readily (≥60%)	No	32 – 34	>283
Envirotemp FR3	Ester	Natural	100% in 10d	No	34	260
MIDEL 7131	Ester	Synthetic	Readily (≥60%)	No	29	260
PFAE – palm fatty acid ester	Ester	Synthetic (monoester)	77%	No*	5,06	178
Shell Naturelle S4 I	Ester	Synthetic	Readily (≥60%)	No	27,2	255



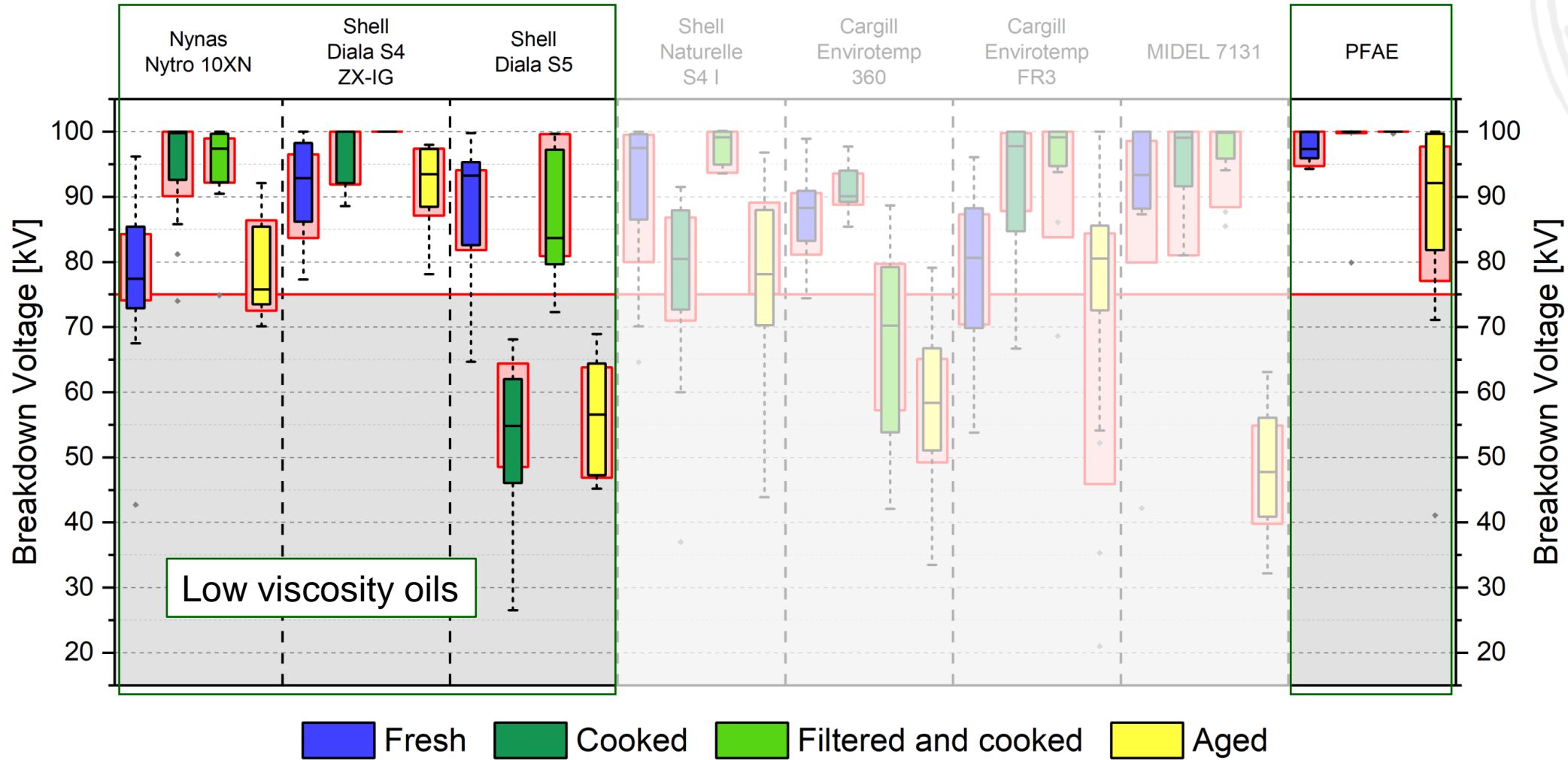
Breakdown voltage statistics



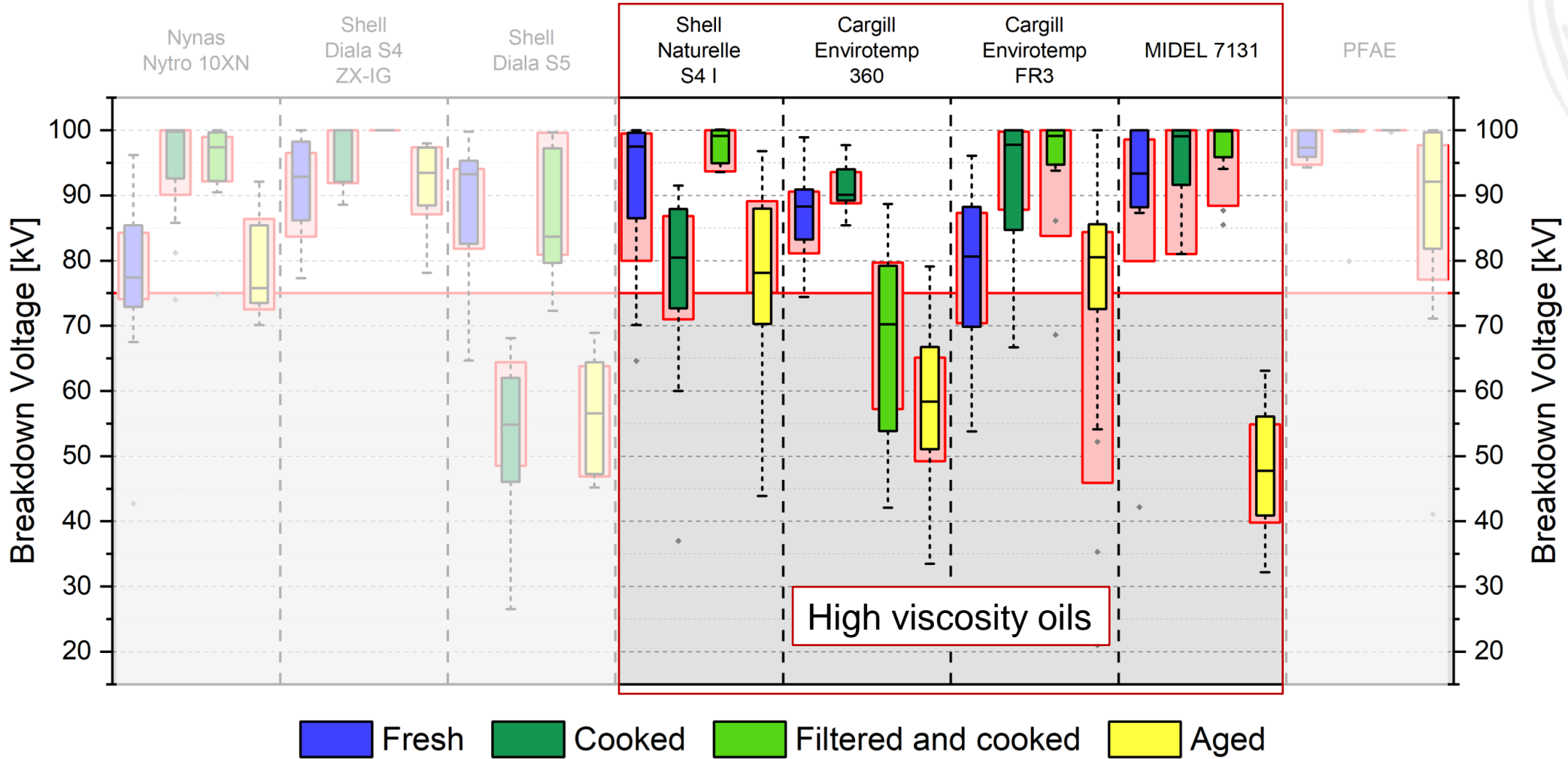
Breakdown voltage statistics – w/o measurements 1-6



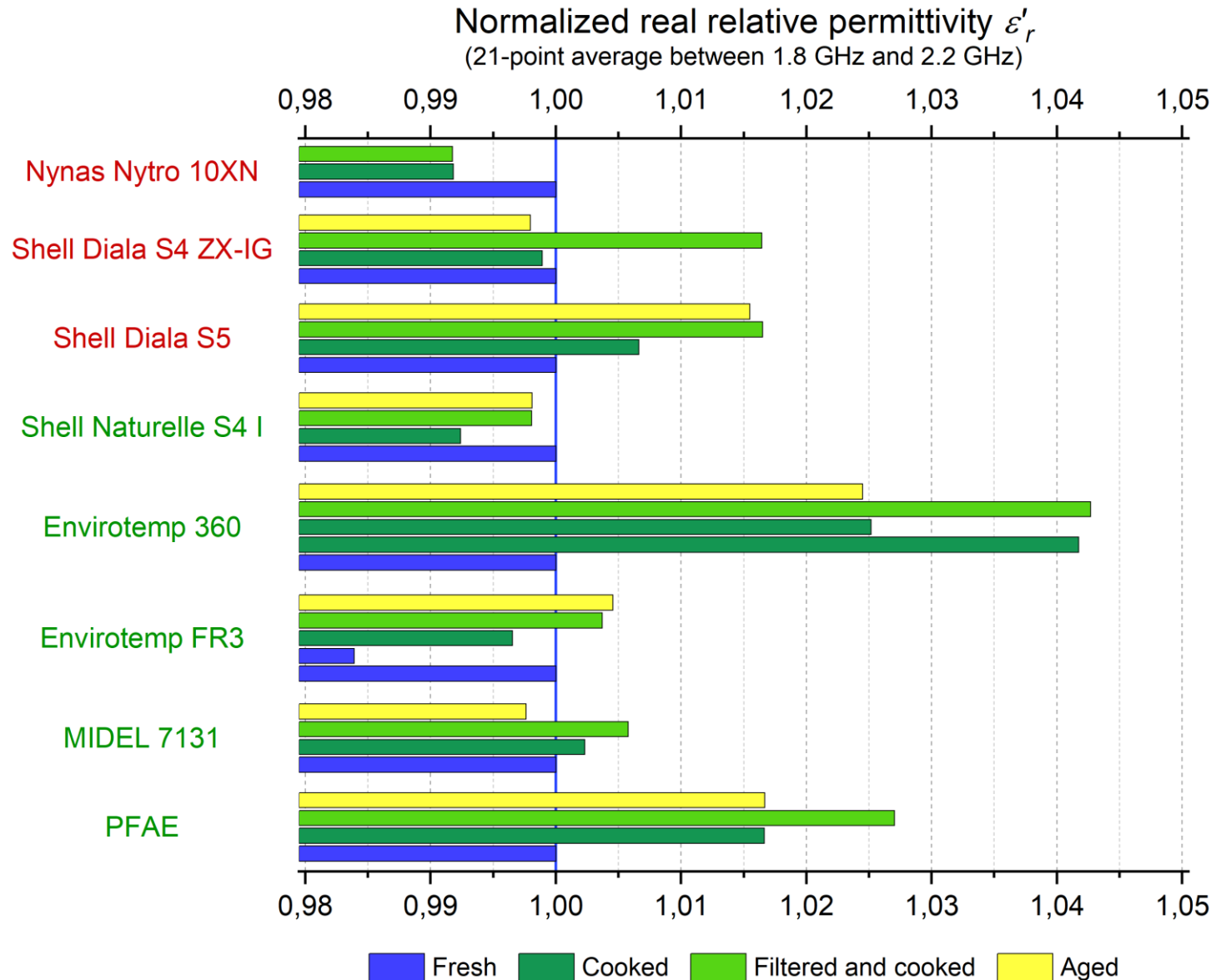
Breakdown voltage statistics – w/o measurements 1-6



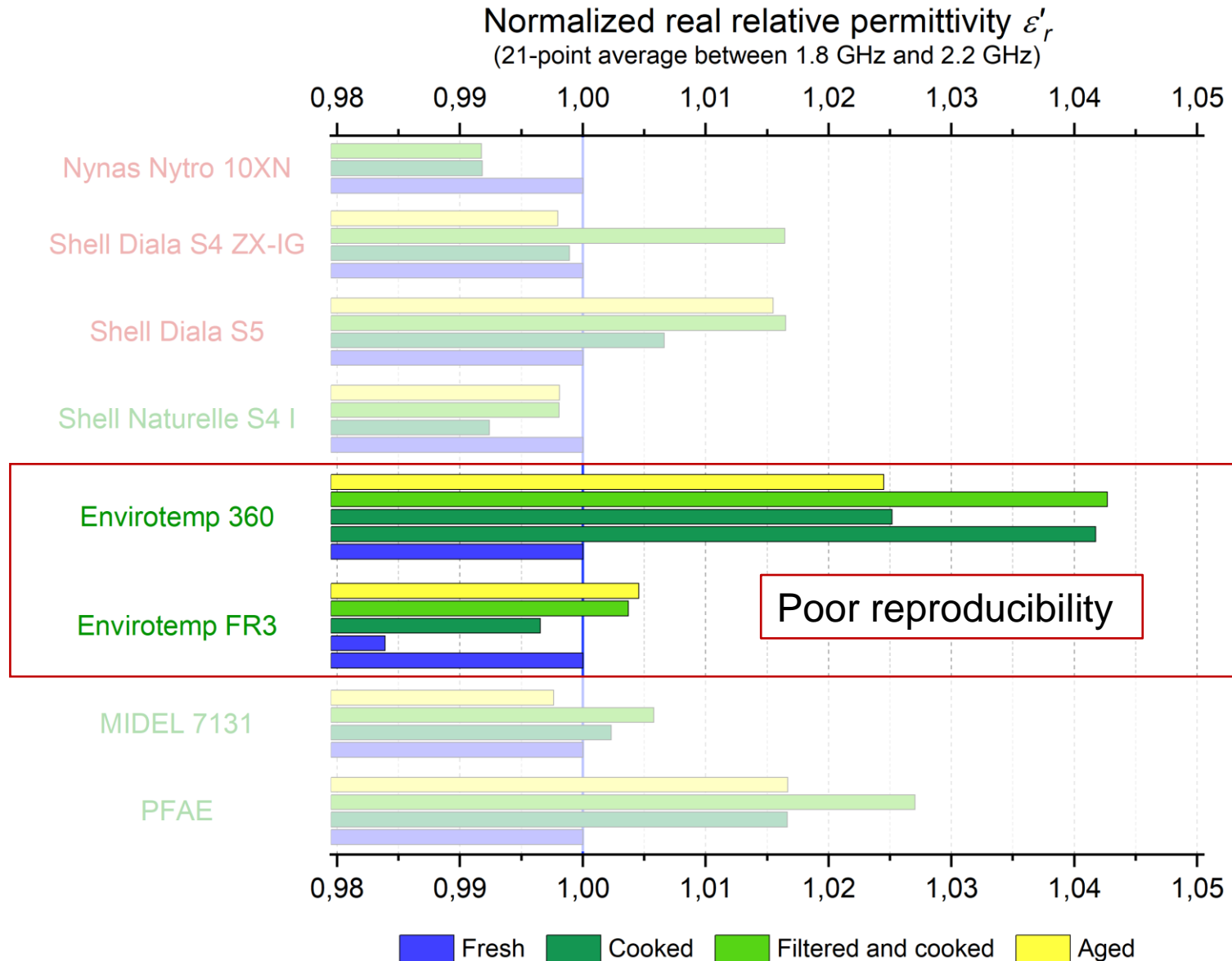
Breakdown voltage statistics – w/o measurements 1-6



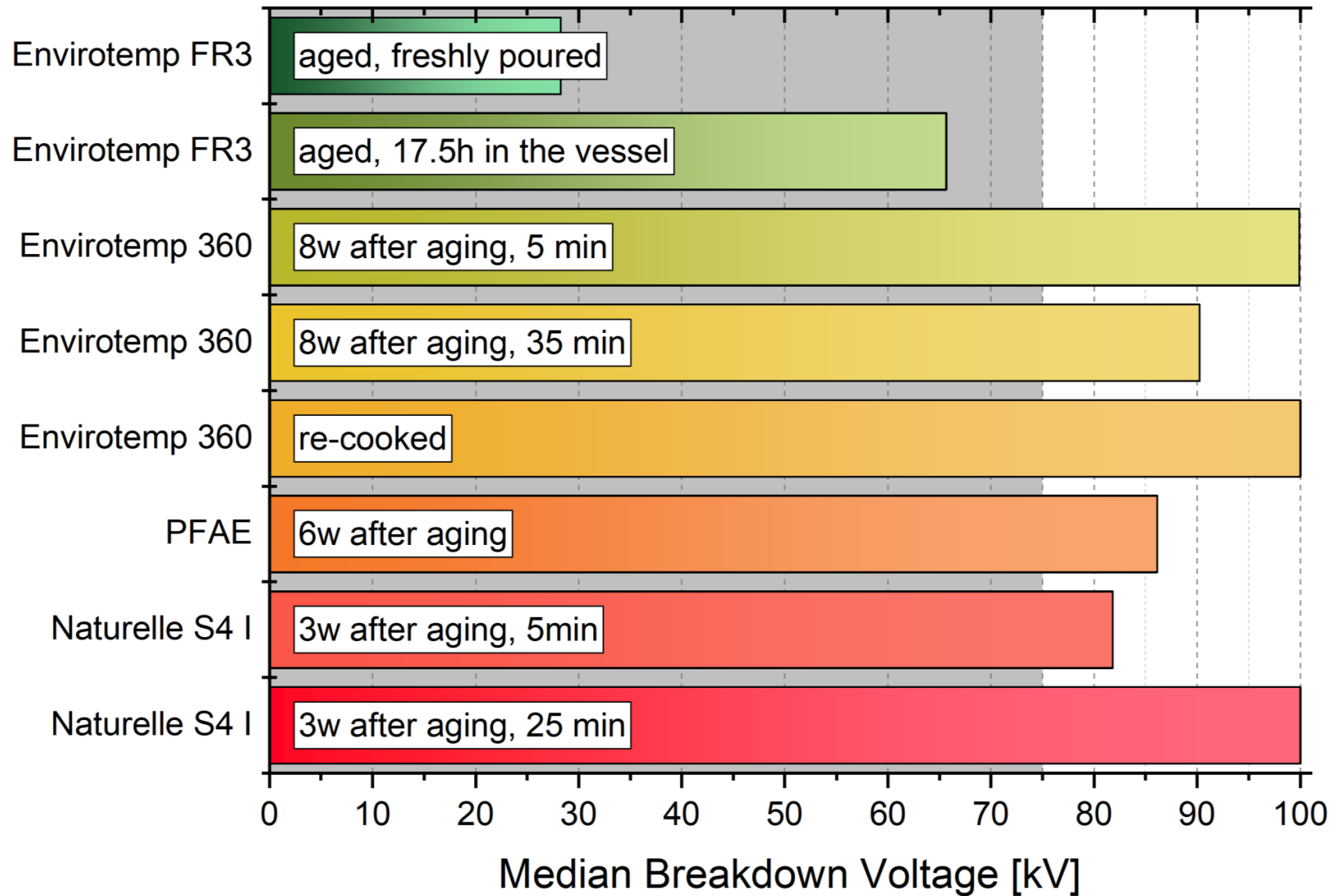
Dielectric probe measurement results



Dielectric probe measurement results



Extra data – incomplete picture





Conclusions and final remarks

- There are good **reasons to replace mineral oil**, but **not all** are **universally applicable**
- Some of the tested **ester oils** performed as well as **mineral oils** in breakdown voltage measurements
- When first poured into an appliance, it's a good idea to **let the oil settle** for 1h or longer, depending on the size of the container
- In the interest of long-term safety and performance, it is advisable to **avoid using natural esters in breathing containers**, unless exceptional oxidation resistance can be guaranteed
- **Cooking and filtering** of oil prior to use can **maximize insulating properties**
- Critical amounts of **moisture cannot be detected** by changes in the **permittivity** of oils
- **PFAE** has shown the most **impressive performance** in most scenarios
- Even high amounts of moisture seem not to have any irreversible detrimental effect on the breakdown performance of ester oils, but no comparison was made with mineral oils



Acknowledgements:
Kévin Pepitone, Dragos Dancila, Yasin Alekajbaf

Thank you

Appendix follows



Some review articles

“Comparative evaluation of alternative fluids for power transformers”, 2013

<https://doi.org/10.1016/j.epsr.2013.01.007>

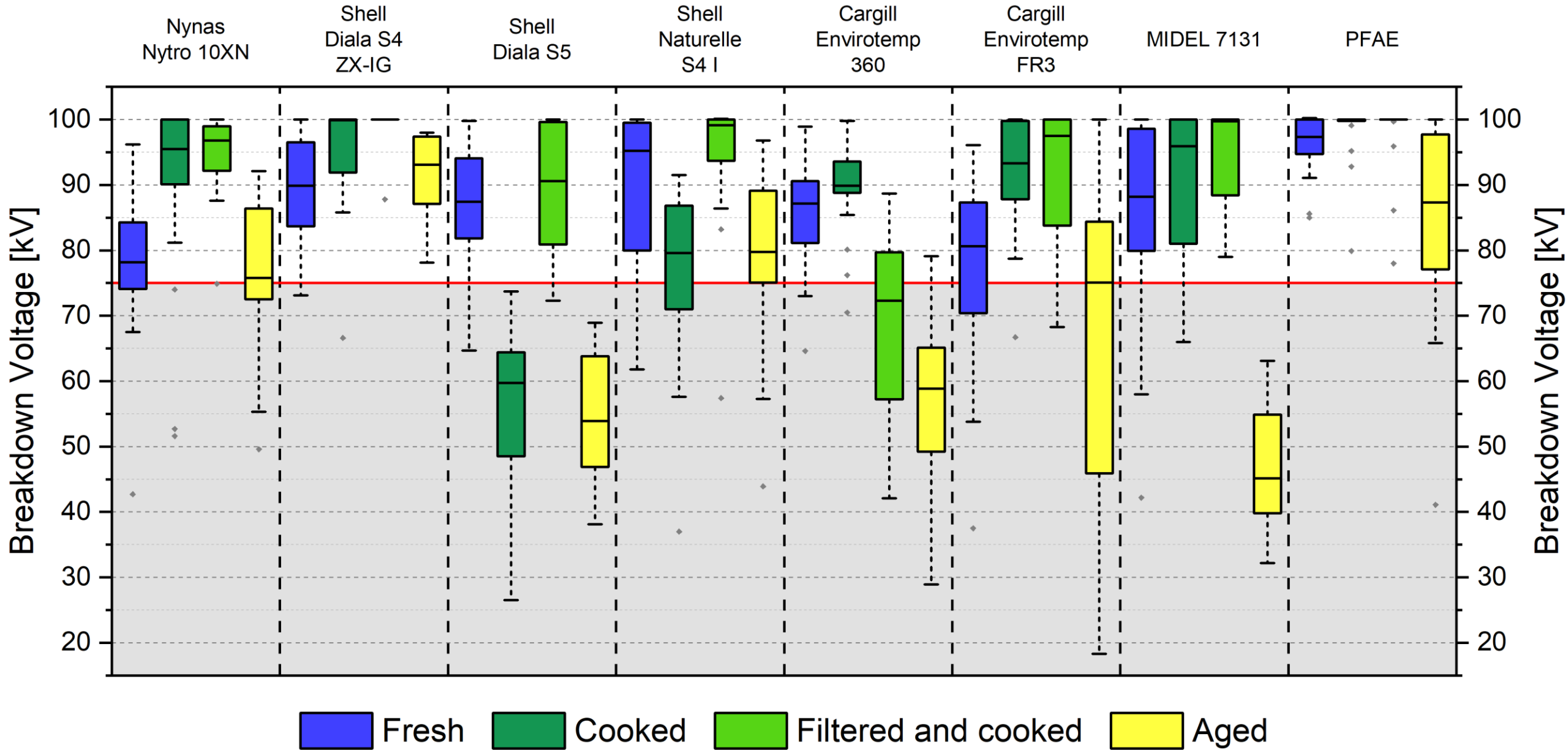
"Alternative Dielectric Fluids for Transformer Insulation System: Progress, Challenges, and Future Prospects", 2019

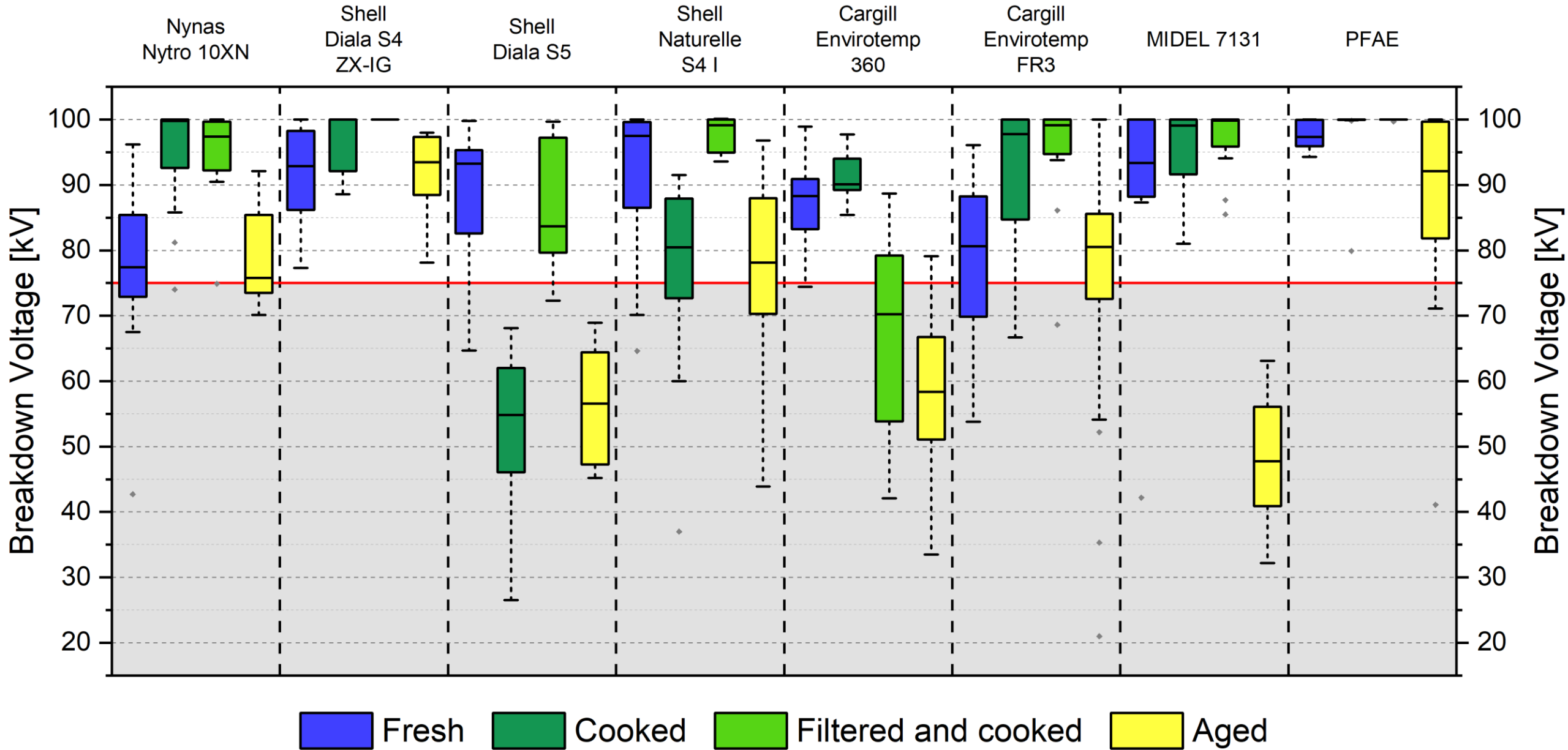
<https://doi.org/10.1109/ACCESS.2019.2960020>

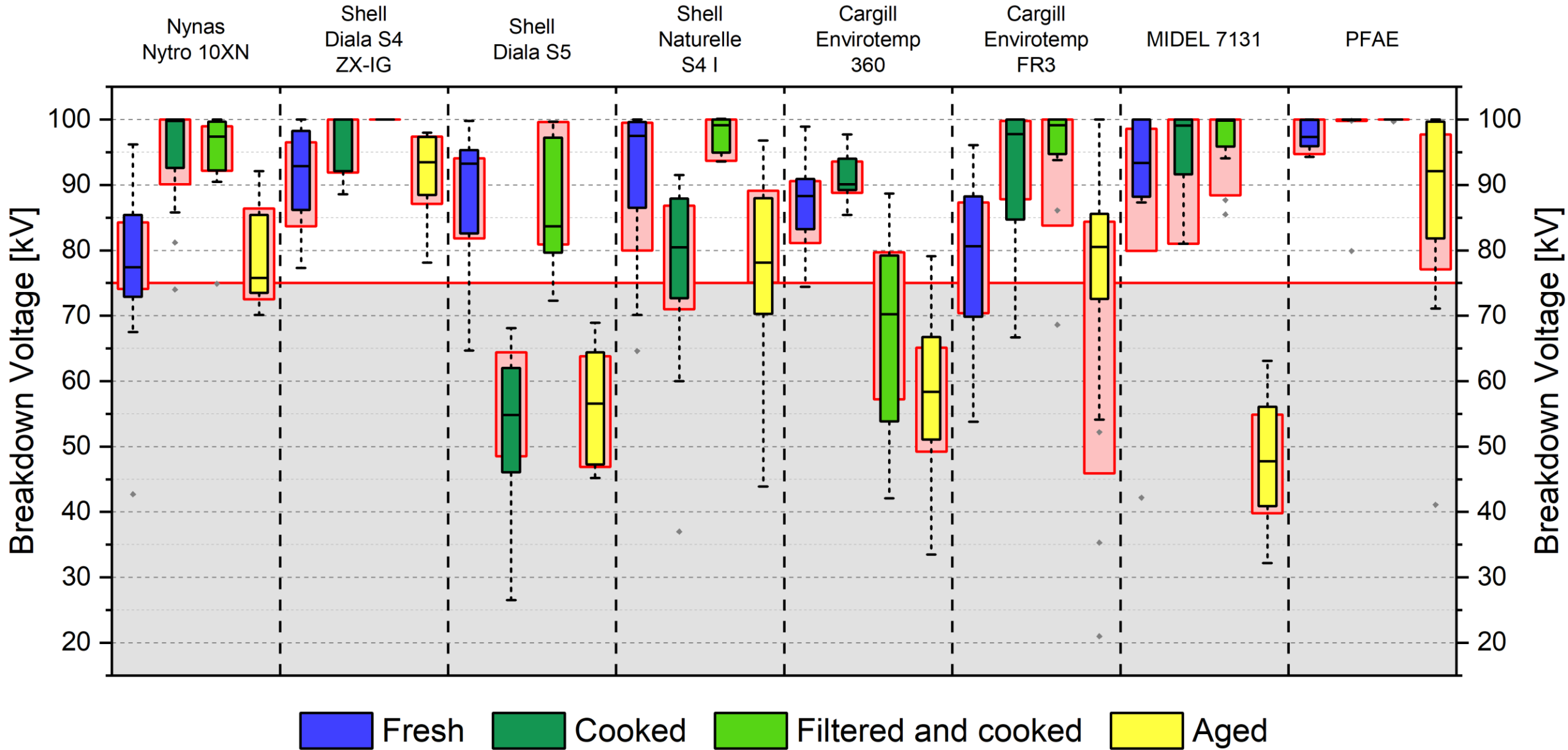
“Palm fatty acid ester as biodegradable dielectric fluid in transformers: a review”

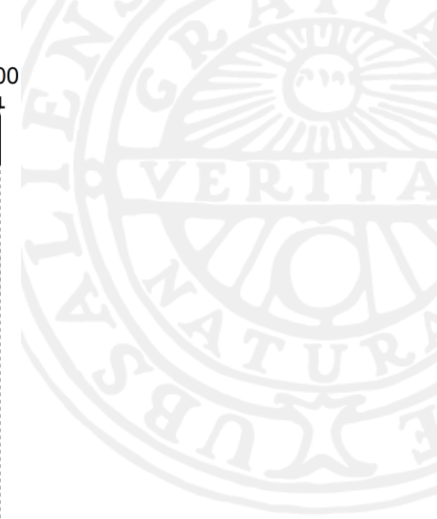
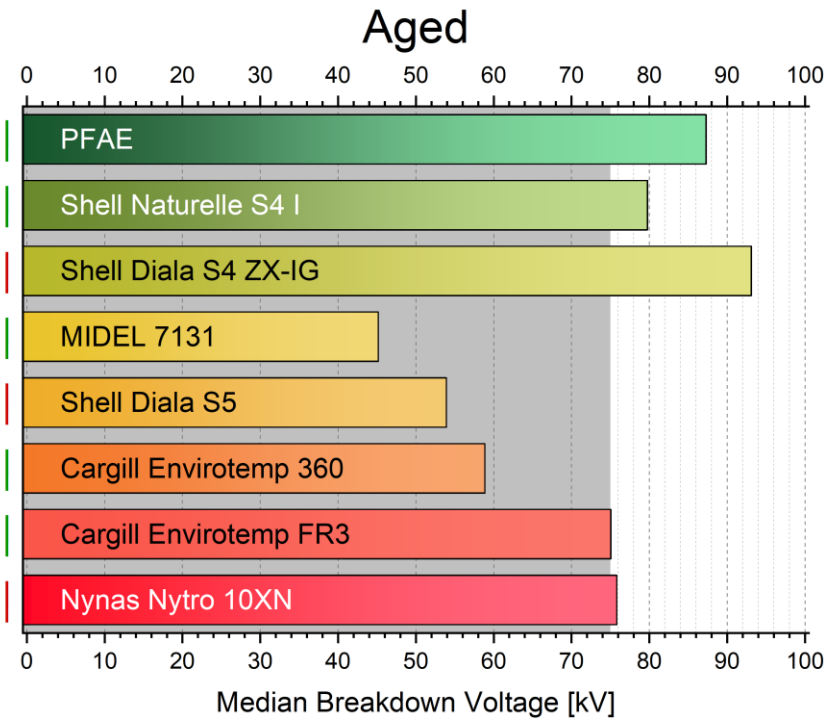
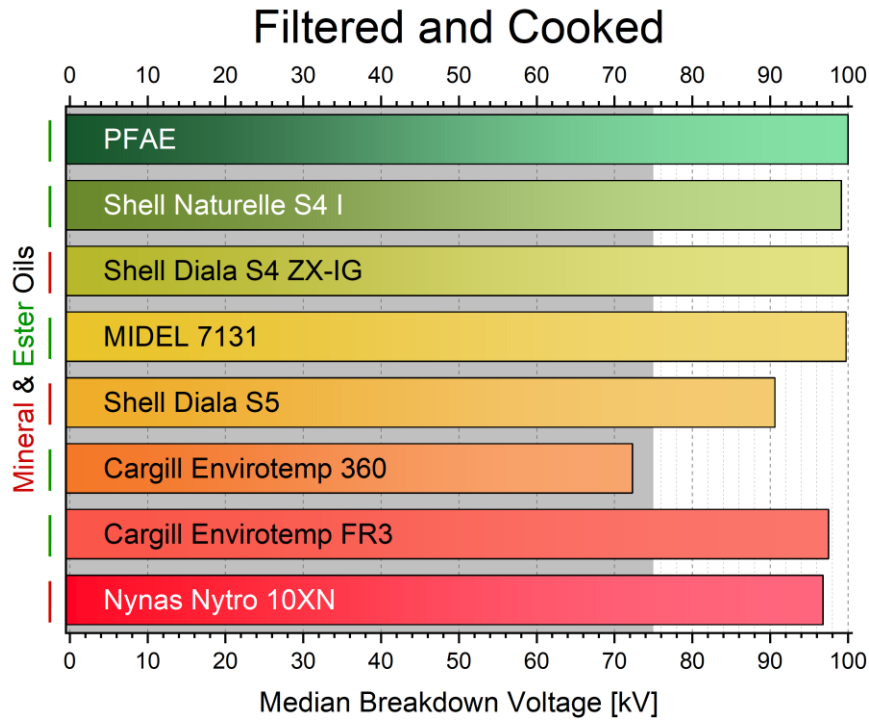
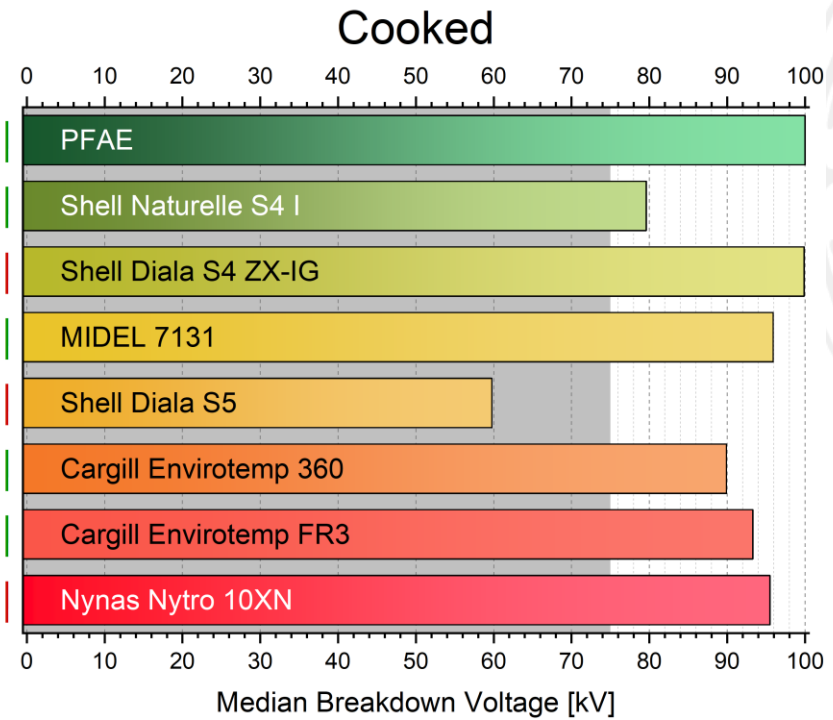
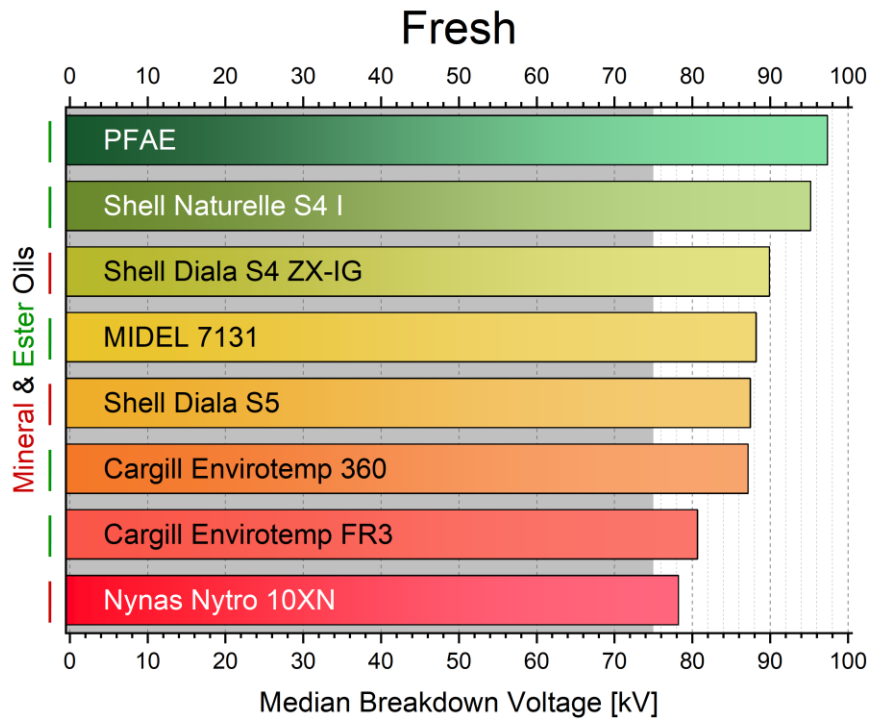
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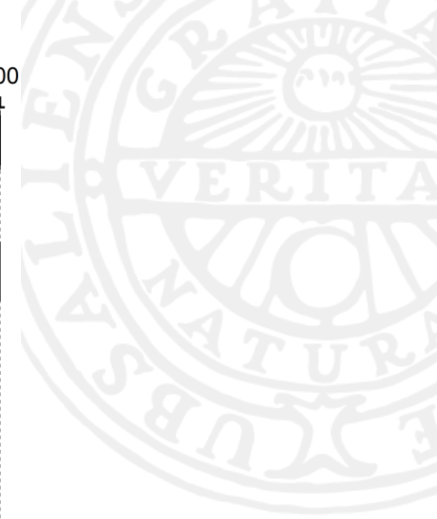
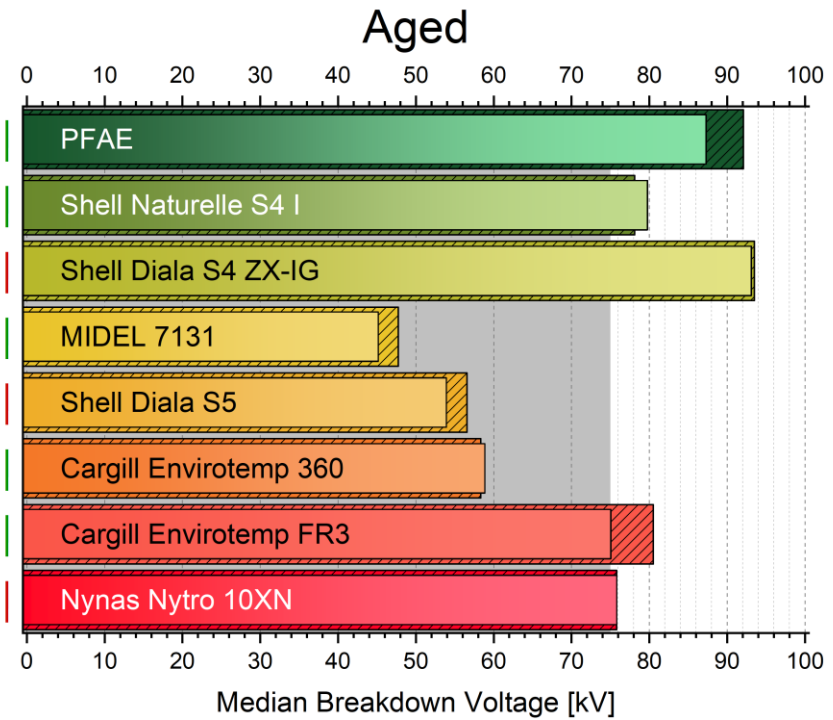
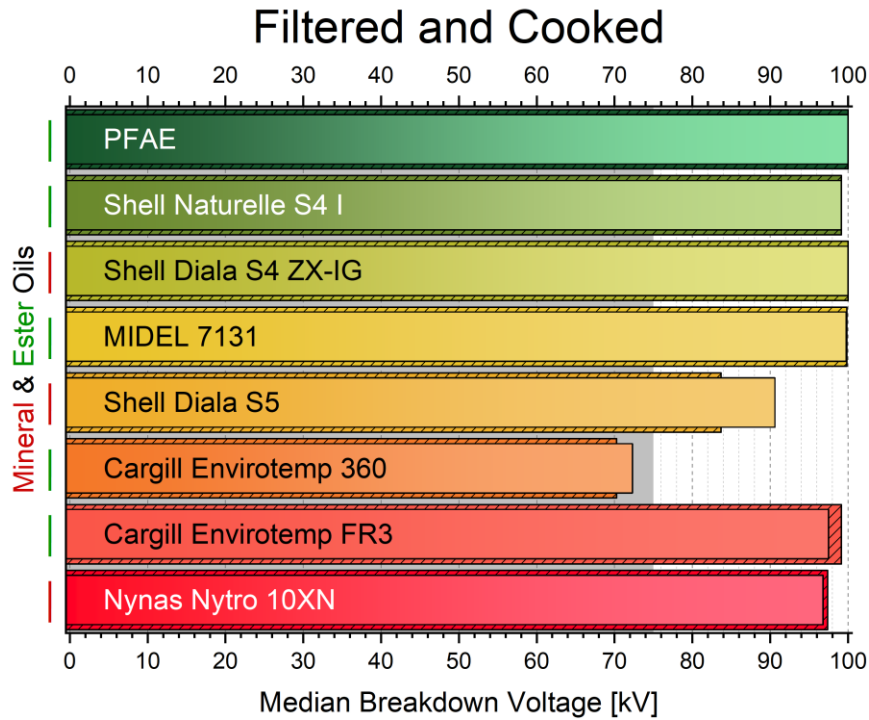
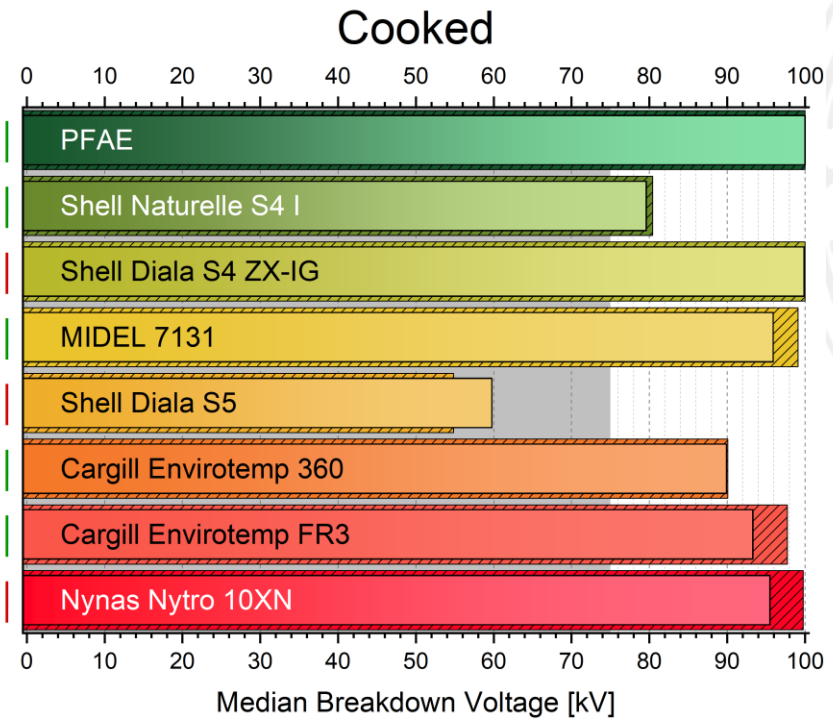
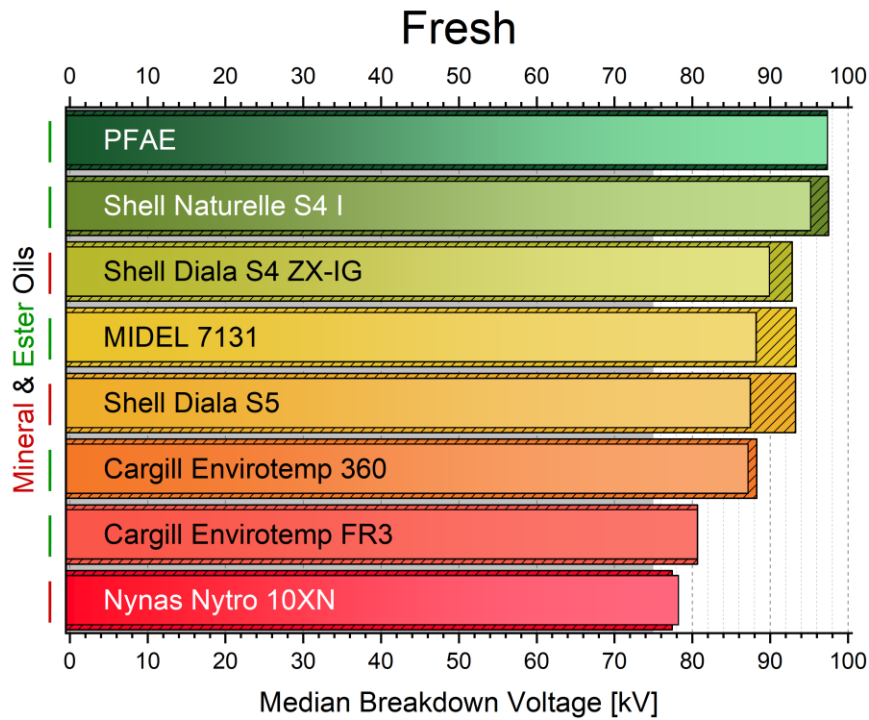




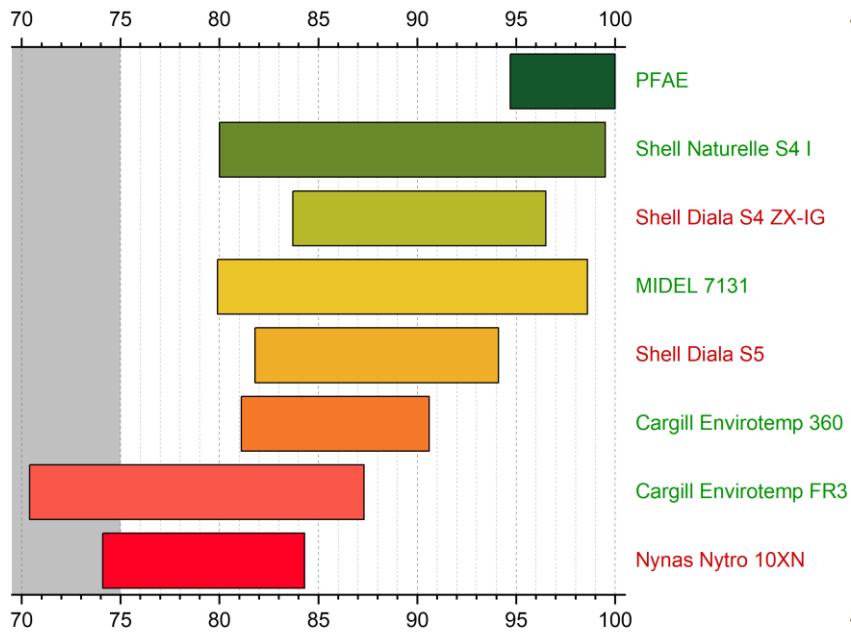




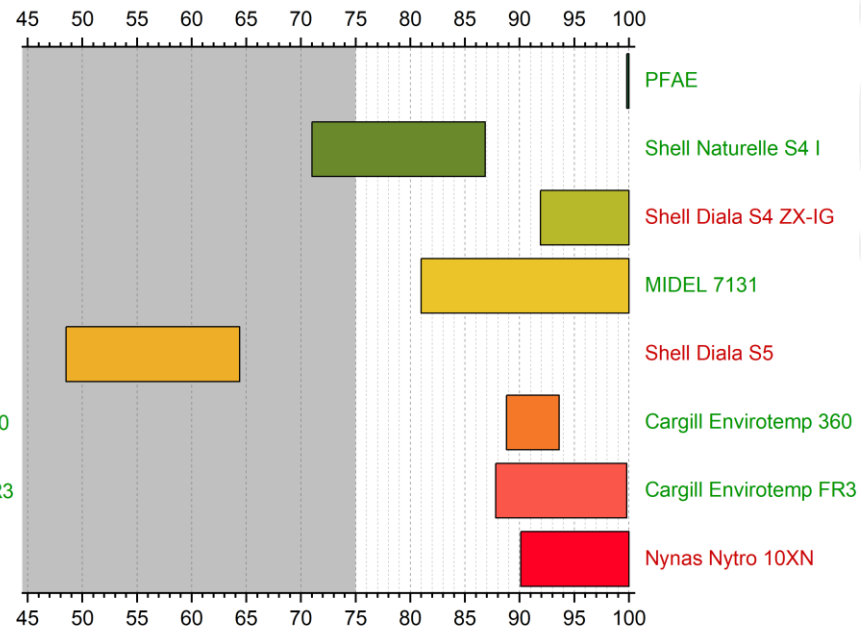




Fresh

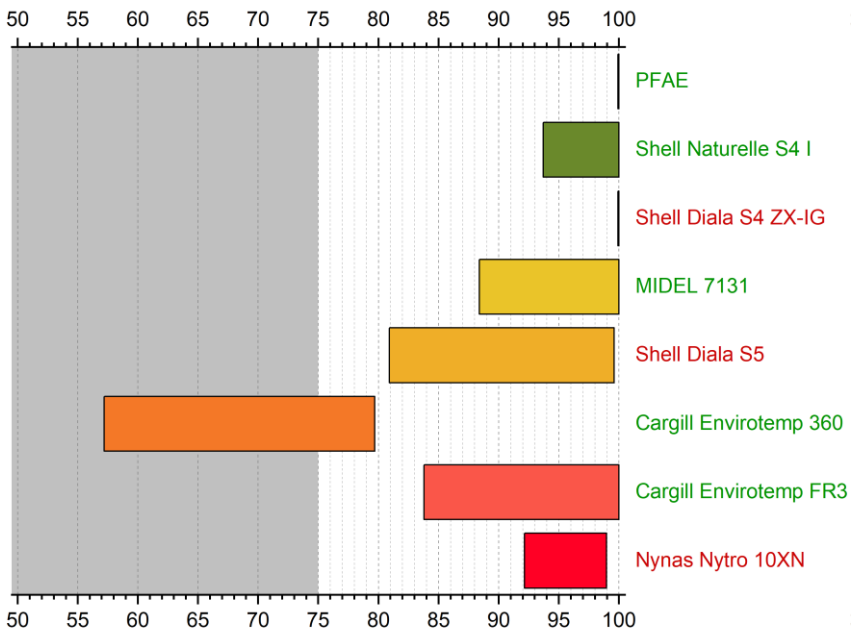


Cooked



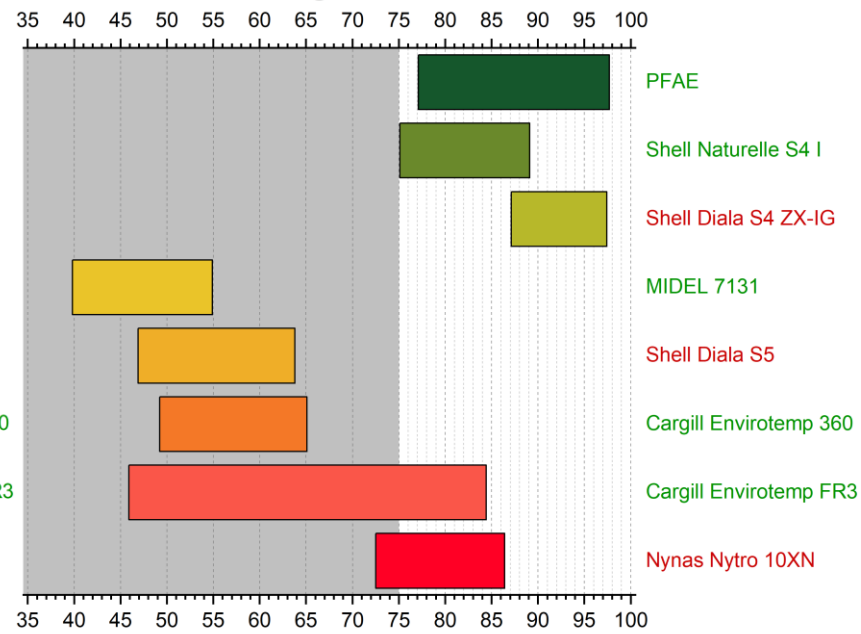
IQR Breakdown Voltage [kV]

Filtered and Cooked



IQR Breakdown Voltage [kV]

Aged



IQR Breakdown Voltage [kV]



