Effects of additives on prebreakdown processes in liquid cyclohexane. Part 1: streamer initiation

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Abstract. Conduction currents and streamer initiation in cyclohexane with various additives have been studied with fast impulses applied to a point plane gap. The additives were perfluoro-n-hexane, N,N-dimethylaniline, 1-methylnaphthalene, di-n-propylether, 1,1-difluorocyclopentane, trans-azobenzene and 1,4-benzoquinone. We have used shadowgraphic imaging and a differential charge-measurement technique with a sensitivity of 0.1 pC to integrate currents induced to the point electrode, below and in the same voltage range where streamers first appeared. Initiation voltages often varied between samples for both point polarities, but with low correlation to a specific additive type and concentration. We observed transient conduction currents of measurable magnitudes in the nano to micro ampere range for voltages around initiation in all samples with a point anode and in 10 out of 23 samples with a point cathode. Systematic variations with the concentrations of the additives were not found, however, for a point anode the more easily ionizable additives N,N-dimethylaniline and 1-methylnaphthalene induced notably larger currents. The results support a hypothesis where electron avalanches vaporize the liquid and initiate streamers in both point polarities. Transient currents may be induced by ions left behind by the avalanches that are not sufficiently developed to initiate streamers.
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1. Introduction
Since air was one of the first insulators used, electrical breakdown in air has been studied extensively, and the breakdown processes in gases is well understood.\textsuperscript{1,2} Today both liquids and solids are used as insulating materials for electrotechnical applications,\textsuperscript{3,4} but less is known about processes leading to breakdown in the condensed phases despite a significant amount of experimental data.\textsuperscript{5}

The type of liquids used in transformers are mainly mineral oils which have been processed to certain standards.\textsuperscript{6} Usually these oils contain paraffinic, naphthenic, aromatic and polyaromatic fractions. Different additives like oxidation inhibitors, pour-point depressants and metal passivators are added to improve particular characteristics.\textsuperscript{3} There is now an increasing tendency to use liquids with better properties in respect of biodegradability, flammability and with lower polyaromatic content.\textsuperscript{3} Presently, insulating properties of liquids are tested in somewhat rough, standardized tests (e.g. IEC) with limited interpretations.\textsuperscript{7}

For liquids, the general picture is that a breakdown is completed through the initiation and propagation of a “streamer”. This is a gas / plasma filled channel which initiates in a region with high electric fields and propagates through the liquid until it bridges the electrode gap and results in a breakdown. The streamer contains molecules of vaporized liquid and liquid decomposition products, both ionized and excited, and quasifree electrons. One often distinguishes between initiation where phenomena like space charge effects play a role, and propagation where conduction effects may dominate; resembling what in gas discharge terminology is called a “leader”.\textsuperscript{8} The events preceding the actual breakdown are called “prebreakdown processes” and have been studied during the last four decades, accompanied by steadily improved measuring techniques.\textsuperscript{5,9}
Prebreakdown processes are usually studied in point-to-plane electrode geometries where high electric fields are easily obtained and effects from voltage polarity can be investigated. It has been reported significant influences from experimental conditions, such as electrode arrangement (gap length and point radius of curvature),\textsuperscript{10-12} applied voltage (shape, magnitude, and polarity),\textsuperscript{13,14} chemical nature of the liquid,\textsuperscript{5} and pressure.\textsuperscript{13,15-17} From an experimental point of view, the study of breakdown processes in condensed phases is favorable in liquids for three main reasons. The optical transparency of many liquids allows for visual observations. Secondly, the liquids can relatively easily be in contact with metallic electrodes of various shapes, and finally, experimental studies of chemical additives are much simpler in a liquid than in a solid.

By applying models originally developed for discharges in gases, considerable progress in the understanding of liquid prebreakdown processes has been achieved.\textsuperscript{18,19} However, the high-field processes taking place at streamer initiation and propagation are still not fully understood and knowledge about basic parameters lacks for most hydrocarbon liquids (e.g. mean free path of electrons and photons, quantum mechanical cross-sections for the processes impact ionization and excitation). The streamer process is complex and involves mechanisms of electronic, ionic, optical, thermal, mechanical, and hydrodynamic nature.\textsuperscript{8,15,20-26} Interactions between energetic electrons and atoms / molecules in the liquid or in the vapor determines the transfer of electrostatic energy and to a large extent the propagation behavior of the streamer. In brief, the electronic high-field process may be divided into two parts; 1) the release of electrons from the electrodes and from the bulk of the material, and 2) the acceleration of electrons by the electric field and the interactions/collisions with liquid molecules. Depending on the electronic properties of the molecules, such as ionization potential and electron affinity, they may act as sources of electrons in the first stage and later during the impacts interact with energetic electrons, resulting in electron capture or multiplication. The ability of a liquid to resist a streamer depends on its ability to prevent a local formation of electrons. Therefore, the molecular
composition of a liquid is important for its performance as an electrically insulating material.

Our study aims at revealing the role of liquid electrochemical properties on liquid prebreakdown processes in a pure and non-polar liquid, and to investigate effects of electronically active components of varying concentrations. The study is done with impulse voltages well below breakdown, activating only the first stages of streamer propagation. In this paper we present measurements on preinception conduction currents and initiation voltages for streamers in cyclohexane with additives of different properties and concentrations. Cyclohexane was chosen as the base liquid since it is a simple and well documented alkane frequently used in prebreakdown and breakdown studies, while it constitutes a simple model liquid for insulating oils. Cyclohexane is also a good solvent for different additives. The study may help to design new synthetic liquids and also to foresee possible unwanted consequences from changes of the composition of conventional liquids due to e.g. environmental restrictions.

2. Experiment

2.1. Instrumentation

The experiment is designed to study the streamer by using a shadowographic depiction technique, and by measuring the electric charge induced on the point electrode before any streamer initiation occurs.

A square high-voltage impulse is applied to the plane electrode of a 10±0.5 mm point-to-plane gap. An in-house made impulse generator supplies high-voltage pulses with variable pulse widths, and with rise and fall times of 15 to 20 ns. Impulse voltages with a steep front are necessary to avoid influence from space charges on the streamers initiation process. The high-voltage pulses are measured by integrating the current from a capacitive probe, using a passive integrator. Injected charge is measured with a 0.1 pC sensitive differential charge-measurement technique. The imaging system consists of a high intensity white LED, an auto-collimator, a lens system, and a single shot intensified CCD camera of type Proxitronic.
NCA Nanocam® with 5 ns minimum shutter time. A xenon flash-lamp replaced the LED in the later experiments. The best obtainable image resolution is 0.7 μm. The experiment is automated and controlled via LabView computer software. Point electrodes have been made by electrochemically etching28 a 100 μm wolfram wire into near-hyperbolically shaped points with point radii in the range 1.3-1.6 μm. The experimental apparatus and conditions used in this study are similar to that used by Dumitrescu et al.,13 Gournay et al.11 and Yamashita et al.10 We used an IRLAB LDTRP low voltage, low frequency conductance-meter to measure the conductivities of the liquids. A 1.5 litre Teflon® (PTFE) test cell, see figure 1, was filled with argon gas prior to sample-filling and placed in an optical bench as shown in figure 2.

The magnitude of the high-voltage pulses was varied in steps of 1 kV, and 30-100 pulse-shots were taken at each voltage level, depending on streamer appearance probability. A minimum 3-minute delay between each shot was used. All experiments were conducted at room temperature and ambient pressure. We used one point electrode per additive, and the tip radius was verified before and after each experiment.

2.2. Liquids
The cyclohexane used in this study is of type Merck LiChrosolv® with a purity of 99.9%. The additives are perfluoro-n-hexane (>99%), N,N-dimethylaniline (>99%), 1-methylnaphthalene (>97%), di-n-propylether (99%), 1,1-difluorocyclopentane, trans-azobenzene (99%), and 1,4-benzoquinone (99.5%). Cyclohexane was first dried with 3 Å Zeochem molecularsieve, degassed in a vacuum reservoir at 70 mbar using an extraction volume ten times the liquid volume, and then mixed with the additive under argon atmosphere over night. The samples were prepared with additive concentrations of 0, 0.1, 1.0, 10 and 50 mg g⁻¹, except for the last three additives where only the three middle concentrations were used. In addition to the samples with dried and degassed cyclohexane, also cyclohexane directly from the bottle without additional purification was studied. Drying of cyclohexane reduced the moisture content from 19 to 1-3 μg g⁻¹. The gas content has not been measured, but has to be well below the saturation of oxygen gas,
carbondioxide, and nitrogen gas in cyclohexane, being 0.47, 3.90, and 0.25 mg g\(^{-1}\), respectively.\(^{29}\) In addition to the above mentioned additives, distilled water was added at concentrations of 10 and 70 ppm to degassed cyclohexane, 70 ppm being about room-temperature saturation.\(^{30}\)

The seven additives represent different electrochemical properties. In particular, N,N-dimethylaniline has a low ionization potential, perfluoro-n-hexane has a large electron-trapping cross-section, and 1-methylnaphthalene possesses both properties. The high molecular density and electronegativity of perfluoro-n-hexane makes it an effective electron scavenger. The partly fluorinated 1,1-difluorocyclopentane was added to investigate additional effects of molecular asymmetry. The lone pair electrons located at the nitrogen atom makes N,N-dimethylaniline easily ionizable, also the molecules containing benzene rings having low ionization potentials due to non-localized \(\pi\)-electrons. Cyclohexane, perfluoro-n-hexane, trans-azobenzene and benzoquinone are non-polar in their equilibrium geometries, the remaining have a non-zero dipole moment.

2.3. Measurements
Electrical measurements of prebreakdown events are based on the time resolved storage of charge on a capacitor connected to the point electrode. As shown in figure 1, a rounded electrode is placed beside the point electrode in a differential arrangement in order to compensate for the charging of the electrode system from displacement currents when the high-voltage pulse is applied. The measured charge is then the charge induced by the prebreakdown event, and it represents an underestimate of the charge in the gap.\(^{31,32}\) A time-derivation of the charge gives an average current, and we present average currents prior to streamer initiation with values averaged over a time period of 20 \(\mu\)s. The minimum detectable current is 10 nA with this setup. A sudden increase in the charge readings corresponds to the initiation of a streamer. In parallel with optical measurements this allows us to calculate probability distributions for the initiation voltages of streamers. Probabilities are calculated by counting the number of streamer events at each voltage level, where the voltage corresponding to 50% probability is traditionally called the “initiation voltage”.\(^{14}\)

3. Results
3.1. Streamer initiation probabilities
Probability distributions for streamer initiation are shown for some samples in figure 3 to figure 12. For most additives there is a weak or no correlation between additive concentration and initiation voltage. However for 1-methylnaphthalene, initiation voltages increases with increasing concentrations. With the large number of experiments around streamer initiation, the binomial distribution for the number of streamers produced at each voltage level can be approximated by a continuous normal distribution, and standard deviations below 5% are found for average streamer initiation probabilities about 50%. With a point anode, streamer initiation probabilities increase from 0% to 100% initiation over a voltage interval of around 4 kV. With a point cathode this voltage range is smaller (1-2 kV). Initiation voltages can be read directly from the probability plots and corresponding axial electric field values at the apex of the point electrode can be calculated by using a hyperbolical approximation for sharp points. The estimated error in the calculated electric field value is 11% based on the error of measurement of the tip radius and the gap length. Calculations for the case with no additive give 14 MV cm\(^{-1}\) for point anode streamers, and 10 to 13 MV cm\(^{-1}\) for point cathode streamers. A comparable value, 13 MV cm\(^{-1}\), has been obtained by Yamashita et al., whereas a lower value, 8 MV cm\(^{-1}\), has been obtained by Lesaint et al., for the same tip radius. Similarly, initiation voltages found here for a point cathode is somewhat higher than previously reported, 8 MV cm\(^{-1}\).

3.2. Conduction currents prior to streamer initiation
For voltages around the onset level for streamers, in absence of streamers, a seemingly continuous current to the point electrode has been measured, see figure 13. The currents sometimes increase the first couple of microseconds after voltage application, and always decrease slowly on a larger timescale as shown in figure 14. In many cases, depending on the discrete voltage levels, it is observed that these currents gradually become of a measurable magnitude. The currents are observed in all samples with a point anode, while with a point cathode only unsystematically in 10 out of 23 samples. Average conduction currents are calculated from the slope of charge versus time, and presented in graphical plots with mean values and standard deviations for some of the additives in figure 15 to
figure 20. The continuous lines are either polynomially fitted to all data or interpolated between a number of averaged values, and they serve as trend-lines to ease the readability of the plots. A minimum of 15 measurements were used in the calculation of each averaged value and standard deviation. Effects of additives were only observed for a point anode for the additives N,N-dimethylaniline and 1-methylnaphthalene as shown in figure 17 and figure 18. Here we measured notably larger currents, increasing with increasing concentration up to the micro-ampere range. However, the currents concentration dependencies vary over the voltage range. For negative point polarity, conduction currents are more often observed in pure cyclohexane when great care is taken to remove and avoid dissolved water and atmospheric gases. There is a reversal of this effect when the same sample is saturated with distilled water or left in open air (not shown). The current-voltage characteristics vary from liquid to liquid, but there generally a quasi-linear increase with voltage. The current magnitudes are not correlated to the low-field conductivities of the liquids, which were seen to vary due to the additives. Normally, nothing is observed optically during conduction currents except for some rare cases with voltages just below 100% streamer initiation. However, in a few cases we accidentally captured a diffuse shadow of a 15-20 μm diameter bubble at a distance from the point electrode. Rare bubbles were observed for all additives (but not for all concentrations) with a point anode, while even more rarely and only with the additive 1,1-difluorocyclopentane with a point cathode.

4. Discussion
We have shown that electric fields necessary to initiate streamers in cyclohexane are in line with what under similar conditions are reported by other authors. Due to a strong local dependence on uncertain parameters such as electrode curvature and surface roughness, it will be difficult to agree on an initiation field with high precision. In addition to unique field conditions introduced for each electrode, there can also be an influence from erosion on the electrode and from particles in the liquid.
According to our hypothesis, electron avalanches are involved in streamer initiation and during propagation also at the tips of the streamers filament. In this context, electronic molecular properties will be important. We will first treat our hypothesis and also consider alternative explanations.

For a point cathode in cyclohexane, streamer initiation is experimentally well documented from dc and impulse conditions and attributed to electron avalanches in the liquid phase. Each avalanche current pulse, being independent of pressure, induces a shock wave and also a single vapor bubble near the point cathode if the hydrostatic pressure is below the critical pressure of the liquid. For positive point polarity it is less clear. According to an experimental study by Lesaint et al. in various non-polar hydrocarbon liquids, the initiation voltage for point anode streamers did not depend on liquid chemistry, but only on electrode gap parameters. Similarly for most of our experiments, we find that changes in initiation voltages from increasing additive concentrations are relatively small compared to changes from replacing the point electrode between additive series. The conduction currents observed here for both point polarities where by Dumitrescu et al. only observed with a point anode. The currents are observed below and in the same voltage range where the streamers first appear, suggesting that they are related to the same process. According to our hypothesis, electron avalanches are responsible for both these currents and for the initiation of streamers. We first assume the availability of a starting electron. It can be produced by mechanisms such as ionization in the liquid (point anode) or field emission at the electrode (point cathode). In an electron avalanche, ionic space-charge concentrates by a rapid (nanosecond) process of multiple collisional ionizations between electrons and liquid molecules. The process requires that the electric field is high enough to allow the free electrons to acquire sufficient energy over their mean free paths. In divergent field conditions, the volume over which this may occur increases with the applied voltage.
During the avalanche, electrostatic energy is effectively converted into thermal energy in very small volumes. If sufficient energy is developed locally to vaporize the liquid, discharges may occur in the vapor cavity and a streamer develops.\textsuperscript{11} In the opposite case, the initiation process halts and we observe a conduction current induced by movement of the remaining space charge. The magnitude of this current reflects the degree of charge separation in the avalanche. Likewise, if a bubble initially formed by the avalanche mechanism does not collapse or initiate a streamer, it moves into the gap in the electrohydrodynamic convection, in line with our observations. Theoretical progress concerning electron avalanches in liquids is required to validate the proposed chain of events leading to formation of bubbles and streamers. A semi-empirical estimate for an avalanche ionization-coefficient in liquid cyclohexane has already been provided by Haidara \textit{et al.} for electric fields above 2 MV cm\textsuperscript{-1},\textsuperscript{38} while specific cross-sectional data for interaction processes such as impact ionization and excitation are needed in order to clarify the high-field energy distribution for electrons in cyclohexane.

Some observed variations for streamer initiation voltages and conduction currents can provide insight into the initiation mechanism. The lower and more defined initiation voltages for streamers from a point cathode suggest that the electron avalanche process responsible for streamer initiation is most effective for this polarity. One element could be that electrons become more abundant due to field enhanced ejection from a point cathode,\textsuperscript{22,39} than for field ionization in the liquid outside a point anode.\textsuperscript{40} At the tip of the point electrode one usually defines a critical volume where the electric field strength will be adequately high over a distance large enough to develop an avalanche above a critical size.\textsuperscript{37} An electron from a point cathode will here be supplied at the location most favorable to start an avalanche, while a suitably placed seeding electron near a point anode is a stochastic event with comparatively low probability. We therefore expect a distribution of
avalanches a distance from the point anode with varying abilities to evaporate the liquid, leaving initiation for this polarity more affected by parameters influencing the evaporation process, e.g. hydrostatic pressure.\textsuperscript{13} Possibly, the conduction currents reflect the low-efficiency tail of the avalanche distribution. The low number of current observations for negative point polarity then either indicates non-measurable currents at the lower voltages, or a more efficient evaporation process. When initiation voltages for point cathode streamers become higher and less defined (when electron reactive components like O\textsubscript{2}, CO\textsubscript{2} and H\textsubscript{2}O are removed), conduction currents are observed more frequently and roughly follow the same current-voltage characteristics as for a point anode. Moreover, conduction currents to a point anode increase notably with the low ionization potential additives 1-methylnaphthalene and N,N-dimethylaniline despite the stochastic nature of these currents, and serves to strengthen the theory of a liquid electron avalanche mechanism. However, the concentration dependence varies over the voltage range and interpretations are not straightforward. In this context, the experiments with perfluoro-n-hexane additive was extreme; we observed large currents with a point cathode with 50 mg g\textsuperscript{-1} additive concentrations, while not for all the lower concentrations. It may be linked to the 100-fold increase in liquid conductivity for this sample compared to a sample with no additive.

Considering a stationary liquid, it is possible to predict the ionic drift using an analytical representation of the electric field between a point and a plane electrode in prolate-spheroid geometry,\textsuperscript{33} and then evaluate the transient current induced by a concentration of ions. In our case, the ions will drift only some micrometers into the gap during the duration of the applied pulse, and charges induced to the point electrode will be limited to values below the measured ones by up to three orders of magnitudes, due to space-charge saturation.\textsuperscript{41} It is however possible that charge-
induced electrohydrodynamic convection in the high-field zone accelerates ions to such an extent to induce such high currents, provided that a sufficiently strong convection develops on a microsecond time-scale.\textsuperscript{42} In order to evaluate the experimental current-voltage characteristics one must first solve the problem of electrohydrodynamic convection in divergent field conditions, since approximate derivations valid for negligible fluid motion only can not be used.\textsuperscript{42}

Amongst the alternatively proposed mechanisms for streamer initiation, Dumitrescu \textit{et al.} suggest a boiling mechanism where the observed conduction currents induce a local heating if emitted from a micro region on the point anode,\textsuperscript{13} whereas Lewis suggests that the primary steps of any streamer initiation may be an electromechanical and highly field-dependent formation of sub-microscopic cavities.\textsuperscript{43} It has also been pointed out that pressure reduction induced by both the electrohydrodynamic motion\textsuperscript{21} and coulomb repulsion between local homocharges,\textsuperscript{44} can be responsible for, or at least assist the formation of a gas phase.

\textbf{5. Conclusion}

With the different additives, streamer initiation voltages in cyclohexane usually vary statistically significantly between samples for both point polarities, but a clear dependence on additive type and concentration is not found. Initiation voltages in cyclohexane are about 9 kV for a point cathode and about 11 kV for a point anode. We also measure conduction currents in the nano to micro ampere range prior to streamer initiation in all samples with a point anode and in 10 out of 23 samples with a point cathode. The current magnitudes are often non-reproducible and increase quasi-linearly with the applied voltage. A systematic variation with additive concentrations has not been found. However, the low ionization potential additives N,N-dimethylaniline and 1-methylnaphthalene give notably larger currents to a point anode. The results support a hypothesis that streamer initiation in both point
polarities are induced by electron avalanches in the liquid. Conduction currents are considered to be ionic and to reflect the inefficiency of less developed electron avalanches to induce a streamer. Differences between positive and negative point polarity are qualitatively explained by the stochastic event of having a seeding electron available and suitable positioned in the high-field zone.
6. References

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[37] Kim M and Hebner R E 2006 *IEEE Transactions on Dielectrics and Electrical Insulation* **13** 1254-60
Figure 1. The cylindrical PFTE-test cell showing the point-to-plane geometry with a rounded probe next to the sharp electrode for displacement current compensation during the charging of the plane electrode. Point electrodes are shielded and effectively grounded while high-voltage is applied to the plane electrode via a micrometer screw for gap-size adjustments.

Figure 2. General outline of the experimental setup, 1) computer, 2) Proxitronic control unit, 3) Proxitronic Nanocam NCA, 4) Stanford Research Systems inc, model DG535 four channel digital delay/pulse generator, 5) pulse circuit for LED, 6) white LED / Xenon flash-lamp 7) 6 kV thyatron 5C22 trigger unit, 8) Spellman SL150 DC high-voltage (0-100 kV) supplier, 9) high-voltage pulse battery, 10) BNC capacitive probe, 11) Sigmond 60 ms passive integrator, 12) PFTE test cell, 13) capacitive voltage divider arms, 14) Lecroy 100 MHz differential amplifier DA1850, 15) Tektronix TDS 540A digitizing oscilloscope.
Figure 3. Initiation probability for point anode streamers in cyclohexane with additive *perfluoro-n-hexane*. Symbols: (▼) dried/degassed, (▲) from bottle, (◄) 0.1 mg g⁻¹, (►) 1.0 mg g⁻¹, (■) 10 mg g⁻¹, (●) 50 mg g⁻¹.

Figure 4. Initiation probability for point cathode streamers in cyclohexane with additive *perfluoro-n-hexane*. Symbols: (▼) dried/degassed, (▲) from bottle, (◄) 0.1 mg g⁻¹, (►) 1.0 mg g⁻¹, (■) 10 mg g⁻¹, (●) 50 mg g⁻¹.
Figure 5. Initiation probability for point anode streamers in cyclohexane with additive \textit{N,N}-dimethylaniline. Symbols: (▼) 0.01 mg g$^{-1}$, (◄) 0.1 mg g$^{-1}$, (►) 1.0 mg g$^{-1}$, (■) 10 mg g$^{-1}$, (●) 50 mg g$^{-1}$.

Figure 6. Initiation probability for point cathode streamers in cyclohexane with additive \textit{N,N}-dimethylaniline. Symbols: (▼) 0.01 mg g$^{-1}$, (◄) 0.1 mg g$^{-1}$, (►) 1.0 mg g$^{-1}$, (■) 10 mg g$^{-1}$. 
Figure 7. Initiation probability for point anode streamers in cyclohexane with additive 1-methylnaphthalene. Symbols: (▼) 0.1 mg g⁻¹, (▲) 1.0 mg g⁻¹, (■) 10 mg g⁻¹, (●) 50 mg g⁻¹.

Figure 8. Initiation probability for point cathode streamers in cyclohexane with additive 1-methylnaphthalene. Symbols: (▼) 0.1 mg g⁻¹, (▲) 1.0 mg g⁻¹, (■) 10 mg g⁻¹, (●) 50 mg g⁻¹.
Figure 9. Initiation probability for point anode streamers in cyclohexane with additive di-n-propylether. Symbols: (►) 1.0 mg g⁻¹, (■) 10 mg g⁻¹, (●) 50 mg g⁻¹.

Figure 10. Initiation probability for point cathode streamers in cyclohexane with additive di-n-propylether. Symbols: (►) 1.0 mg g⁻¹, (■) 10 mg g⁻¹, (●) 50 mg g⁻¹.
Figure 11. Initiation probability for point anode streamers in cyclohexane with additive 1,1-difluorocyclopentane. Symbols: (►) 1.0 mg g⁻¹, (■) 10 mg g⁻¹, (●) 50 mg g⁻¹.

Figure 12. Initiation probability for point cathode streamers in cyclohexane with additive 1,1-difluorocyclopentane. Symbols: (►) 1.0 mg g⁻¹, (■) 10 mg g⁻¹, (●) 50 mg g⁻¹.
Figure 13. Oscilloscope capture of charge on a capacitor induced by a conduction current (ch. 2: 1 pC/div). The impulse voltage (ch. 4: 2 kV/div), and the camera synchronization pulse (ch 1) are also shown. Horizontal timescale is 1 μs per division.

Figure 14. Charge on a capacitor induced by conduction current of various magnitudes. A constant high-voltage is applied. Calculation of average conduction currents are based on the first 20 microseconds of integration.
Figure 15. Mean conduction currents to a point anode in cyclohexane with additive perfluoro-n-hexane. Symbols: (▽) dried/degassed, (▵) from bottle, (<) 0.1 mg \text{ g}^{-1}, (▼) 1.0 mg \text{ g}^{-1}, (□) 10 mg \text{ g}^{-1}, (○) 50 mg \text{ g}^{-1}.

Figure 16. Mean conduction currents to a point cathode in cyclohexane with additive perfluoro-n-hexane. Symbols: (▽) dried/degassed, (○) 50 mg \text{ g}^{-1}.
Figure 17. Mean conduction currents to a point anode in cyclohexane with additive *N,N*-dimethylaniline. Symbols: (●) 0.1 mg g⁻¹, (▷) 1.0 mg g⁻¹, (□) 10 mg g⁻¹, (○) 50 mg g⁻¹. A dashed reference line for the case with no additive is included.

Figure 18. Mean conduction currents to a point anode in cyclohexane with additive 1-methylnaphthalene. Symbols: (●) 0.1 mg g⁻¹, (▷) 1.0 mg g⁻¹, (□) 10 mg g⁻¹, (○) 50 mg g⁻¹. A dashed reference line for the case with no additive is included.
Figure 19. Mean conduction currents to a point anode in cyclohexane with additive di-n-propylether. Symbols: (∗) 0.1 mg g⁻¹, (∗∗) 1.0 mg g⁻¹, (□) 10 mg g⁻¹. A dashed reference line for the case with no additive is included.

Figure 20. Mean conduction currents to a point anode in cyclohexane with additive 1,1-difluorocyclopentane. Symbols: (∗) 0.1 mg g⁻¹, (∗∗) 1.0 mg g⁻¹, (□) 10 mg g⁻¹. A dashed reference line for the case with no additive is included.