Investigation of impulsive breakdown of interfaces formed by ester insulating liquids and solid dielectrics

C. Williamson[1], I. Timoshkin[1], S. MacGregor[1], M. P. Wilson[1], M. J. Given[1], M. Sinclair[2], A. Jones[2]

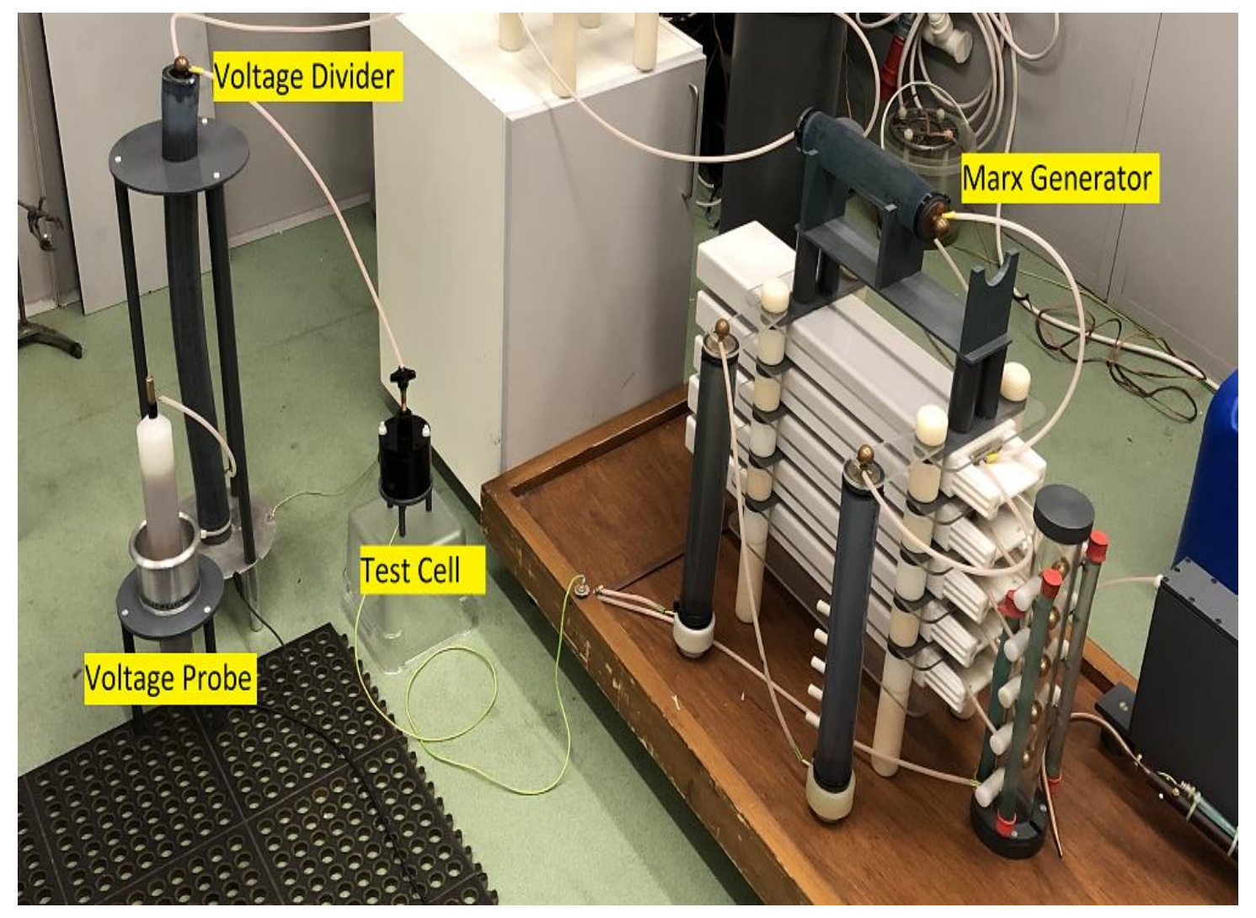
1- Department of electronic and electrical engineering University of Strathclyde, Glasgow 2- AWE PLC Aldermaston, UK

As naphthenic mineral oils are classified as a Class 1 water hazard, both the power and pulsed power industries are actively investigating suitable replacement liquid insulation. Natural and synthetic ester liquids present a possible alternative to these naphthenic mineral oils, primarily due to their comparable dielectric properties. Furthermore, ester liquids offer a number of additional benefits over conventional naphthenic oils such as improved biodegradability, reduced toxicity, increased flash point and the ability to absorb large amounts of moisture, as a consequence of the higher saturation point of ester liquids. For these reasons, significant research efforts have focused on the suitability of esters in the replacement of naphthenic mineral oils. However, most published research has examined ester liquids as the insulating medium within bulk insulating systems, with little known of the performance of liquid-solid interfaces formed between esters and solid polymers used in practical high voltage power and pulsed power systems

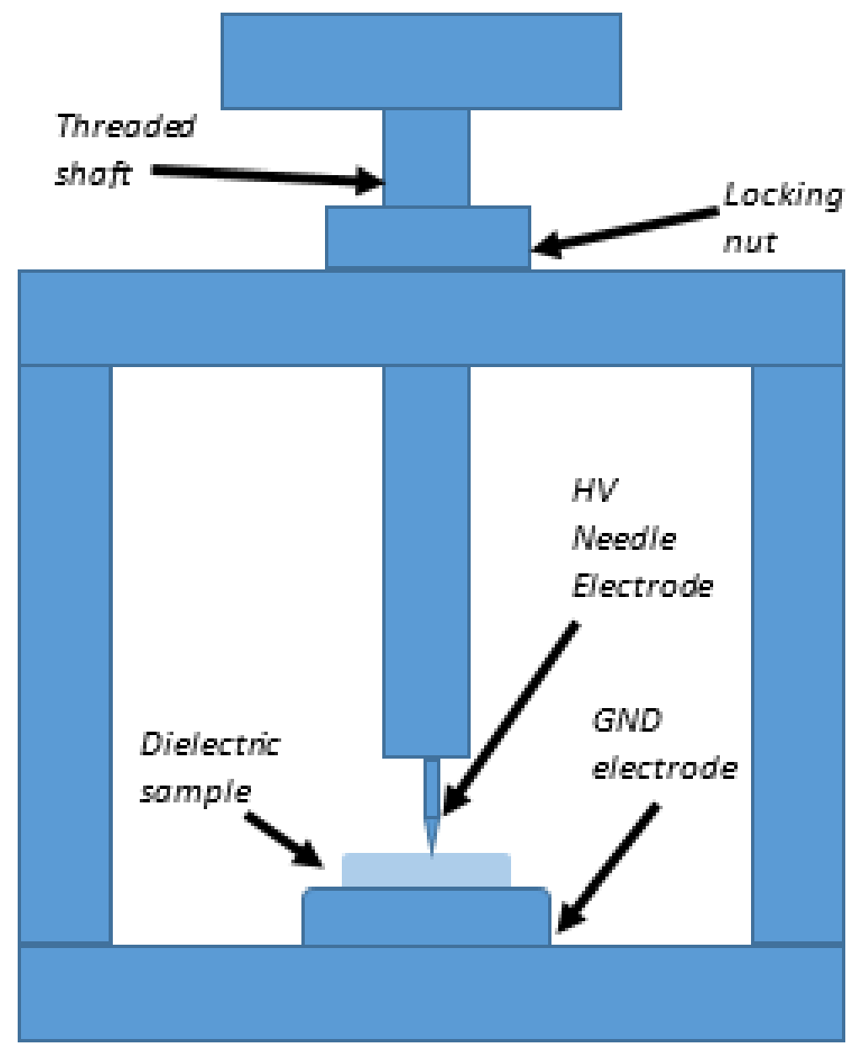
This work presents the breakdown performance of liquid-solid interfaces formed by MIDEL 7131 synthetic ester, FR3 natural ester and different solid dielectric materials, Nylon 66, Perspex and PVDF. These interfaces were stressed with impulse voltages (7/170µs) of negative polarity, following the IEC 60897 methodology. This standard uses a point sphere geometry generating a highly divergent field. Key breakdown characteristics, such as breakdown voltage and time to breakdown were obtained and compared with those for liquid-solid interfaces formed between the same chosen solid dielectric materials and naphthenic mineral oil.

Experimental Setup

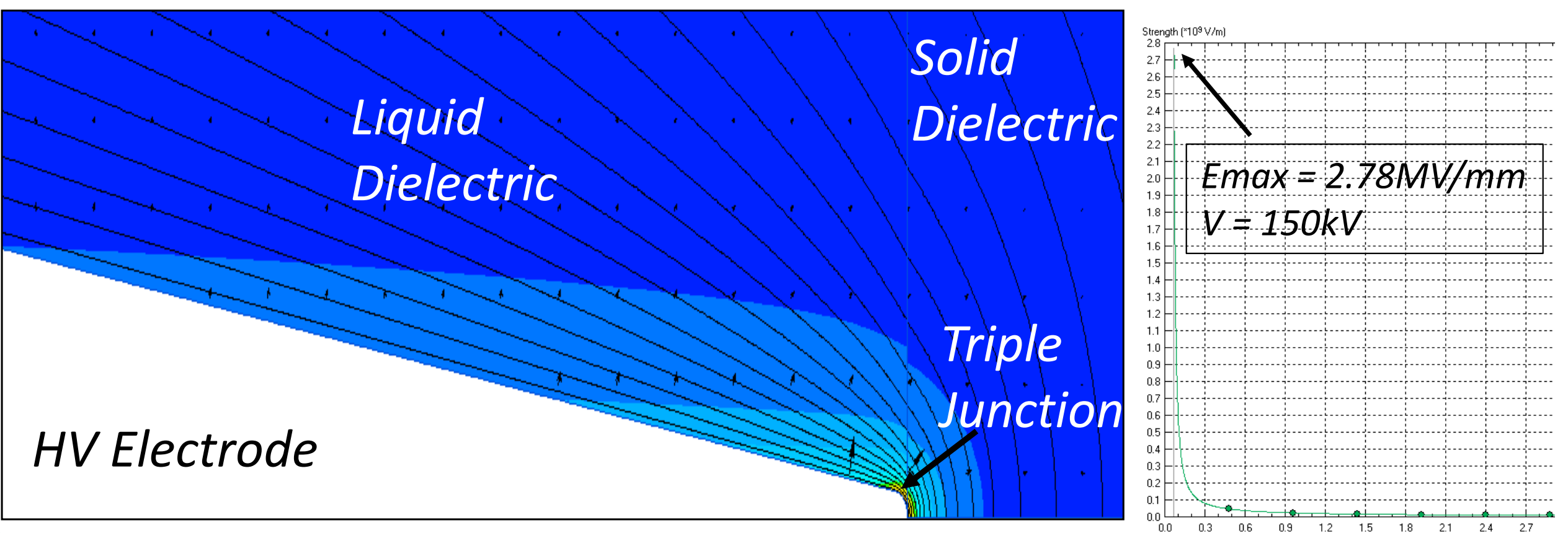
- Dc Voltage source: 100kV Glassman Inc. USA (V_{CH} **= 20kV**)
- Impulse generator: 5-stage air insulated, inverting Marx generator
- Wave-shaping resistor: 14kΩ aqueous copper sulphate tube
- Diagnostic devices:
  - North Star PVM-5 HV probe (80MHz, 1:1000)
  - $CuSO_4$ – water solution resistive voltage divider (1:9.6)
  - Tektronix TDS3054C Oscilloscope (500 MHz)



- Perspex test cell
- ***HV electrode tip radius 25µm***
- ***Ground electrode Ø 40mm***
- ***High Field*** utilisation factor



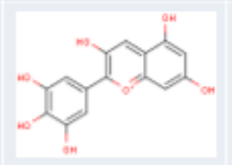
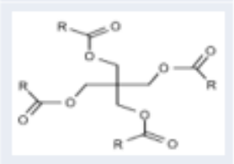
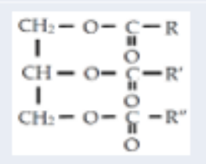
Electrostatic Field Modelling



Emax = 2.78MV/mm
V = 150kV

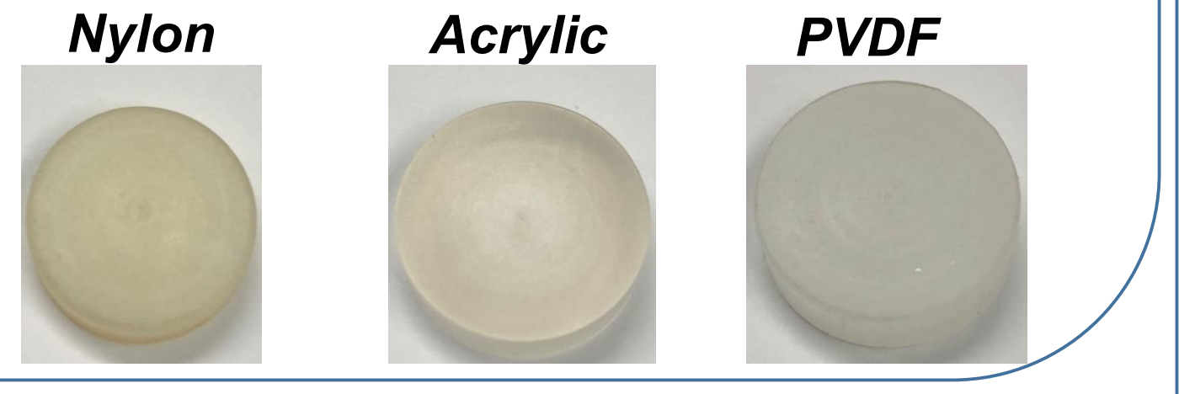
Dielectrics used in experimentation

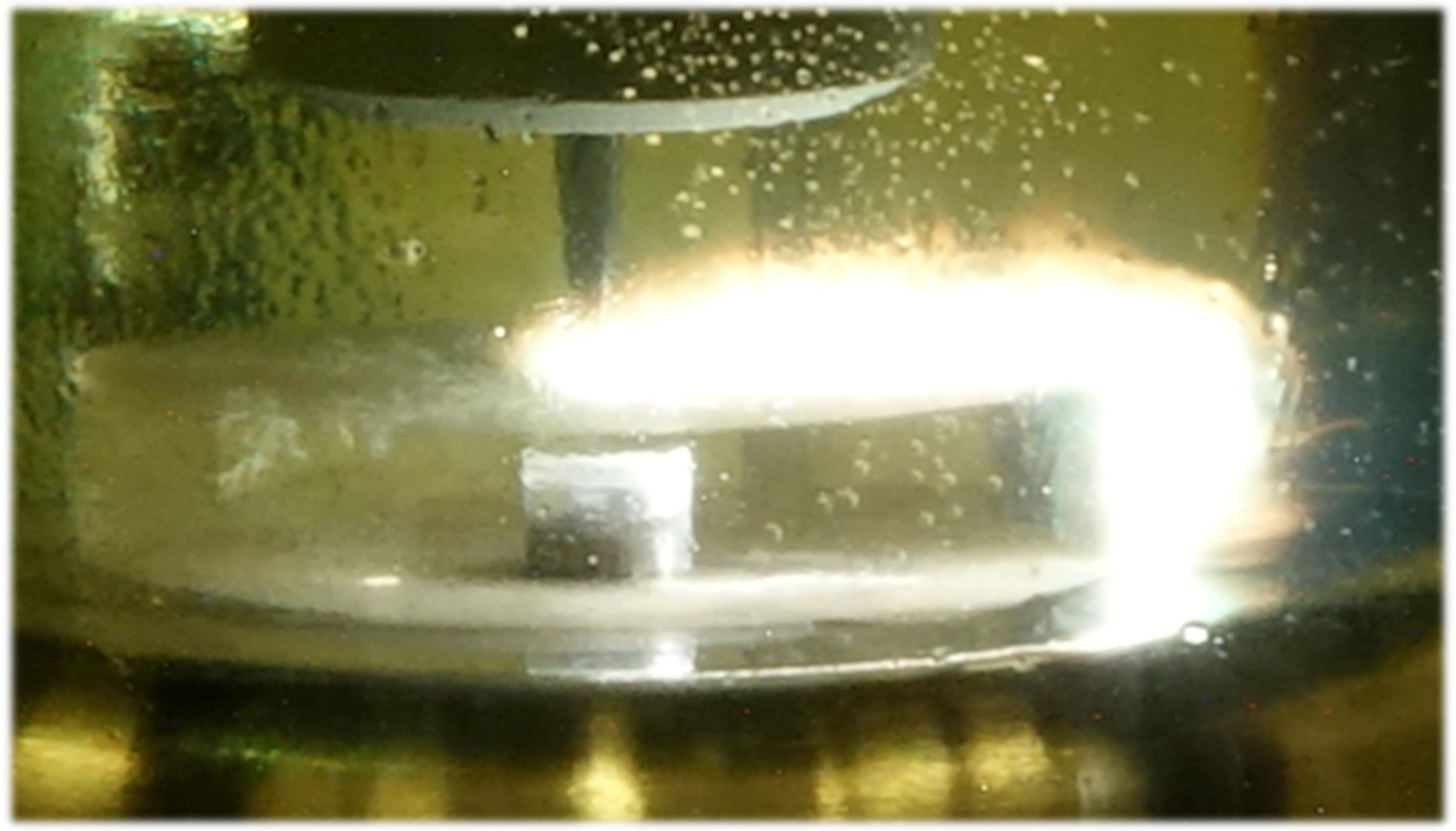
Liquid Dielectrics

	Shell Diala S4 ZX-I	*Midel 7131*	*ENVIROTEMP FR3*
Composition	*Mix of hydrocarbons*	*Pentaerythritol tetra ester*	*Plant based ester*
Chemical structure			
DOB	*Non-biodegradable*	*Highly biodegradable*	*Highly biodegradable*
Oxidation	*Mild susceptibility*	*Non-susceptible*	*Susceptible*
Water Saturation	*70ppm*	*2600ppm*	*1100ppm*
Flash point	*191°C*	*260°C*	*316-330°C*
Permittivity	*2.2*	*3.2*	*3.2*
Dielectric strength	*60kV*	*75kV*	*56kV*

Solid Dielectrics

	Nylon	Acrylic	PVDF
Composition	*Polyamide*	*Polymethylmetacrylate*	*Fluoropolymer*
Density	*1.14g/cm³*	*1.19g/cm³*	*1.78g/cm³*
Dielectric strength	*27kV/mm*	*27kV/mm*	*27kV/mm*
Dielectric constant	*3.8*	*3.5*	*7.4*
Surface resistivity	*>10¹³Ω*	*>10¹³Ω*	*>10¹³Ω*

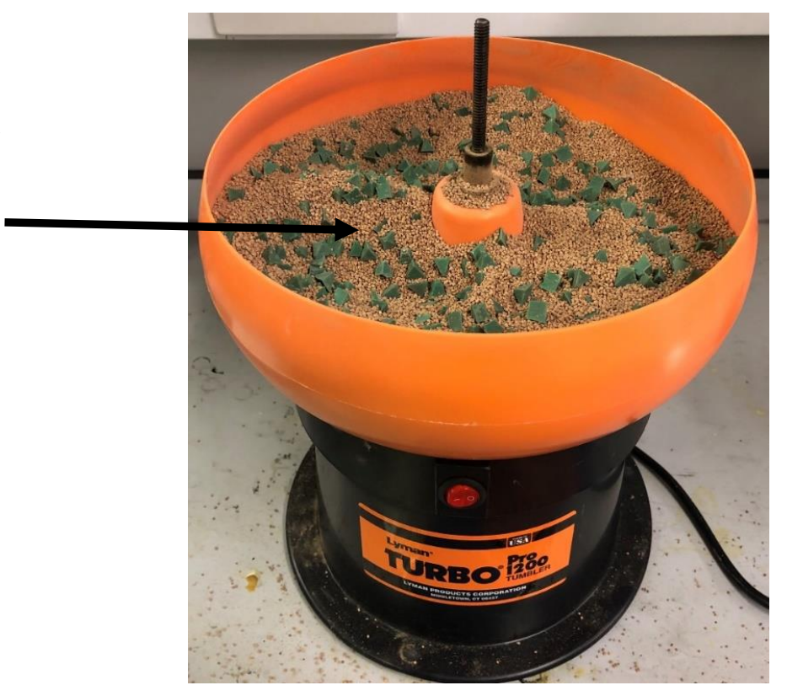




Sample Preparation

- The decision was taken to use puck shaped samples of the chosen solid dielectrics, this would help mitigate any field enhancement which may arise from a sample of square geometry
- Sample thickness of 6mm was selected as this presented the best compromise between ensuring suitable bulk dielectric strength and ultimate propagation distance for any streamers across the liquid-solid interface to reach ground
- Due to the process utilised to produce the samples a number of visible rings were present on the surface of the solid dielectric
- To mitigate any influence these asperities may have on measured breakdown voltage samples were treated using a vibrating tumbler for ~24hrs

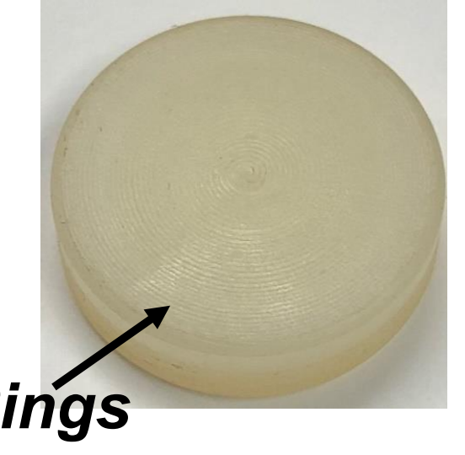
Samples placed inside tumbler



Polishing medium

Walnut

Pyramids



Sample before treatment

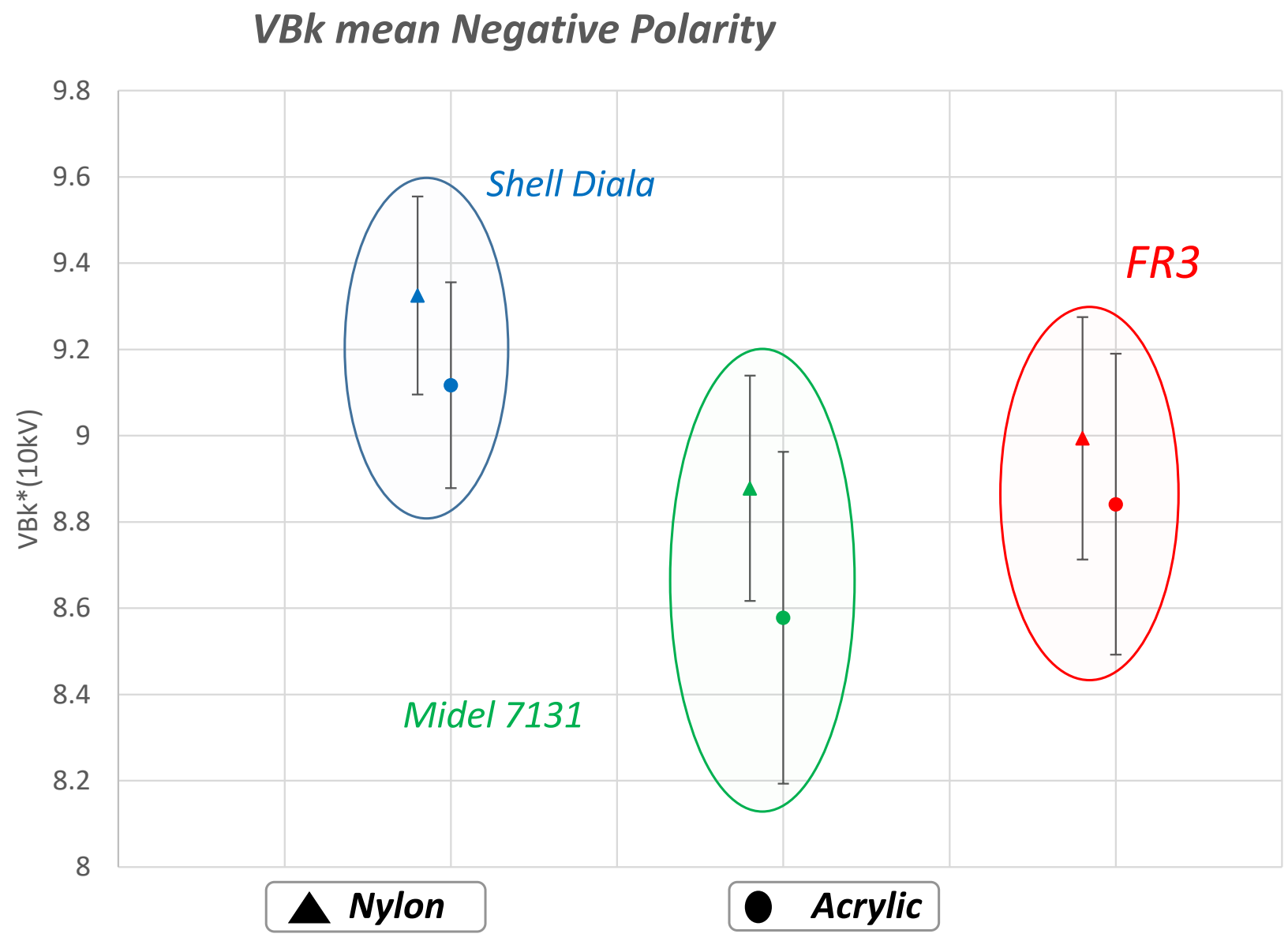
Sample after treatment

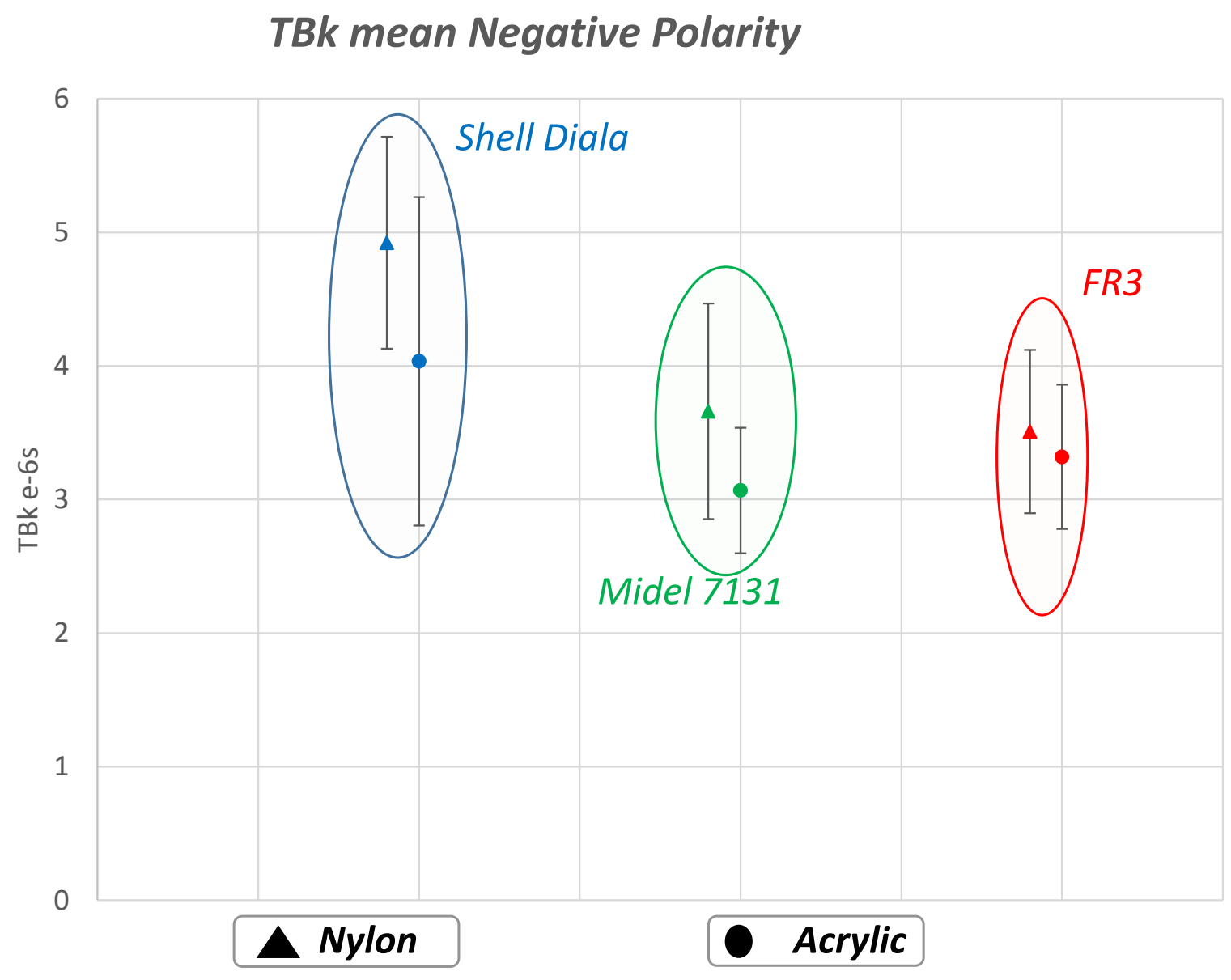
Experimental Results

Upon commencement of the initial breakdown tests for a liquid-solid interface formed with PVDF as the solid insulating medium one particular issue quickly became apparent, samples were experiencing bulk breakdown rather than the desired surface flashover. As such experimental results for PVDF will not be discussed at this stage. A similar phenomenon was observed during testing of the nylon samples, however, unlike the PVDF this bulk breakdown of the sample did not occur periodically.

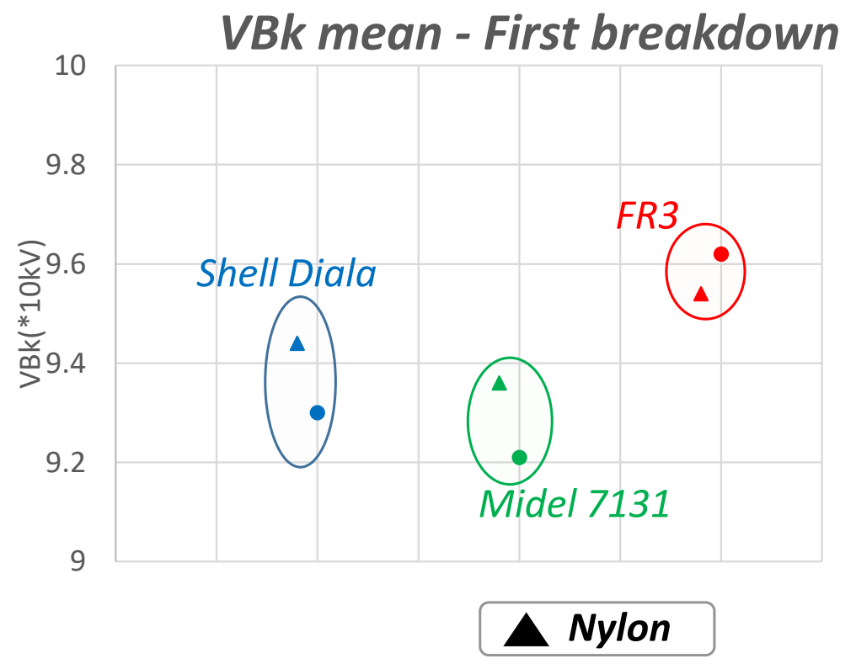
Damage caused to PVDF samples

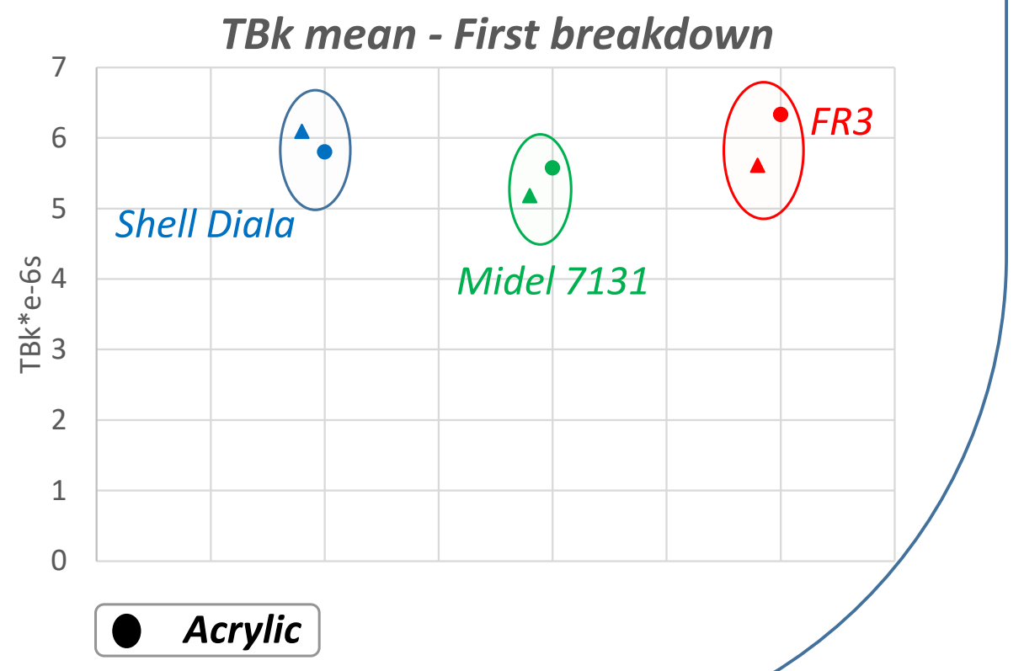
Damage caused to Nylon samples





	VBK (kV)		***TBK (µs)***	
Liquid	***Nylon***	***Acrylic***	***Nylon***	***Acrylic***
Shell Diala	***93.3***	***91.2***	***4.92***	***4.03***
Midel 7131	***88.8***	***85.8***	***3.66***	***3.07***
FR3	***89.9***	***88.4***	***3.51***	***3.32***





Conclusions

- There is no statistically significant difference in the dielectric strength of the composite insulating systems
- In all cases the Nylon dielectric exhibits the highest VBk and TBk with mineral oil outperforming the ester fluids
- PVDF testing has proved problematic as samples have experienced bulk breakdown, as such, further investigation is required
- Bulk breakdown was also observed in the nylon samples however due the sporadic nature of these events it is hypothesised that this is due to breakdown of micro bubbles present within the insulating system
- When examining the first breakdown events Nylon again displays the highest VBk. Although in natural ester is seen to perform best based on this data
- TBK for the initial breakdown is much longer than subsequent event, attributed to the development of conductive tracks form as the streamer propagates over the material

Further work

- Identify the cause for bulk breakdown of the PVDF with the aim to derive a means of mitigation
- Substantiate the hypothesis around the cause of nylon bulk breakdown
- Apply the same testing regime to PVDF samples
- Investigate how these liquid-solid insulating systems perform when the liquid medium is at varying levels of moisture saturation
- Determine what effect impulse polarity has on the dielectric performance of the composite insulating system
- Evaluate how different $\frac{dv}{dt}$ values can influence the breakdown characteristics of the liquid-solid insulating system