Mechanisms Responsible For Electrostatic Discharges Associated With Liquid Filtration

Part 2: Electron Transport Model

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A student charged to 100,000 volts by a Van de Graff generator.
Even simple processes such as walking on carpets can develop high voltages. These voltages are developed by relatively tiny amounts of electric charge and maintained by very high electrical resistance between object and ground. Note that high RH reduces voltages by up to 2 orders of magnitude. At high RH water vapor condenses to a thin conductive coating (several molecules thick), allowing charges to bleed to ground.

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**Examples of Typical Static Generated Voltages**

<table>
<thead>
<tr>
<th>GENERATION METHOD</th>
<th>10-25% RH</th>
<th>65-90% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking On Carpet</td>
<td>35,000 V</td>
<td>1,500 V</td>
</tr>
<tr>
<td>Walking On Vinyl Tiles</td>
<td>12,000 V</td>
<td>250 V</td>
</tr>
<tr>
<td>Worker At Bench</td>
<td>6,000 V</td>
<td>100 V</td>
</tr>
<tr>
<td>Picking Up Polyethylene Bag From Bench Top</td>
<td>20,000 V</td>
<td>1,200 V</td>
</tr>
<tr>
<td>Chair With Urethane Foam Pad</td>
<td>18,000 V</td>
<td>1,500 V</td>
</tr>
</tbody>
</table>
TOPICS

1. OBJECTIVES OF ELECTROSTATIC & FILTRATION PROGRAM
2. ELECTROSTATIC TERMS & FUN FACTS
3. ELECTRONS TRANSPORT MODEL OF FILTER ELECTROSTATICS
4. CONCLUSIONS
5. NEXT STEPS
6. Q & A
ELECTROSTATICS & FILTRATION PROGRAM
OBJECTIVES

1. Identify The Mechanisms For Filter Charging In Hydrocarbon Liquids.

2. Model Filter Charging In Hydrocarbon Liquids.

3. Recommendations & Guidelines For Primary Stakeholders
   A) Filter OEM’s
   B) System Designers
   C) End Users
ELECTROSTATICS TERMS & FUN FACTS

DEFINITION OF ELECTROSTATICS

1. Moving Charges Create And Are Affected By Magnetic Fields

2. When Magnetic Forces Are Significant: Electrodynamics

3. When Magnetic Forces Are Negligible: Electrostatics
   (Charges may move, but not enough to create significant magnetic fields.)
These are the fundamental equations of electricity. Because magnetic field $\mathbf{B} \sim 0$, equations are considerably simplified.
Electrical forces are many orders of magnitude greater than gravitation force. Tiny imbalances between positive charges (protons) and negative charges (electrons) on the order of $10^{-20}$ create chemistry, life, and ESD.
ELECTROSTATICS & FILTERS

1. Always Continuous Current Between Filter and Ground!!
2. Always Continuous Current Between Downstream Fluid and Ground!!
3. Yet Negligible Electrochemical Reactions Products!!
4. Electrostatic Charging of Filter Increases With:
   1. Increasing Fluid Flow Velocity (F)
   2. Decreasing Oil Electrical Conductivity
   3. Decreasing Filter Media Electrical Conductivity
   4. Decreasing Oil Temperature
5. Electrostatic Charging of Oil Increases With:
   1. Increasing Fluid Flow Velocity (F)
   2. Decreasing Oil Conductivity
   3. Increasing Oil Temperature
6. When Charging of Filter Excessive ➔ ESD Within Filter Media & Between Media & Grounded Conductors
7. Prolonged ESD Produces Surprising Little Damage To Filter!!
8. No ESD When Oil Conductivity ≥ 1000 pS/m
Contact Charging of Metals

Electrons flow from metal with higher Fermi level to metal with lower Fermi level. Analogous to water flowing downhill from vessel with higher surface to vessel with lower surface.
When solid insulators rub, triboelectrons are released. Lewis acids are electron pair acceptors and become negatively charged. Lewis bases are electron pair donors and become positively charged.
Distance between fibers ~1-25 um. Flow of hydrocarbon liquids through these channels leads to Reynolds Numbers ≤ 1. Flow is laminar.
Laminar flow within filter media leads to stationary boundary layers surrounding fibers. No rubbing of one insulator against another. Nevertheless there is charge separation at the solid:liquid interface.
The surface of glass charges positive. These positive charges attract negative counter-ions, forming the Double Layer. A portion of the negative counter-ions are immediately adjacent to positive charges on the glass. The remainder of the negative counter-ions form a Diffuse Layer in the vicinity of the interface.
Double Layer Model Of Solid: Liquid Interface

\[ V = V_0 e^{-\lambda x} \]

\[ \lambda = \text{Debye Length} \]

\[ \lambda = (K/ \varepsilon \varepsilon_0 D)^{1/2} \]

D is the diffusion constant
K is oil conductivity,
\( \varepsilon \) is dielectric constant of the oil.

For low conductivity liquids, 1-1000 pS/m, the diffuse layer extends from 2-80 um.
When flow=0, there is an equilibrium between positive charges on the glass and negative charges on the fluid side of the interface.
Fluid flow through the filter disrupts the equilibrium. Some negative charges are swept downstream, leaving the upstream portion of the filter media with a net positive charge.
Schematic for measuring current to the upstream side of the filter media, and current from the downstream fluid.
When flow starts through a filter a transient current from the downstream fluid may be expected. However, instead of a transient current, a continuous current of electrons is detected flowing out of the downstream fluid. Continuous electron current is also detected flowing into the filter media. Continuous currents require a closed circuit. Note: Only a portion of the downstream fluid current (red dots) was collected by the probe. The remainder of the current discharged against system metallic piping.
ELECTROSTATICS & FILTERS

1. **Always** Continuous Current Between Filter and Ground!!

2. **Always** Continuous Current Between Downstream Fluid and Ground!!
The Electron Transport Model proposes that a portion of the current flowing into the filter media is due to mobile electrons in glass fibers.
Electrical conductivity for different glasses varies by 7 orders of magnitude. Some is due to proton migration. Some due to mobile electrons.
Glass is an insulator with high band gap energy between valence and conduction bands. However in very high electric fields (200 MV/m), sufficient electrons are promoted from the top of the valence band up to the conduction band to make glass a conductor – this is dielectric breakdown of glass. At the somewhat lower electric fields found in filter media (~20 MV/m), sufficient numbers of electrons are promoted to the conduction band to make glass a ‘quasi-semiconductor’.
This slide outlines the Model. Glass acts a Lewis Base. Electron pairs are donated from the glass surface to organic compounds in the liquid lubricant. Fluid flow moves these temporary ions downstream in the Liquid Current. This leaves upstream layers of glass fiber filter media positively charged, while an excess of negative charges accumulates in the downstream layers of media. Some of the ions carried by the liquid deposit their electrons onto downstream layers of filter media. Other ions are carried through the filter and discharge electrons on grounded system metal piping. Electrons are resupplied to the upstream layers of media by two mechanisms: 1) Mobile carriers in the glass, induced by high electric fields, and 2) Negative ions migrating upstream in the boundary layer.
This slide illustrates the situation for filter media supported by upstream and downstream metal meshes, both of which are grounded. Upstream positive charges are mostly neutralized by electrons flowing in from ground. Downstream negative charges are mostly discharged by conduction to ground.
3. Electrostatic Charging of Filter Increases With:
   1. Increasing Fluid Flow Velocity (F)
   2. Decreasing Oil Electrical Conductivity
   3. Decreasing Filter Media Electrical Conductivity
   4. Decreasing Oil Temperature

4. Electrostatic Charging of Oil Increases With:
   1. Increasing Fluid Flow Velocity (F)
   2. Decreasing Oil Conductivity
   3. Increasing Oil Temperature
Flat Sheet Charging Apparatus

- Kevlar Housing
- Non-Metal Filter Media
- Perforated Gold Plated Steel Disc

$I_L$ and $I_F$
Electron current to the upstream surface of glass filter media increases with flow velocity. Note most of the current is produced by only 1 layer of media.
In this graph the yellow and green lines contain glass fibers. The glass acts as a Lewis Base. By donating electrons to the lubricant the glass charges positively and electron current flows from ground to the positive layers of glass media. In contrast, the red line is for a PVC-based fiber media. PVC is a Lewis Acid, and therefore an electron acceptor. The PVC media charges negatively, and electron current flows from the negative media to ground.
Increasing flow velocity → increasing number of ions in the diffuse double layer swept downstream. Result: higher voltages and electric fields.
For media with grounded metal mesh supports, current flow into the upstream layers of filter media, and away from the downstream layers of filter media. These currents prevent excessive charge build-up and ESD in filters with metal mesh supports.
ELECTROSTATICS & FILTERS

6. When Charging of Filter Excessive → ESD Within Filter Media & Between Media & Grounded Conductors
Metal-free filter elements (a.k.a. non-metal filters) do not have upstream and downstream metal mesh supports. Only minimal contact with ground through a central steel core. This makes it much more difficult to resupply electrons lost from upstream layers, and similarly more difficult to pass electrons gained by downstream layers back to ground.
Lacking an upstream electron current from ground, and with minimal downstream current to ground, metal-free (non-metal) filter elements are much more prone to excessive charge build-up and ESD, compared to metal mesh supported filter elements.
Although the actual unit for electric field is newton/coulomb, a commonly used derivative unit is volt/meter. When electric field exceeds the dielectric strength of a non-conductor, the material breakdowns, and an electric arc occurs within the material. Hydrocarbon lubricants and hydraulic fluids have dielectric strengths between 10-45 MV/m. Note the dielectric strength of glass of 200 MV/m.
ESD When Electric Field Exceeds Dielectric Strength

\[ \bar{E} = \frac{V}{d} \]

Arcing Between A and B
When Reach Breakdown Voltage \( V_B \)
\[ \frac{V_B}{d} = \bar{E}_B \geq \text{Dielectric Strength} \]

**Typical Lubricant Breakdown Voltage**

\[ V_B = \bar{E}_B \times d \]
\[ V_B = (20 \times 10^6 \text{ V/m}) \times (2 \times 10^{-3} \text{ m}) \]
\[ V_B = 40 \times 10^3 \text{ V/m} \]
6. Prolonged ESD Produces Surprising Little Damage To Filters!!
Flow through a metal-free element was ramped up until arcing occurred, and then ramped back down. A second element was run with the maximum arcing rate of ~90 arcs/minute for 6 hours, for a total of > 320,000 arcs!
After > 320,000 arcs, although damage was observed, most of the media remained intact. The above shows one of the worst sections.
Dielectric constant can be thought of as resistance to electric field. Most liquid lubricants have dielectric constants near 2.2, meaning an external electric field applied to the liquid is reduced by a factor of 2.2 within the liquid. A typical value for glass fibers in filter media is 7.5.

<table>
<thead>
<tr>
<th>SUBSTANCE</th>
<th>DIELECTRIC CONSTANT 25 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>1.0</td>
</tr>
<tr>
<td>TRANSFORMER OIL</td>
<td>2.2</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>45</td>
</tr>
<tr>
<td>50:50 Cyclohexane:Benzene</td>
<td>2.12</td>
</tr>
<tr>
<td>N-Hexane ( (C_{6}H_{14}) )</td>
<td>1.88</td>
</tr>
<tr>
<td>Benzene</td>
<td>2.27</td>
</tr>
<tr>
<td>N-Dodecane ( (C_{12}H_{26}) )</td>
<td>2.02</td>
</tr>
<tr>
<td>Polyester</td>
<td>21.7</td>
</tr>
<tr>
<td>Nylon</td>
<td>3.5</td>
</tr>
<tr>
<td>Glass</td>
<td>4 - 10</td>
</tr>
<tr>
<td>Paper</td>
<td>1.5-4.0</td>
</tr>
<tr>
<td>Water</td>
<td>80</td>
</tr>
</tbody>
</table>
In might be expected that introducing glass (high dielectric strength) into a volume previously filled with lubricant (lower dielectric strength) would increase the voltage needed for dielectric breakdown. Counter-intuitively, the presence of glass concentrates the electric field in the lubricant, reducing by 17% the voltage needed for lubricant breakdown.
Because the electric field is concentrated in the lubricant, and because the dielectric strength of glass is 5-10 times greater than the lubricant, arcs avoid glass fibers and travel in the lubricant. This explains the observed surprisingly minor damage to filter media from ESD. In the above illustration the upper arc is from an upstream positive layer to a downstream negative layer, analogous to atmospheric cloud-to-cloud lightening. The lower arc is from a positive layer to grounded metal, analogous to cloud-to-ground lightening.
7. No ESD When Oil Conductivity $\geq 1000$ pS/m
Higher fluid conductivity preempts ESD by reducing the number of ions swept downstream, and by increasing the concentration of conducting ions in the boundary layer.

\[ V = V_0 e^{-\lambda x} \]

\[ \lambda = \left( \frac{K}{\varepsilon \varepsilon_0 D} \right)^{\frac{1}{2}} \]

\( D \) is the diffusion constant
\( K \) is oil conductivity,
\( \varepsilon \) is dielectric constant of the oil.

For low conductivity liquids (1-1000 pS/m),
the diffuse layer extends from 2-80 um.

- Liquids with conductivities > 1000 pS/m
  1) Diffuse Layer ~100 nm,
     few ions swept downstream.
  2) Increased Boundary Layer current,
     short-circuiting charge accumulation.
Summary & Next Steps

1. A Model for Filter-Related Electrostatics Has Been Developed.

2. The Model Is Based On Transport of Electrons
   1. From Lewis Bases to Lewis Acids.
   2. On Temporary Charge Carriers In The Liquid Lubricant.
   3. Within Filter Media Materials (Especially Glass Fibers).
Next Steps

1. Improve The Model, Including:
   1. Quantify High-Field Electron Conductivity of Relevant Insulators.
   2. Clarify Charge Transfer Processes Across Media-Liquid Interfaces.


3. Write It All Up and Publish in Tribology Transactions.
THANK YOU

QUESTIONS?
COMMENTS?

Please contact Bill Needelman at: bneedelman@filtrationscience.com

Thanks.