Reaching Higher Temperatures with Film Capacitors

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for Oil & Gas

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Two things to remember come question time…
Presentation Outline

• High Temperature Applications (Existing / Trending)
• Oil & Gas Downhole Tools
  • Commonly used capacitors (Ceramics / Wet Tantalum)
  • Film Capacitors Use Today
• Film Dielectric Options
• Advantages of Film Capacitors/ Self-Clearing
• Summary
High Temperature Applications: Current

Industries with extremely harsh environments continue to press for increased reliability & performance

- Oil & Gas Downhole tools
- Defense & Aerospace
- Geothermal energy

Source: Baker Hughes
High Temperature Applications: Trending

• Wide band gap
  • Transition to SiC or GaN
  • Higher voltage & frequencies to facilitate miniaturization
  • Increased current / power generates heat

• More Electric Aircraft
• Pulse power
• Automotive Electrification
Oil & Gas Downhole Tools

Often regarded as a proving ground for new power electronics technology
Power Electronics for Downhole Drilling Tools

**Mudflow**: drives mechanical drilling  
**Hydraulic Mudmotor**: Converts flow into AC  
**Rectifier / DC Link / Inverter**: to drive various actuators for steering, communications, or sampling.
Drilling & Measurement

- 150-200°C
- 50uF – 400uF
- Significant shock & vibration
- Hundreds of hours
Intelligent Completions

- 150-175°C
- 1 – 10uF
- Minimal electrical stress
- 20 years downhole

Source: Airbus
Source: Halliburton
Three game-changing trends

1. A world of resource abundance
2. Profound technological advances
3. Demographic shifts

1. A world of resource abundance is leading to sustained lower oil prices and a focus on cost, efficiency, and speed. Talent is no longer scarce, exploration capability is less of a differentiator, megaprojects are not the only way to grow, and market opportunities may only be economical for the earliest movers in a basin. Meanwhile,

2. Profound technological advances are disrupting old ways of working and enabling step changes in productivity. Jobs, including knowledge work, are being replaced by automation on a large scale, and those that remain require increased human-machine interaction. Data generation continues to grow exponentially, as every physical piece of equipment wants to connect with the cloud. This explosion of data—combined with advanced analytics and machine learning—to harness it—creates opportunities to fundamentally reimagine how and where work gets done.
Commonly Used Capacitors: X7R Ceramics

(~80 share within Oil & Gas Downhole Tools)

Advantages
- High Temperature & Voltage Capability
- High Capacitance per Volume
- Non-Polar
- Cost (increasing with supply constraints)

Disadvantages
- Variable Capacitance in Use (Temp / Voltage dependent)
- Fracturing / Fail Short Failure Mode

Emerging Alternative
- Class I C0Gs are considered over X7R to address In Use Variability, however, smaller Cp per capacitor requires large quantities of units

Commonly Used Capacitors: Wet Tantalum
(~ 10% share within Oil & Gas Downhole Tools)

Advantages
• High Temperature & Voltage Capability
• High Capacitance per Volume

Disadvantages
• Polar
• Variable Capacitance in Use (Temp / Voltage dependent)
• Failure mode / corrosive

Emerging Alternative
• Hermetically sealed solid tantalum design

Image Source: http://electricalacademia.com/basic-electrical/capacitor-types-construction-and-uses/
Film Capacitors in Oil & Gas Today

Typical Use

• Predominantly thick film PTFE
• Small (<5µF for analog sensors)
• <10% share within Oil & Gas tools

Why not for bulk Power Supply requirements?

• Volume Efficiency / Larger for comparable Capacitance (lower K, thicker films)
• Generally considered reliable up to 125°C; with needs as high as 200°C
• Higher Cost
Film Capacitor Construction

Physical Design

- Metalized film capacitors are two metalized films wound together and connected on each end with end spray (schoopage).

- Film-foil capacitors are constructed from separate dielectric and conductive metal foil:
  - 25-80X thicker metal than in metallized film design
  - Do not effectively self clear
## Film Capacitor Dielectrics

<table>
<thead>
<tr>
<th>Film Material</th>
<th>Common Trade Name</th>
<th>Typical Max Temperature (°C)</th>
<th>K factor</th>
<th>DWV @ T noted (V/um)</th>
<th>Dissipation Factor (1kHz)</th>
<th>Availability</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>Treofan</td>
<td>105</td>
<td>2.2</td>
<td>800 (RT)</td>
<td>.0002</td>
<td>Available since 1950s</td>
<td>Dominant Film Capacitor Dielectric (50%)</td>
</tr>
<tr>
<td>PTFE</td>
<td>Teflon</td>
<td>225-250</td>
<td>2.0</td>
<td>450 (RT)</td>
<td>.0001</td>
<td>Available since 1950s</td>
<td>Typically thick film/foil; small caps for analog;</td>
</tr>
<tr>
<td>PI</td>
<td>Kapton</td>
<td>200</td>
<td>3.3</td>
<td>200-250 (150°C)</td>
<td>.0020</td>
<td>Available since 1950s</td>
<td>Space, Corona discharge; Typically thick film/foil; Poor clearing</td>
</tr>
<tr>
<td>PET</td>
<td>Mylar</td>
<td>85-125</td>
<td>3.1</td>
<td>~200 (150°C)</td>
<td>.0050</td>
<td>Available since 1950s</td>
<td>Widely used. Less so in higher current applications (40%);</td>
</tr>
<tr>
<td>PPS</td>
<td>Torelina</td>
<td>125</td>
<td>2.8</td>
<td>482 (RT)</td>
<td>.0018</td>
<td>Available since 1980s</td>
<td>Common PC replacement; poor clearing</td>
</tr>
<tr>
<td>PEN</td>
<td>Teonex</td>
<td>125-150</td>
<td>2.95</td>
<td>400 (RT)</td>
<td>.0035</td>
<td>Introduced ~ 2012</td>
<td>Thickness variation challenges</td>
</tr>
<tr>
<td>PEI</td>
<td>Ultem</td>
<td>150</td>
<td>3.2</td>
<td>495 (150°C)</td>
<td>.0022</td>
<td>Emerging</td>
<td>5um and 7um films introduced recently</td>
</tr>
<tr>
<td></td>
<td></td>
<td>225-250</td>
<td>2.0</td>
<td>750 (RT)</td>
<td>.0001</td>
<td>Emerging</td>
<td>Establishing initial use in Oil &amp; Gas</td>
</tr>
</tbody>
</table>

Sources: Capacitors Technology & Trends – R. P. Desphande; Manufacturer’s Websites & Whitepapers; Teflon, Kapton, Mylar, and Teonex are trademarks of E. I. du Pont de Nemours and Company or its affiliates; Torelina is a trademark of Toray; Ultem is a trademark of Sabic; Gore is a trademark of W. L. Gore & Associates.
Higher Strength PTFE

• Expanded PTFE is >10x stronger than conventional PTFE

• Enables progressively thinner films with enough mechanical strength for winding

• Improved thermal dimensional stability
Dielectric Breakdown Strength Comparison
(Film @ ~25°C)

• A high breakdown voltage for a given film thickness enables optimization of volume and weight reductions while meeting high voltage requirements.

• ¼” aperture test, ramp rate of 500v a second

<table>
<thead>
<tr>
<th>Polymer film</th>
<th>Scale (a) V/µm</th>
<th>Shape (β)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPE</td>
<td>360</td>
<td>9</td>
</tr>
<tr>
<td>Cast PTFE</td>
<td>443</td>
<td>8</td>
</tr>
<tr>
<td>PPS</td>
<td>482</td>
<td>23</td>
</tr>
<tr>
<td>PEN</td>
<td>566</td>
<td>32</td>
</tr>
<tr>
<td>Gore Film</td>
<td>756</td>
<td>15</td>
</tr>
<tr>
<td>BOPP</td>
<td>812</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Breakdown Voltage (V/µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative Failure</td>
</tr>
<tr>
<td>99.9%</td>
</tr>
<tr>
<td>95.0%</td>
</tr>
<tr>
<td>63.2%</td>
</tr>
<tr>
<td>25.0%</td>
</tr>
<tr>
<td>10.0%</td>
</tr>
<tr>
<td>5.0%</td>
</tr>
<tr>
<td>2.0%</td>
</tr>
<tr>
<td>1.0%</td>
</tr>
<tr>
<td>0.2%</td>
</tr>
</tbody>
</table>

Breakdown Voltage (V/µm)
Dielectric Breakdown Strength Over Temperature
(Room Temperature to 200°C)

- High temperature negatively impacts breakdown strength so care must be taken to apply appropriate capacitor de-ratings for the intended use.

- Attempts to increase breakdown strength by adding coatings, generally negatively impacts the loss and stability over temperature.
Dielectric Loss Over Temperature
(Film @10kHz)

- Films with low loss over a wide temperature range are favorable to minimize internal heating and the potential for thermal runaway in use.
Dissipation Factor and Self-heating

10µF PEN film cap
DF  0.0035 (1kHz)

10µF High Strength PTFE film cap
DF  0.0001 (1kHz)

Temperature range 24°C to 35°C
3A testing ~45V @1kHz
~20minutes
Advantages of Film Capacitors

• Stable, high reliability
• Wide range of capacitance and voltage values
• High current handling
• Low DF (dissipation factor)
• Capacitance stability over frequency and temperature
• Self healing (clearing)
Self Clearing

- A flaw in the metalized film material results in a dielectric breakdown
- Localized heating causes combustion of the film, melting the surrounding metallization
- A successful clear removes the metal surrounding the flawed area, isolating the fault from the rest of the device.
Breakdown at the Dielectric Film Level
Self Clearing – Size and Diagnostics

In perspective, each self-clearing event is relatively small compared to the overall capacitor effective area.
Benefit of Self-Clearing

• Ability to tolerate overvoltage transient events

• Predictable performance with capability to monitor degradation over time
Summary

• Ceramic capacitors have lead the market (~80%) in high temperature applications historically with film as a minor participant (mostly thick PTFE)

• Leaders in the oil & gas market are reconsidering film capacitors to achieve new levels of reliability as new dielectric choices unlock:
  • High temperature capabilities combined with self-healing
  • Improving energy density

• As wide band gap, and other application trends increase the need for high temperature / power performance, keep in mind the emerging film capacitor options
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Thank You

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