# ELECTRICAL TREEING IN SILICONE RUBBER

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**Abstract**: Electrical treeing has been widely studied in a range of polymeric materials. In these investigations, the morphology and PD patterns associated with the growth of electrical trees in a model transparent silicone rubber were investigated using a new system recently developed at Southampton. With increasing voltage the trees became more complex in appearance but nevertheless grow more rapidly. As the tree evolves the PD pattern becomes more intense which may provide a method of monitoring the extent of treeing in opaque samples. Raman studies indicate that treeing and breakdown channels are hollow, carbonaceous entities, a finding consistent with other studies.

## 1 INTRODUCTION

Electrical treeing has been widely reported in many polymeric materials such as polyethylene [1], polypropylene [2], synthetic resin bonded paper [3], epoxies [4-6], unfilled silicone rubber [7] and cross-linked polyethylene (XLPE) [8]. Electrical trees form through localised electrical discharge events which cause localised erosion of the material, leading to a fractal like network of channels within the dielectric [1-2, 8] and eventual breakdown of the insulation. A needle-plane geometry is used in laboratory tests to localise tree growth [1-8], a process which is accompanied by partial discharge (PD) activity [3-6]. In unfilled silicone rubber, electrical trees are white in colour, non-conducting and propagate rapidly [7] whereas in polypropylene, polyethylene and XLPE, the trees are often black in colour, electrically conducting and propagate relatively slowly [1-2, 8, 9]. In epoxy resins both types of tree have been reported depending on the temperature [4-6]; this distinction has led to the widely used terminology “non-conducting” or “conducting” tree respectively [1, 8, 9]. Furthermore it has been reported that the morphology of an electrical tree depends on the applied voltage, with rather simple filamentary structures giving way to complex bush shaped objects at higher voltages [4, 7, 9].

In these initial investigations on silicone based systems, a transparent, unfilled silicone resin was selected. This has the advantages of optical clarity, and enabled electrical trees to be grown over sensible timescales using reasonable voltage levels [7]. To do the experimental work, a new apparatus was constructed incorporating an optical microscope with real time video recording, a PD free high voltage power supply and a PD monitoring system. We have considered the effects of applied voltage on tree growth and have measured both the morphology and PD patterns as the tree evolves. The kinetics of tree growth from initiation to eventual failure was followed.

## 2 EXPERIMENTAL

### 2.1 Materials and sample preparation

A commercial silicone resin kit (Sylgard 184) was obtained from Farnell and was used as supplied. The resin/hardener was mixed in the recommended 10:1 ratio, degassed at room temperature under dynamic vacuum and then cast into a 6 mm deep polished mould. After further degassing, the mould was transferred into a fan oven maintained at 100 $^{o}$C for a period of 30 minutes to cure the resin. Samples approx. 10 x 10 mm were cut from the prepared sheets which were then mounted into a Perspex test cell incorporating an earth plate and a needle holder. The sample was placed firmly against the earth plate and a fresh hypodermic needle (Becton Dickenson Microlance 19, 38 mm length) was inserted into the opposite side. The gap between the needle and earth plate was then adjusted to 2 mm (± 0.5 mm) [7] with the aid of an optical microscope, taking care not to introduce voids.

### 2.2 Treeing apparatus

The apparatus (Figure 1) is based around a Prior Scientific Zoom 65 optical microscope which was equipped with a GXCAM-1.3 digital camera (GT Vision). The PD measurement system was comprised of a wideband LCR probe constructed in accordance with IEC60270:2000 [4, 10] (resonance 200 kHz, coupling capacitor 33 pF) along with a 1:1000 resistive divider reference probe. Both probes were connected to a Picoscope 4224 PC oscilloscope for data collection using a 1 MHz sampling rate. Prior to use the system was calibrated with a Robinson PD calibrator and a calibrated high voltage meter. The test cell was placed into a small plastic oil bath containing silicone fluid (Dow Corning 20/200 CS) which was then backlit for observation. The whole apparatus was enclosed in an interlocked metal box to ensure electrical safety and to guard against any external electrical noise.

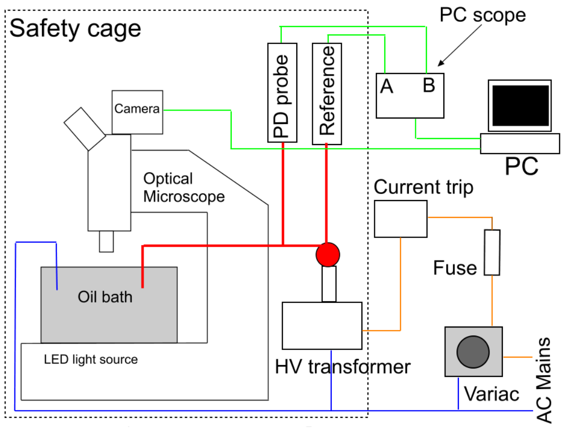


**Figure 1:** Schematic of the treeing apparatus.

## 3 RESULTS

### 3.1 Morphology and applied voltage

A number of electrical trees were grown at voltages between 8 and 18 kV rms and some examples are shown here. At low voltages (8-10 kV) single or doubly branched trees are formed

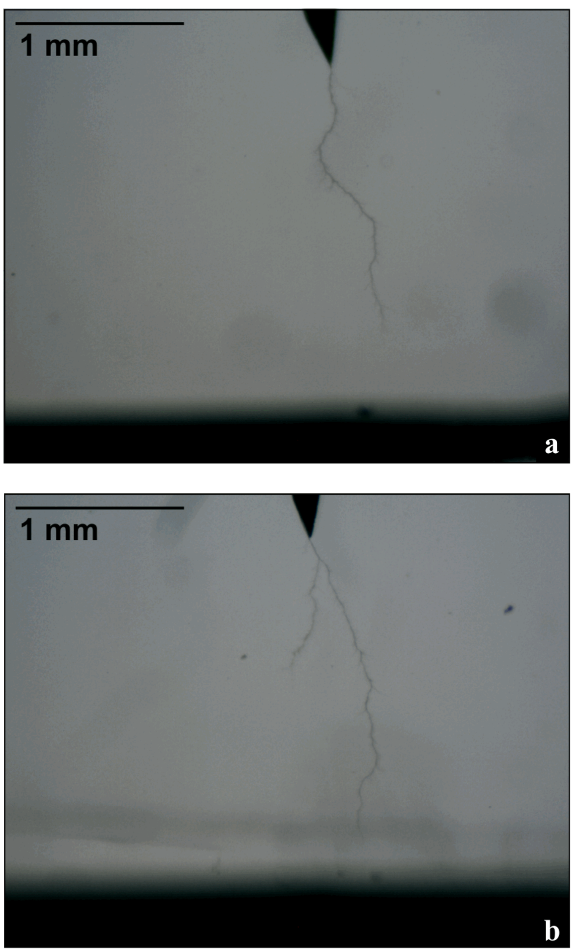


**Figure 2:** Morphologies of trees grown at (a) 8 kV, (b) 10 kV. Earth plate bottom, needle at top.

(Figure 2), whilst at intermediate voltages (Figure 3a), more complex multiply branched structures are formed. At the highest voltages, complex structures with multiple sub-branches are formed (Figures 3b, 3c). The progression from simple to complex objects with increasing voltage has been reported elsewhere [4, 7, 9].

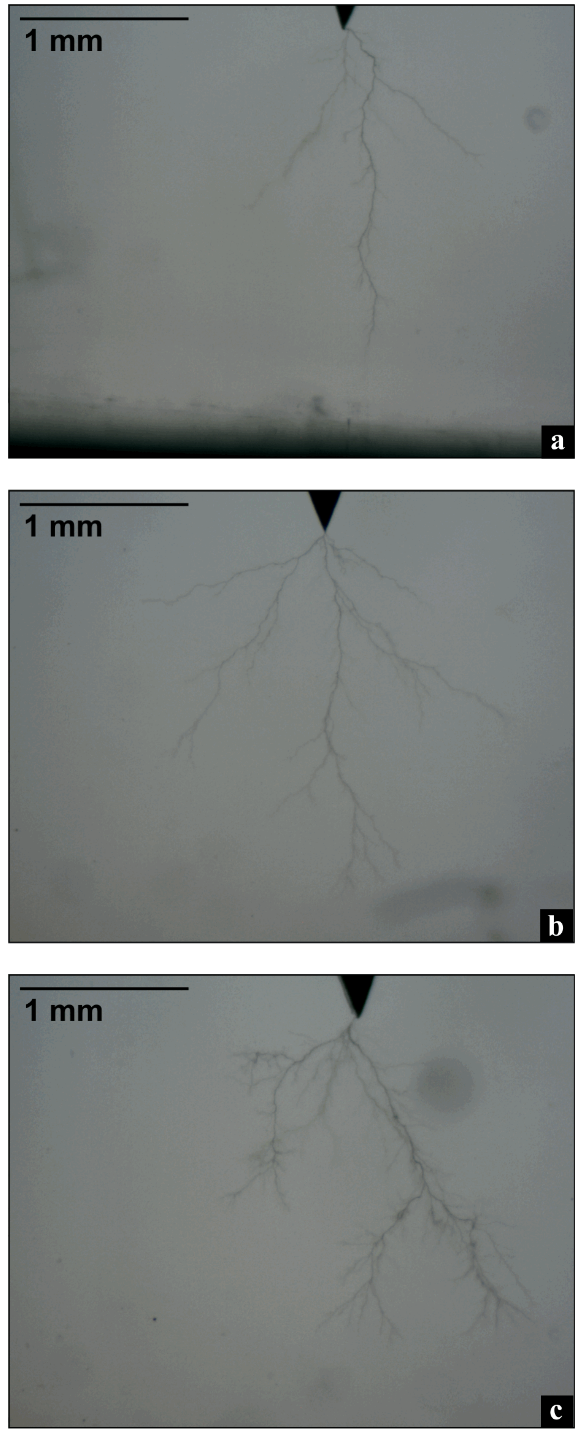


**Figure 3:** Morphologies of trees grown at (a) 12 kV, (b) 16 kV, (c) 18 kV. Earth plate bottom, needle at top.

### 3.2 Growth dynamics

After an initiation period, which can range from several seconds to several tens of minutes, where no structure is formed and no PD activity was recorded, the structure grows rapidly through the dielectric [9] before it becomes necessary to turn off the power to avoid a breakdown. Growth is rapid in the seconds following initiation (Figure 4a),

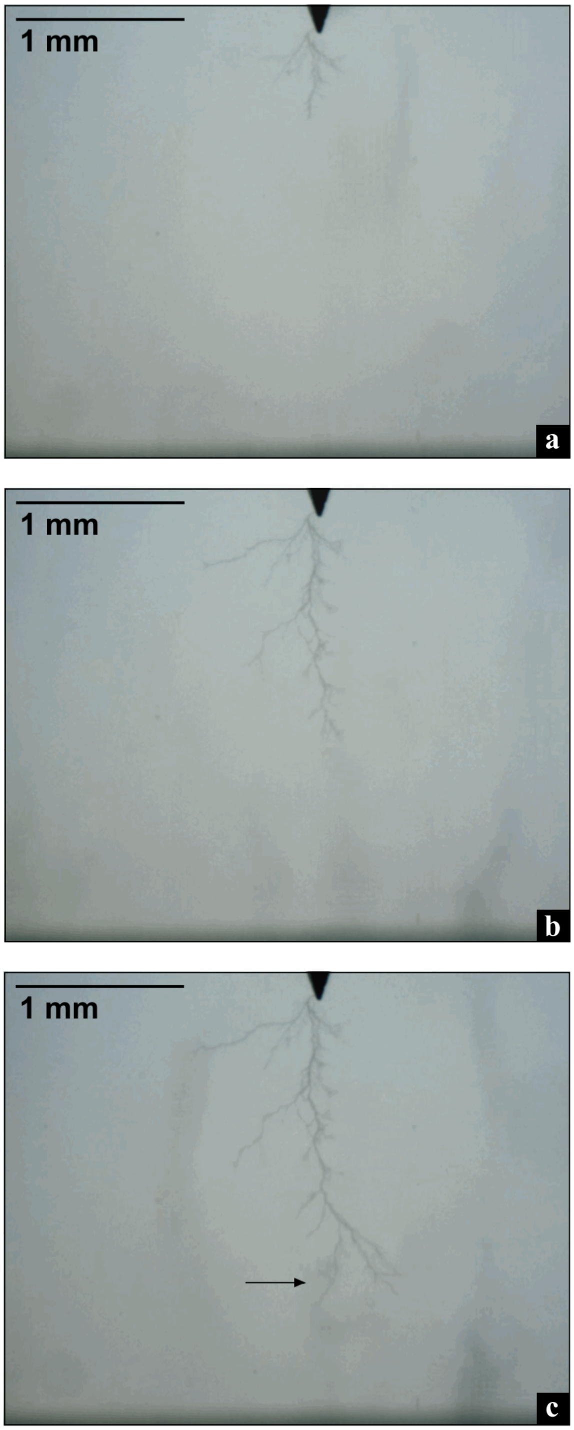


**Figure 4:** Progressive growth steps of a tree grown at 14 kV, (a) 3 s after initiation, (b) 10 s, (c) 20 s.

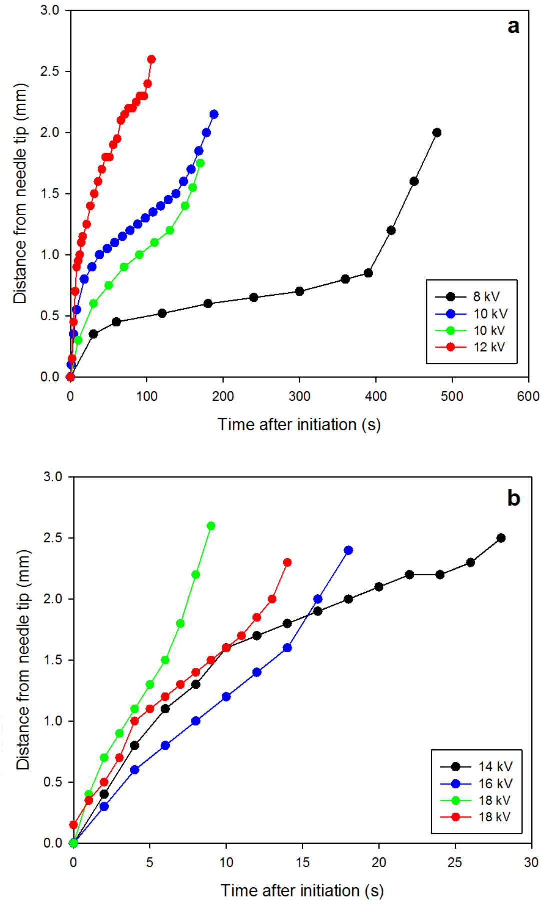


**Figure 5:** Growth rate plots for a typical selection of trees grown at (a) 8 – 12 kV, (b) 14 – 18 kV.

after which a period of slower growth ensues (Figure 4b) until finally a “leader” (Figure 4c, arrowed) rapidly approaches the earth electrode requiring the power to be shut off to avoid a breakdown which would otherwise destroy the tree. It is interesting that the structure is tree-like even at the earliest stages of growth (Figure 4a).

Figure 5 shows some representative growth rate plots, the length shown is that measured from to the furthest tree tip to the end of the needle (hence some measurements are > 2 mm when the tree grows at an oblique angle to the earth plate). Whilst over 20 structures were grown for these investigations, many which showed similar characteristics have been removed here for clarity whilst preserving some data to illustrate the variability between trees grown at the same voltage level. It was observed that in most cases, tree growth is most rapid in the moments just after initiation and also at the final stages of growth when a “leader” approaches the earth electrode. Despite the inherent variability between trees grown at the same voltage, there is a general trend that trees grow faster at higher voltages despite their increasing complexity.

### 3.3 Partial discharge patterns

*3.2.1 Effects of voltage* Over the 20 or so trees considered, it was observed that the intensity of the associated PD activity increased with applied voltage. Figure 6 shows a selection of phase resolved PD patterns obtained over a 5 second sampling window near the midpoint of tree growth, each dot representing a single PD event. The PD activity is centred in the 1st and 3rd quadrants, that is, where the AC voltage is rising to its maximum positive or negative value respectively [3-6, 8]. Trees grown at 8 kV (Figure 5a) are accompanied by "low level" PD activity (<200 pC) with relatively few "high level" (>1000 pC) discharge events occurring during the sampling period. These high level discharges predominantly occur during the negative going half cycle (i.e. quadrant 3). Increased voltage then results in an increase in both the low level activity and the high level discharge events, some of which clearly overwhelm the detector (> 5 nC, Figure 5c).

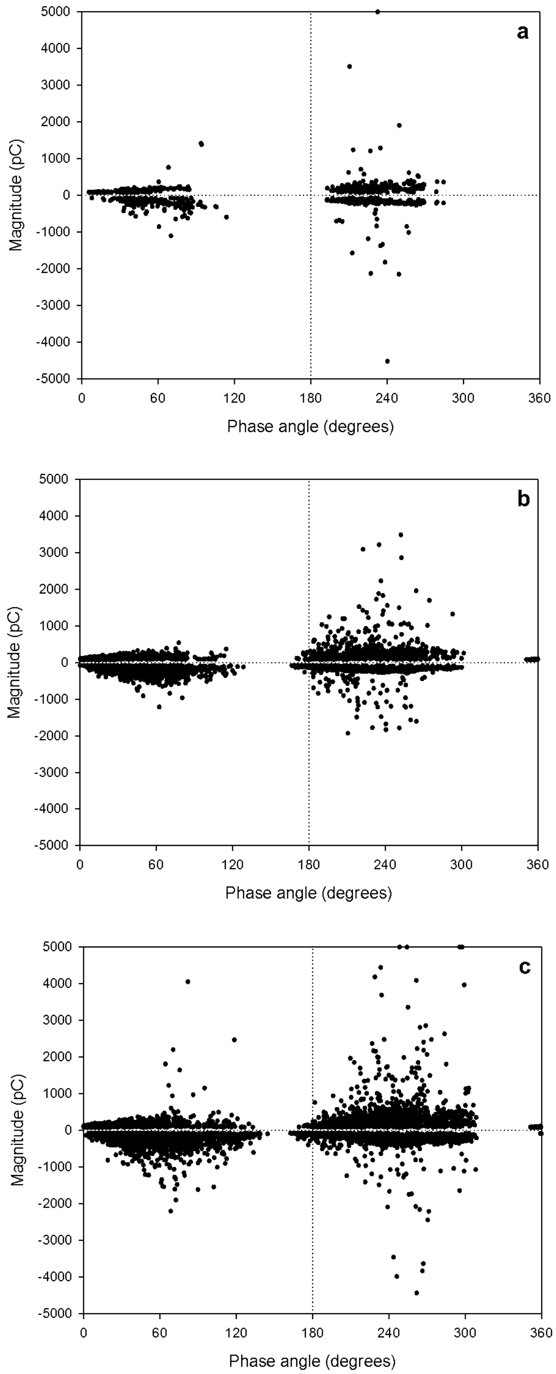


**Figure 6:** Phase resolved PD patterns collected over 5 s intervals for trees grown at (a) 8 kV, (b) 14 kV, (c) 18 kV.

*3.2.2 Time dependence* Above, we have deliberately chosen PD patterns obtained near the midpoint of tree growth, this was because it was also noted that the intensity and frequency of PD events increased as the tree structure became larger and more complex. A typical example of this behaviour is shown in Figures 7 and 8 for a tree grown at 12 kV (see Figure 3a for morphology). Initially (Figure 7a) only a few low level discharges (< 200 pC) per AC cycle occur, these then intensify to a level of ~400 pC at a rate of 3-5 per AC cycle (Figure 8a). Finally many more high level discharges (>1000 pC) occur as the tree approaches the earth electrode (Figure 8b). It is

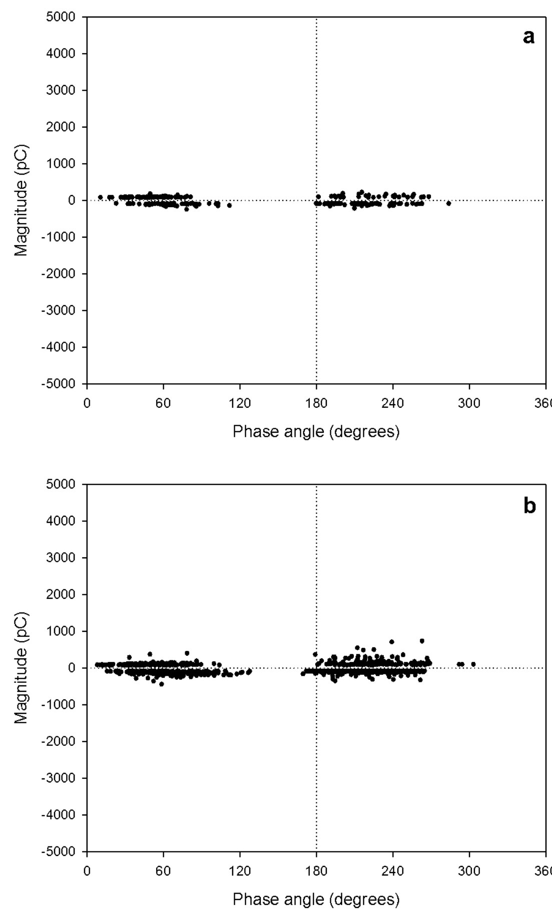


**Figure 7:** Phase resolved PD patterns collected over 5 s intervals for a tree grown at 12 kV (a) 5 s after initiation, (b) 10 s after initiation.

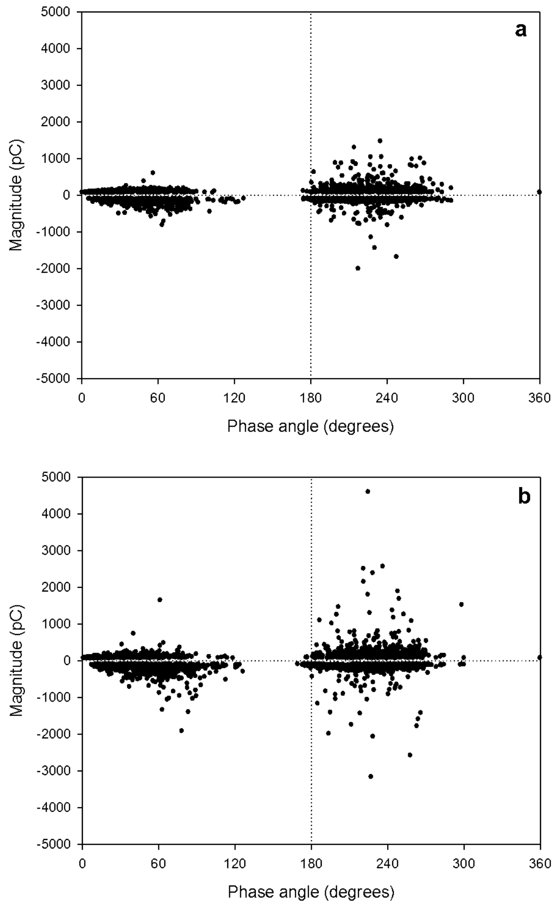


**Figure 8:** Phase resolved PD patterns collected over 5 s intervals for a tree grown at 12 kV (a) 20 s after initiation, (b) 30 s after initiation.

clear from these patterns that they are related to the extent of tree growth; the high level activity in particular is associated with the later stages of tree growth and it may be possible to use this type of activity to diagnose items of plant for the presence of damaging electrical trees.

### 3.4 Analysis of tree structure

Two samples were taken for further analysis. Sample 1 had undergone treeing and breakdown at 18 kV, whereas sample 2 had undergone treeing at 14 kV without breakdown. Both samples were cut open to reveal breakdown and tree channels respectively, using a RMC ultra-cryomicrotome operated at -100 $^{o}$C. They were then examined in a Renishaw Ramascope 1000 operated in non-confocal mode with an excitation wavelength of 785 nm provided by a 25 mW diode laser. Scans taken at various points near the breakdown channel in sample 1 are numbered in Figure 9. Well away from the breakdown channel (area 5), the Raman spectrum shows characteristic peaks associated with silicones. Visibly darker areas of the breakdown channel (area 3) show the D and G bands (arrowed) of graphitic carbon [1]

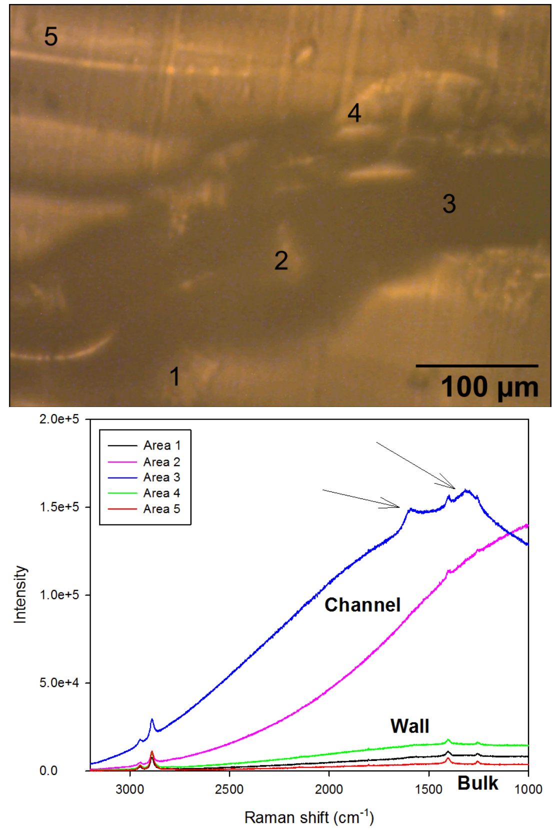


**Figure 9:** Photograph and Raman of sample 1.

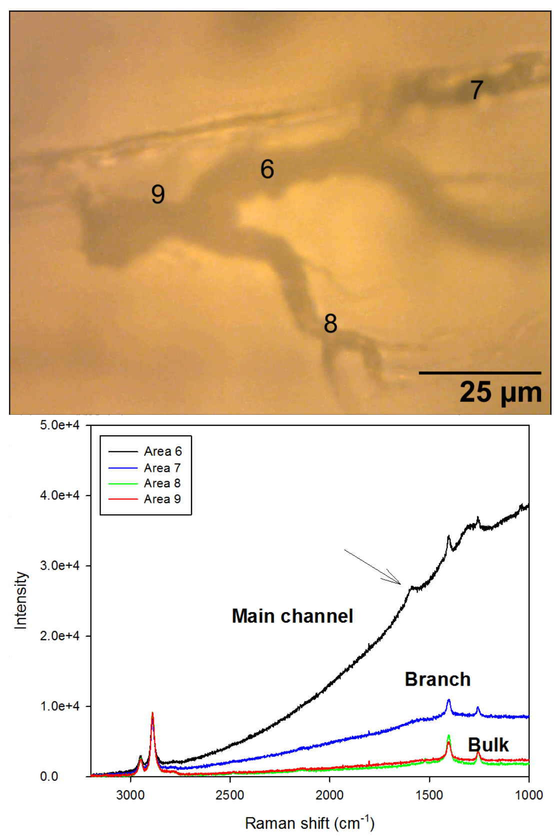


**Figure 10:** Photograph and Raman of sample 2.

whereas, in lighter areas (area 2), the dominant feature is the rising fluorescent background. The behaviour of sample 2 (Figure 10) is comparable; within the tree channel (area 6) the associated spectra shows evidence of graphitic carbon (arrowed) whereas near the tree tips (areas 7 and 8) they show signs of silicone and some fluorescence. It is clear that both the tree and breakdown channels are hollow entities with carbonaceous walls and that the associated degradation is a localised phenomenon. These findings are in agreement with Raman studies of electrical trees in polyethylene [1] despite the very different material used here.

## 4 CONCLUSIONS

A new piece of apparatus was constructed at Southampton University for the study of electrical treeing in solid and liquid samples. In this paper we have evaluated its performance and capabilities using a transparent silicone rubber and have studied the evolution of electrical trees as a function of both voltage and time. The use of voltages between 8 and 18 kV with a needle-plane geometry resulted in electrical trees being formed over reasonable timescales.

With increasing voltage, the trees became more complex, ranging from single channels at 8 kV to complex, multiply branched structures at 18 kV. Despite this increased complexity, the trees form more quickly at higher voltages with growth rates being highest in the moments following initiation and in the final stages of growth, where a leader is observed to rapidly approach the earth electrode.

The intensity and frequency of the associated PD activity increases with voltage and as the tree matures. This could provide a useful diagnostic tool in opaque samples where electrical trees cannot be imaged optically or in items of high voltage plant.

The tree channels were shown to be hollow, carbonised structures in agreement with our previous studies of treeing in polyethylene. Future work will consider the effects of inclusions and voids on the growth of electrical trees in silicone rubber.

## 5 ACKNOWLEDGMENTS

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