High Temperature Capacitor Applications in More Electric Aircraft

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W. L. Gore & Associates
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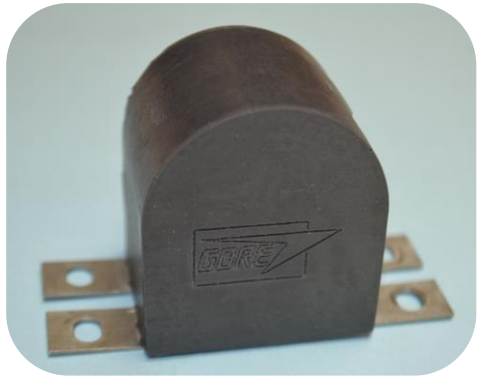


GORE
Creative Technologies Worldwide

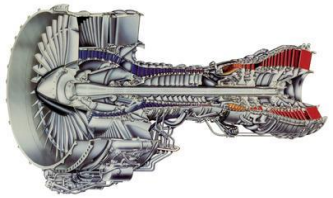
Agenda

- More Electric Aircraft (MEA)
- MEA Motivation
- High Temperature Design Constraints
- Dielectric Film/Capacitor Testing
- Example MEA Application
- Summary

What is the More Electric Aircraft (MEA)?

Replacing traditionally engine driven Hydraulic, Pneumatic (bleed-air) and Mechanical sub-systems with Electrical driven sub-systems

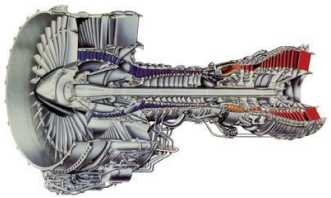
TRADITONAL ARCHITECTURE



- **Gearbox Driven ELECTRICAL Generator**
  - Avionics
  - Lights
  - Entertainment
- **Gearbox Driven HYDRAULIC Pumps**
  - Control Actuators
  - Braking
  - Landing Gear
- **Gearbox Driven MECHANICAL Pumps**
  - Oil Pumps
  - Fuel Pumps
- **"Bleed-Air" PNEUMATIC**
  - Cabin Pressurization
  - Climate Control
  - Ice Protection

VS

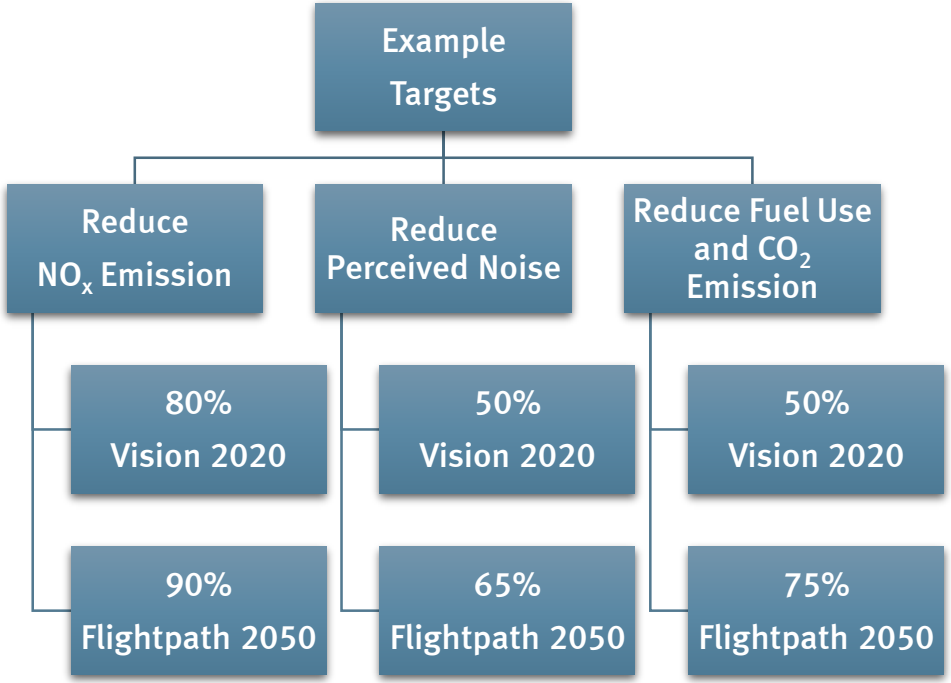
MEA ARCHITECTURE



- **Engine Driven ELECTRICAL Generators**
  - Avionics
  - Lights
  - Entertainment
  - Control Actuators
  - Braking
  - Landing Gear
  - Oil Pumps
  - Fuel Pumps
  - Cabin Pressurization
  - Climate Control
  - Ice Protection

Why the More Electric Aircraft?

- **Industry Objectives**
  - Reduced Operating Costs
  - Reduced Fuel Burn
  - Reduced Environmental Impact

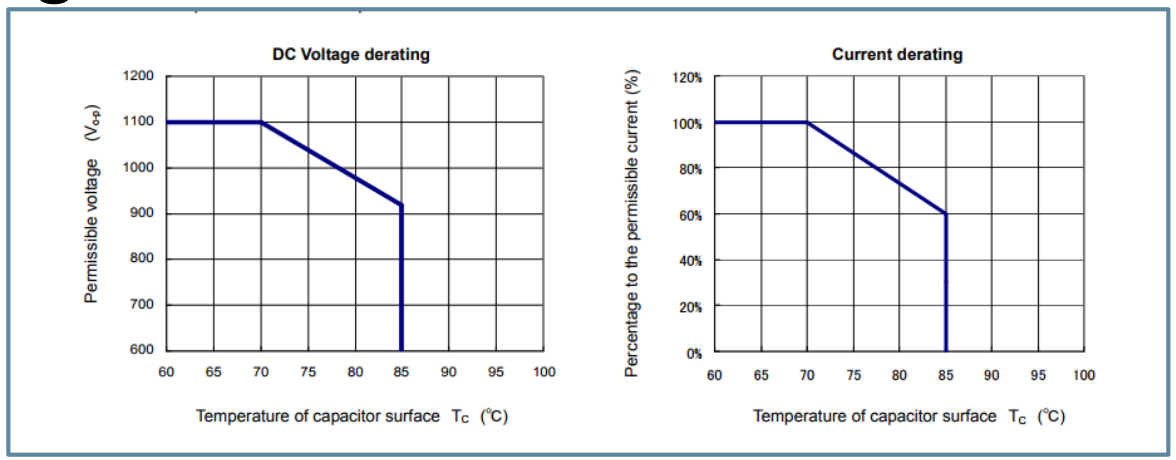


Industry Trend

- **Move to Megawatt Power Generation has created many challenges for capacitors:**
  - 125˚C and above ambient operating conditions becoming the new normal, with some applications up to 200˚C+
  - Desire to increase operating voltage and frequency to reduce total package size
  - High RMS currents, due to switching frequency, increases internal heating

Capacitor Challenges

- **High operating voltages (›500V) , temperatures (›125˚C) and RMS currents (›10A per section)**
  - Limited dielectrics available
  - Typical film capacitors require significant voltage de-rating at elevated temperature leading to larger physical size
  - Higher currents leads to higher temperature rise, that leads to more de-rating



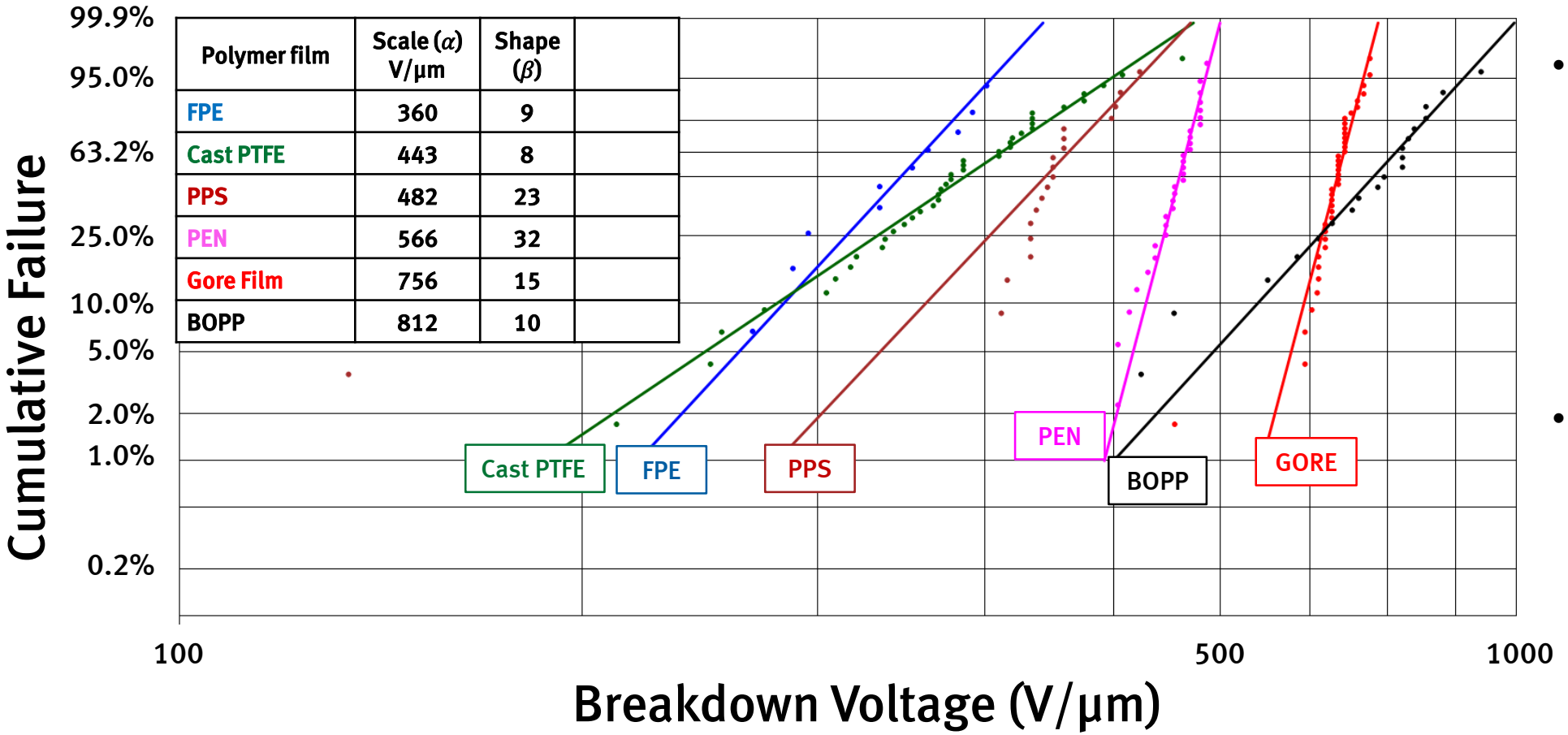
"Full use of high frequency feature of SiC devices require thin film capacitor with high current carrying capability at high temperature"

-Dr. Ajay Misra NASA

Dielectric and Capacitor Testing

Comparative Performance Testing

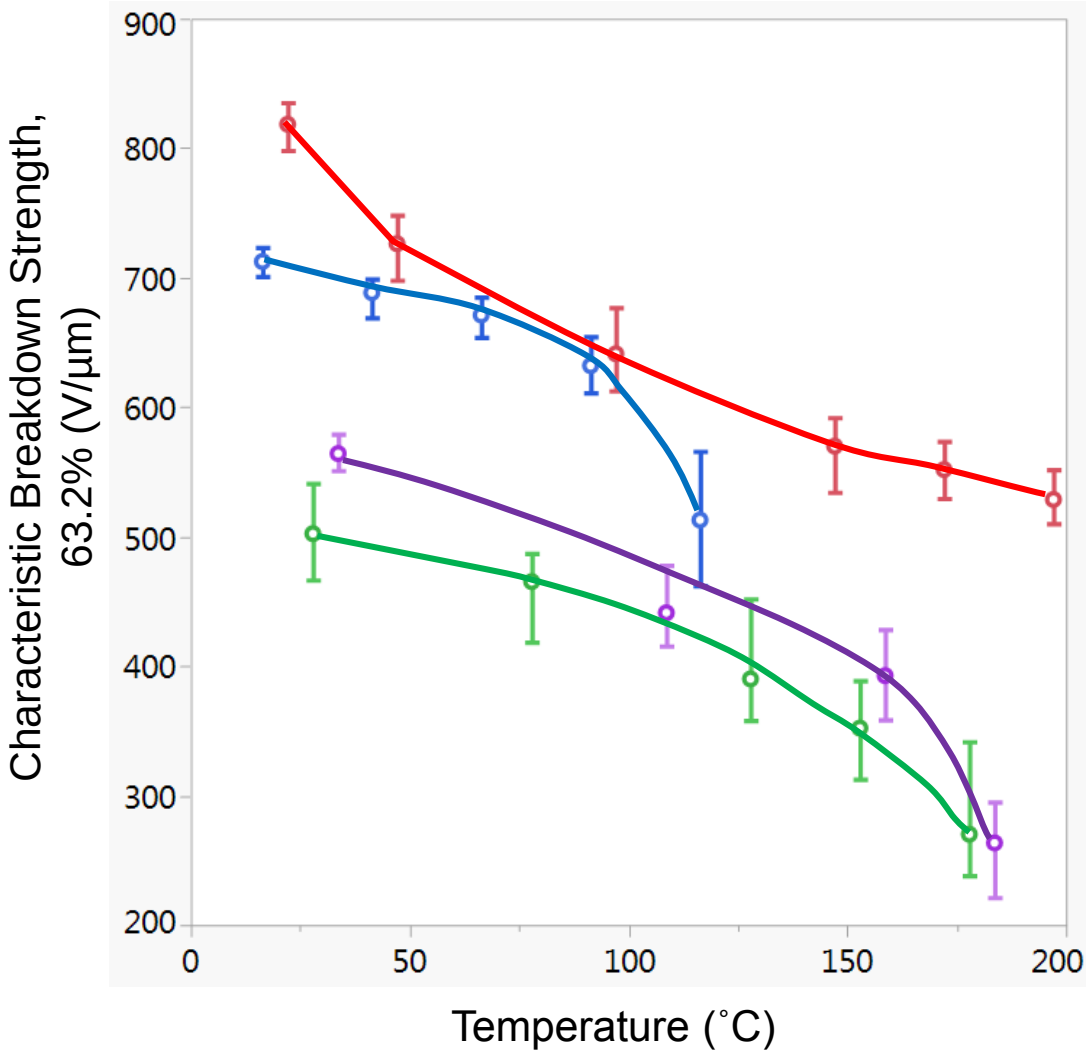
Dielectric Breakdown Strength Comparison
(Film @ ~25°C)



Polymer film	Scale (α) V/µm	Shape (β)
FPE	360	9
Cast PTFE	443	8
PPS	482	23
PEN	566	32
Gore Film	756	15
BOPP	812	10

- 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

Dielectric Breakdown Strength Over Temperature
(Film Room Temperature to 200˚C)



- Gore Film
- Polypropylene (BOPP)
- Polyether ether ketone (PEEK)
- Polyethylene naphthalate (PEN)

- 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

Maintain High Insulation Resistance and Low Loss Over Temperature

- **High dielectric loss ($tan\delta$) over temperature and frequency can negatively impact capacitor reliability**
  - Changes in loss can contribute to changes in the DC-conductivity of the polymer, which can lead to "thermal runaway"
- **Maintaining high insulation resistance is also important to long term capacitor reliability.**

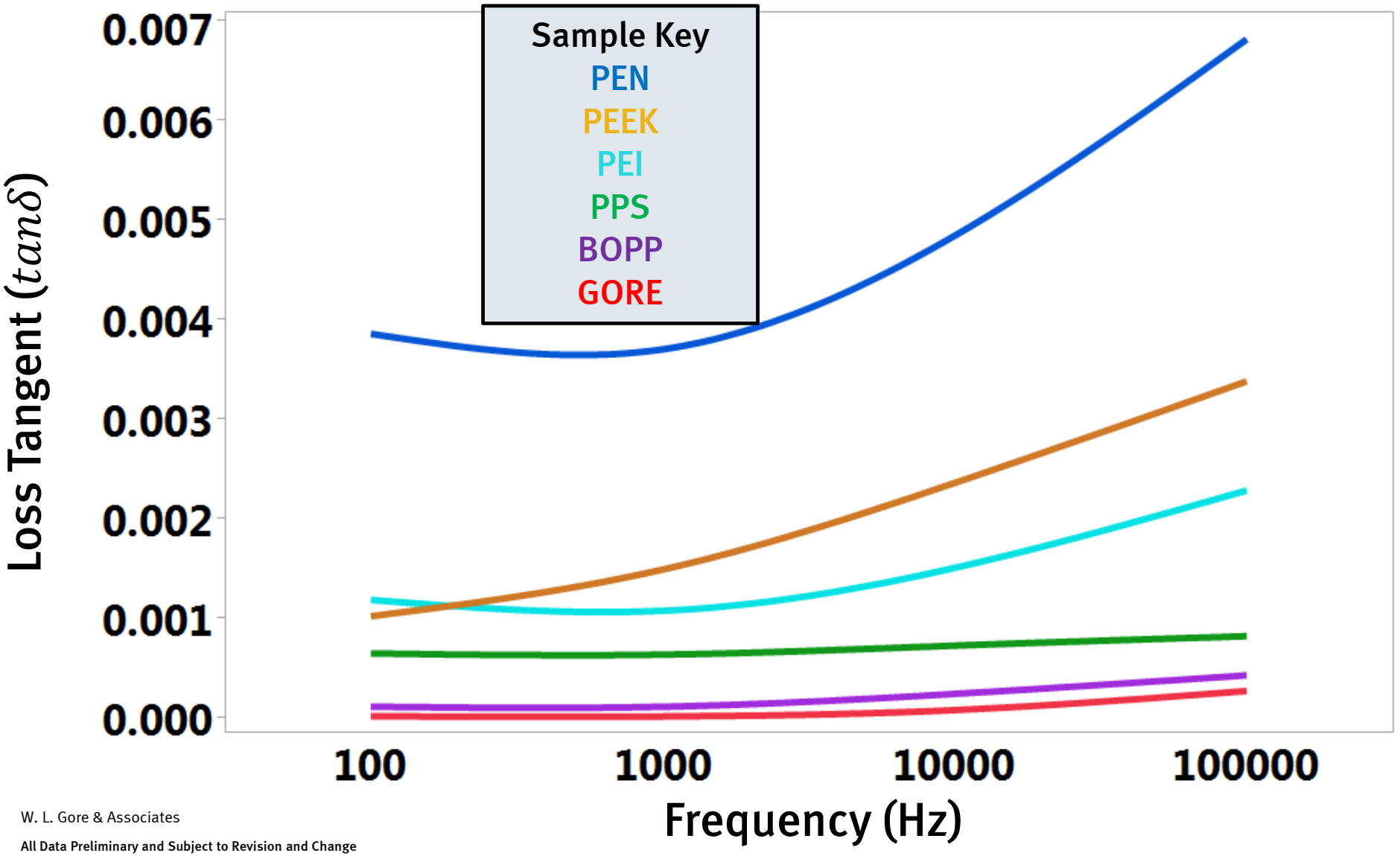
$$tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon''_{relax} + \varepsilon''_{DC}}{\varepsilon'} = \frac{\varepsilon''_{relax}}{\varepsilon'} + \frac{\sigma}{\varepsilon'\omega}$$

$\varepsilon'\varepsilon''$ = real and imaginary part of dielectric constant

σ = DC-conductivity

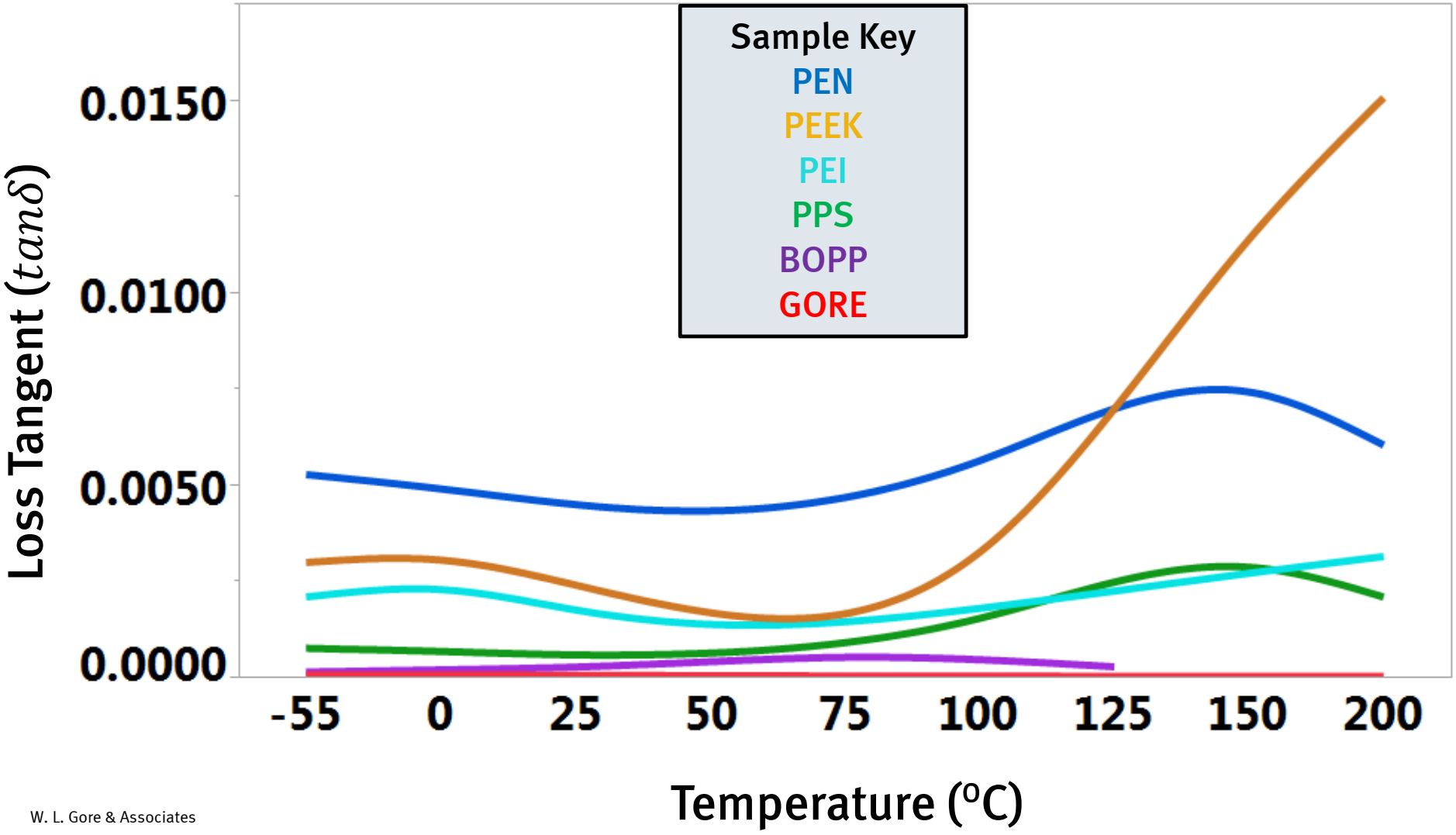
ω = angular frequency

Dielectric Loss Over Frequency (Film @25˚C)



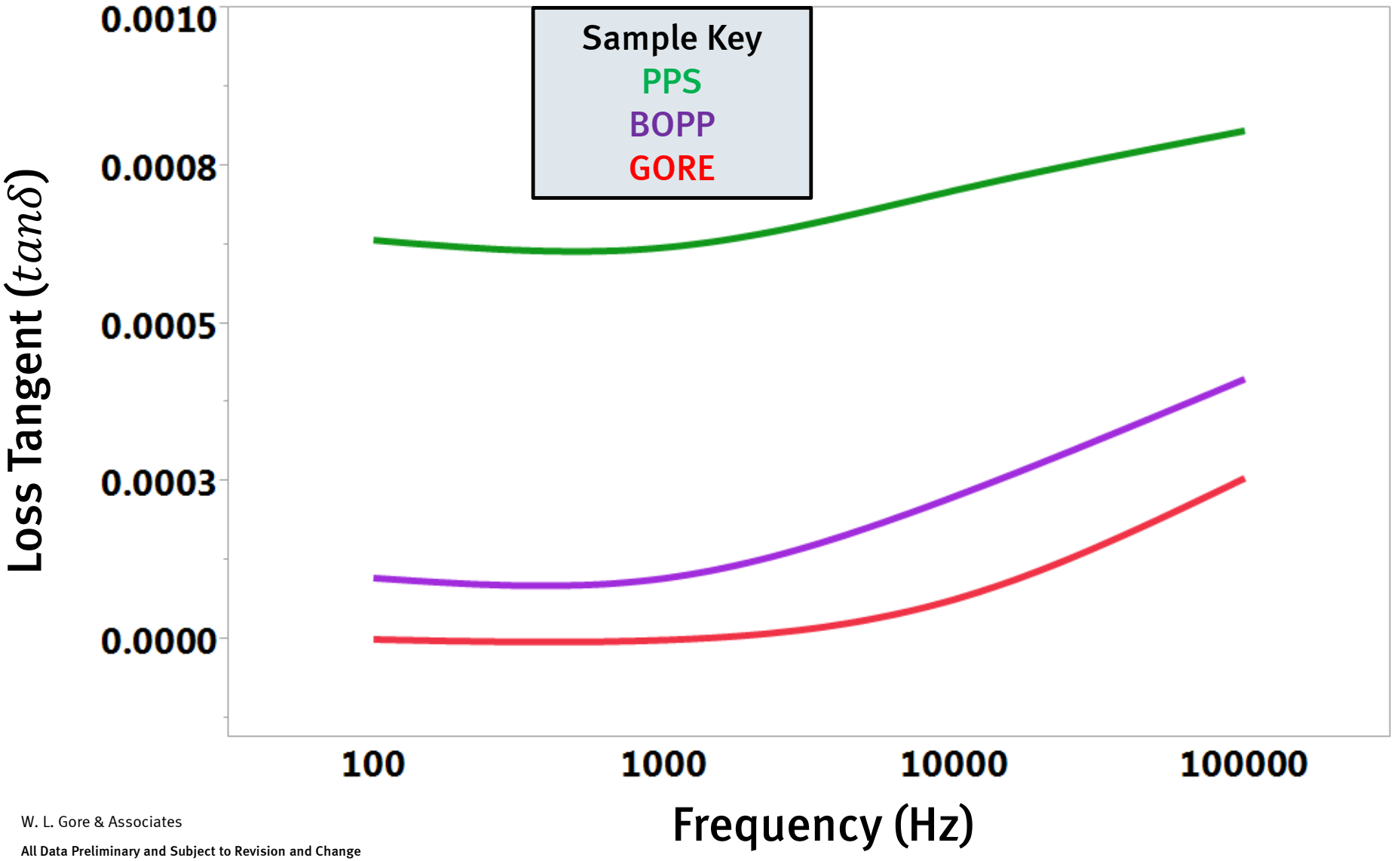
- Films with low loss over a wide frequency range are favorable to minimize internal heating and the potential for thermal runaway

Dielectric Loss Over Temperature (Film @10kHz)



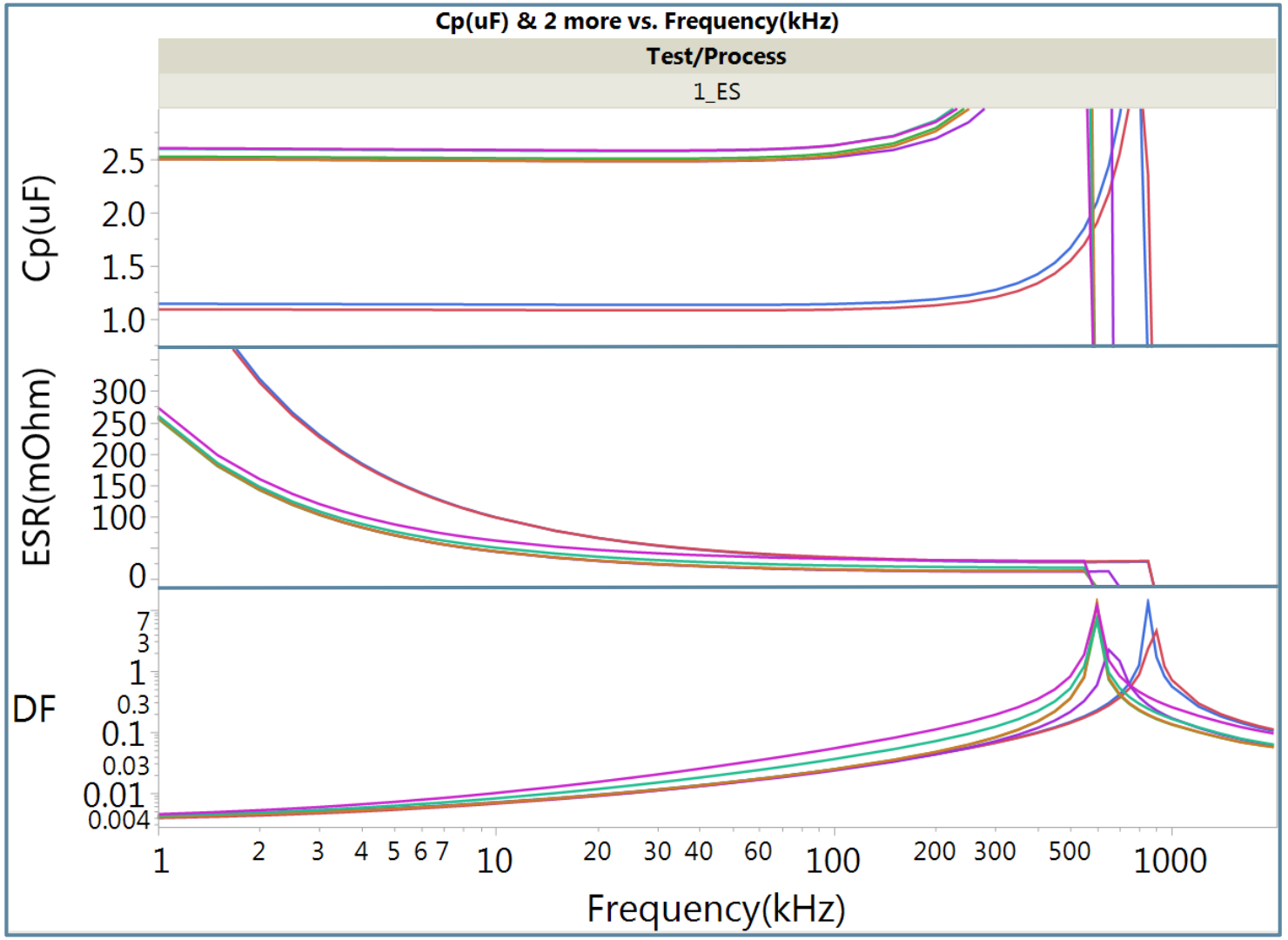
- Likewise, films with low loss over a wide temperature range are favorable to minimize internal heating and the potential for thermal runaway in application use

Dielectric Loss Over Frequency (Film @25˚C)



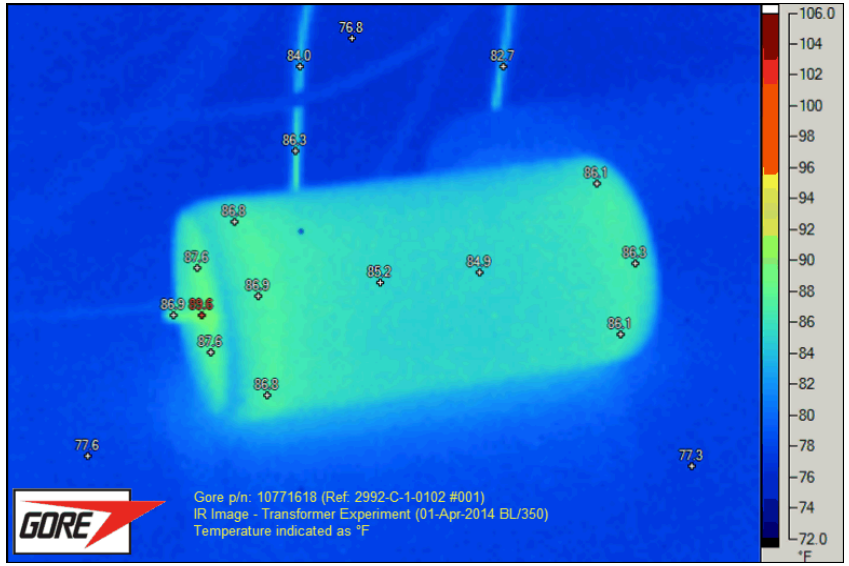
- Gore film and BOPP are near the measurement floor of the testing capabilities

PEN Capacitors

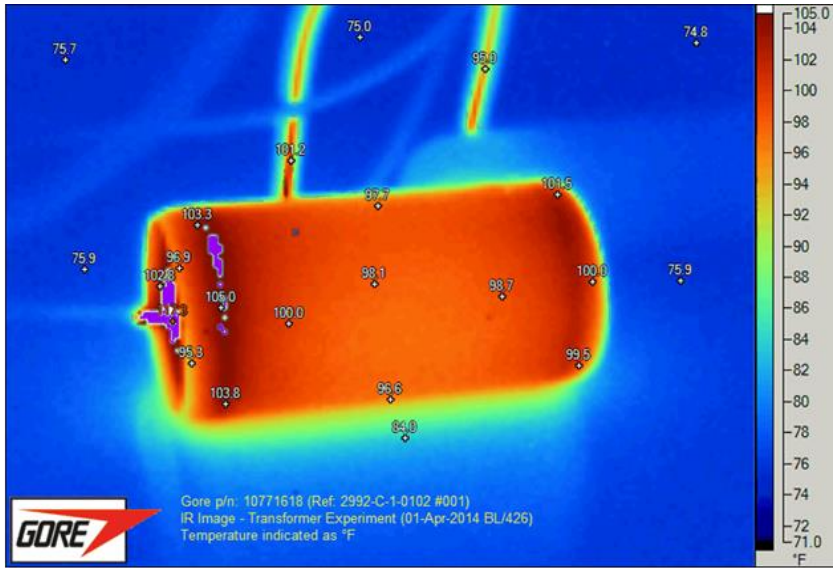


- At lower frequencies ESR is dominated by dielectric loss
- At higher frequencies the ESR is dominated by the electrode thickens and end connection quality.

High Current Effects on Temperature



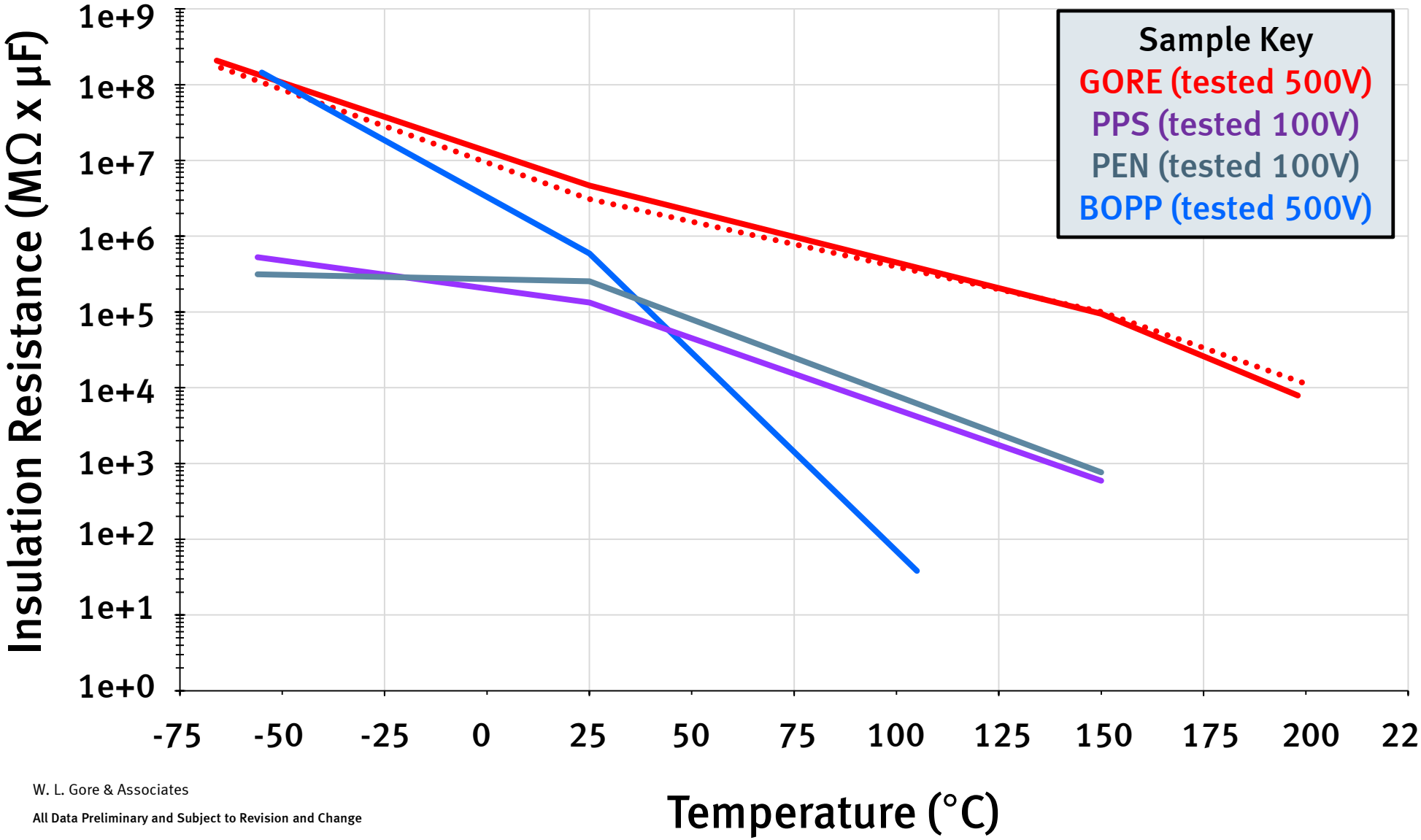
50µF Capacitor tested at $5A_{rms}$



50µF Capacitor tested at $20A_{rms}$

- Self Heating is the key limitation of RMS current handling
  - $P = I^2 \times R$ in the case of a capacitor R = ESR

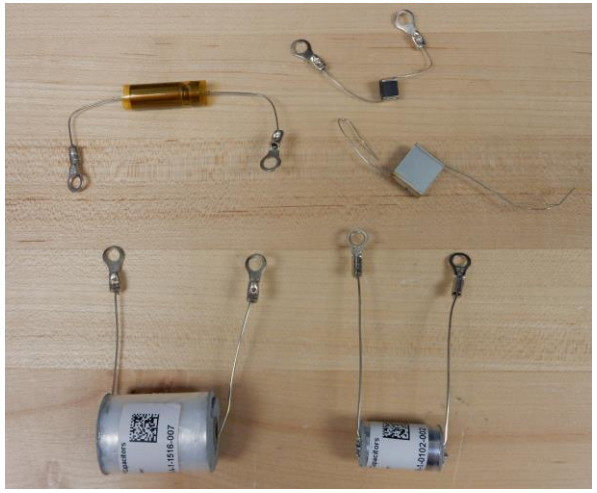
Insulation Resistance Over Temperature (Capacitors)



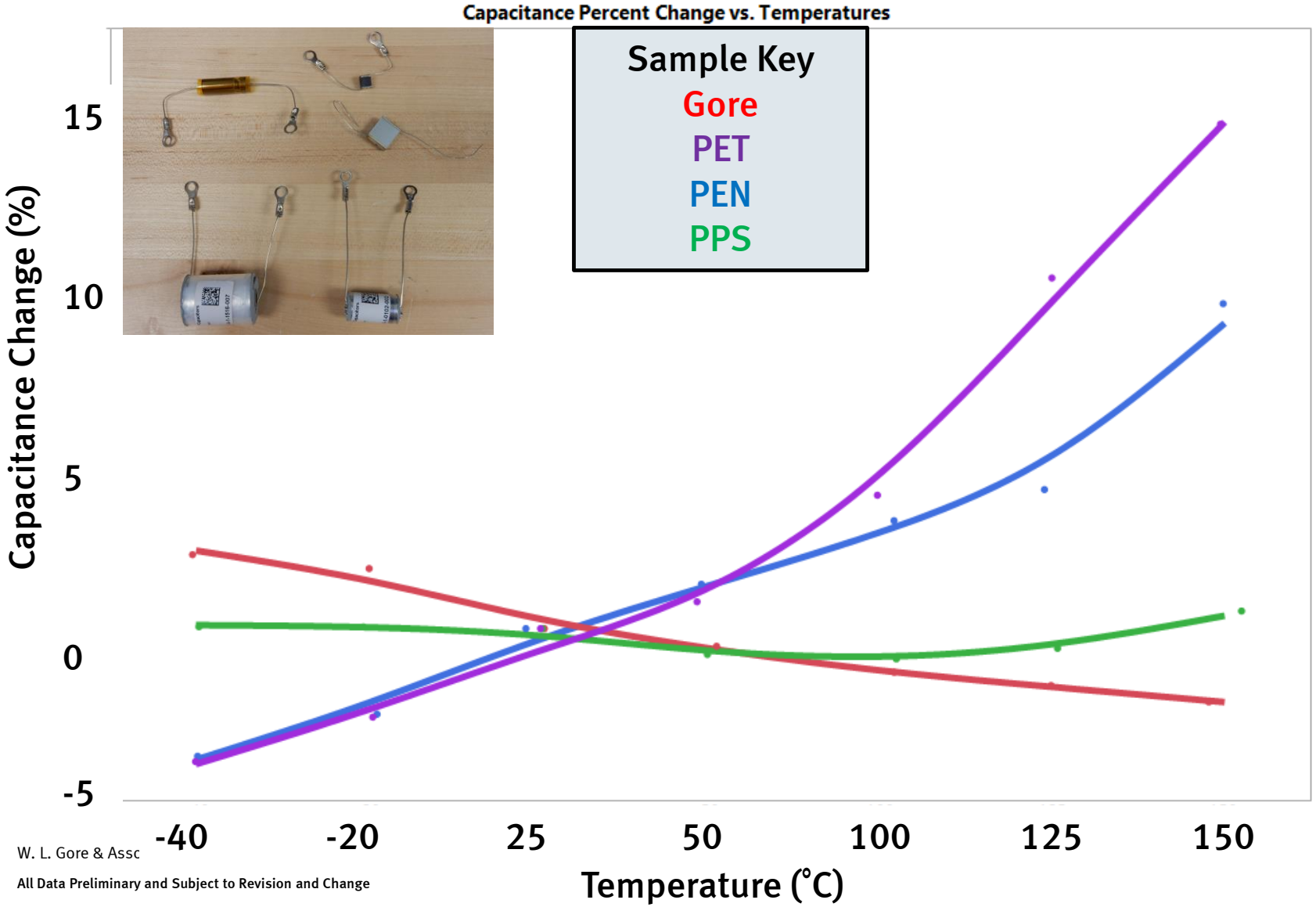
- GORE™ High Temperature Film Capacitors exhibit and maintain a high insulation resistance over a broad temperature range
- BOPP has a very high initial IR but even by 100°C it has dropped significantly
- PPS and PEN capacitors are lower over the working temperature range, they also had to be tested at a much lower voltage due to rating

Capacitance Stability Testing

- **Capacitors Tested**
  - **Film caps (PEN/PPS/PET/Gore)**
  - **Alternative technologies (Wet Tantalum, XR7 ceramic)**
- **Test protocol**
  - **Monitor capacitance and ESR by performing LCR sweeps with Agilent 8940 at varying temperature set-points**
    - **-40/-20/25/50/100/125/150/(˚C)**

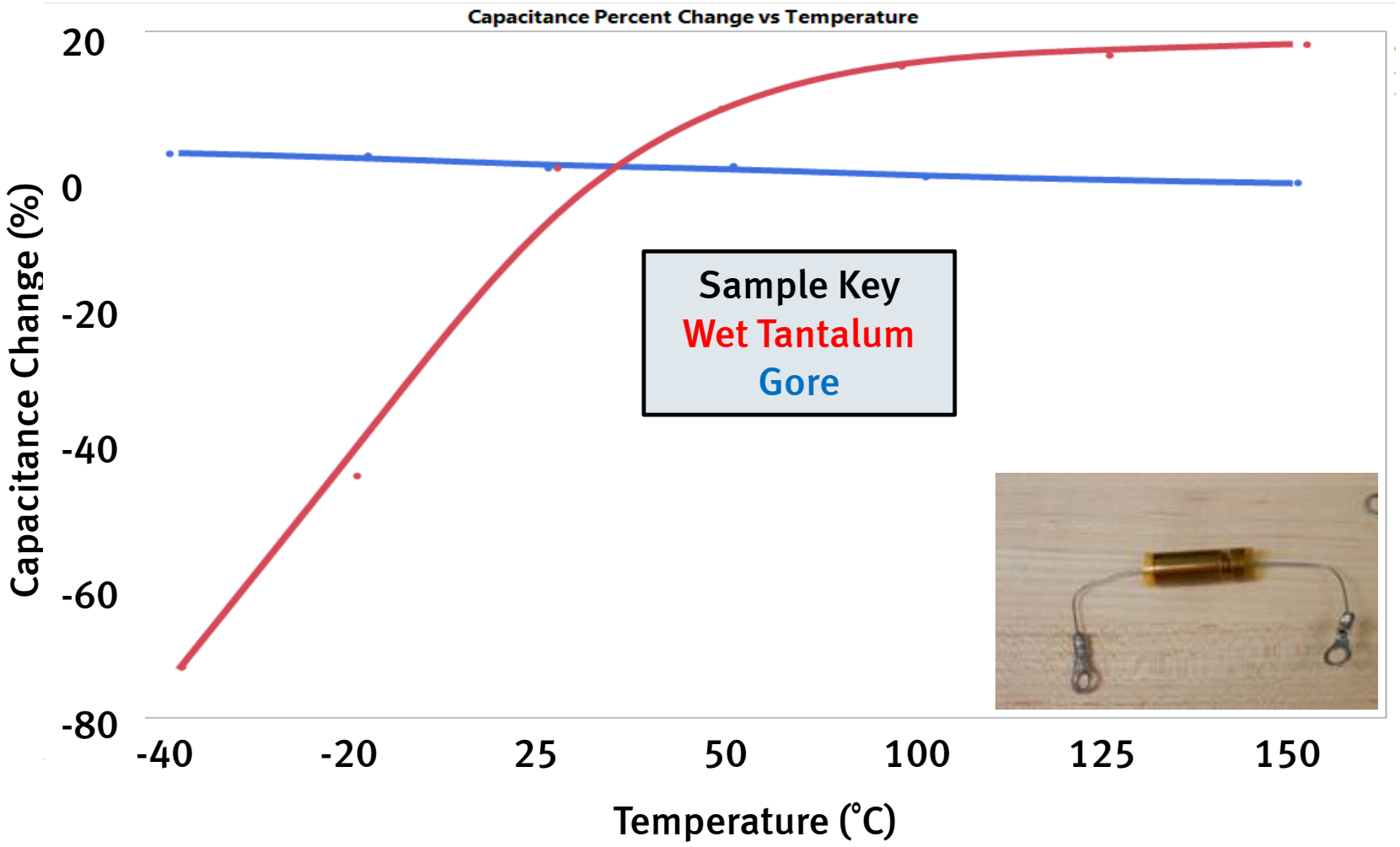


Capacitance Change Over Temperature



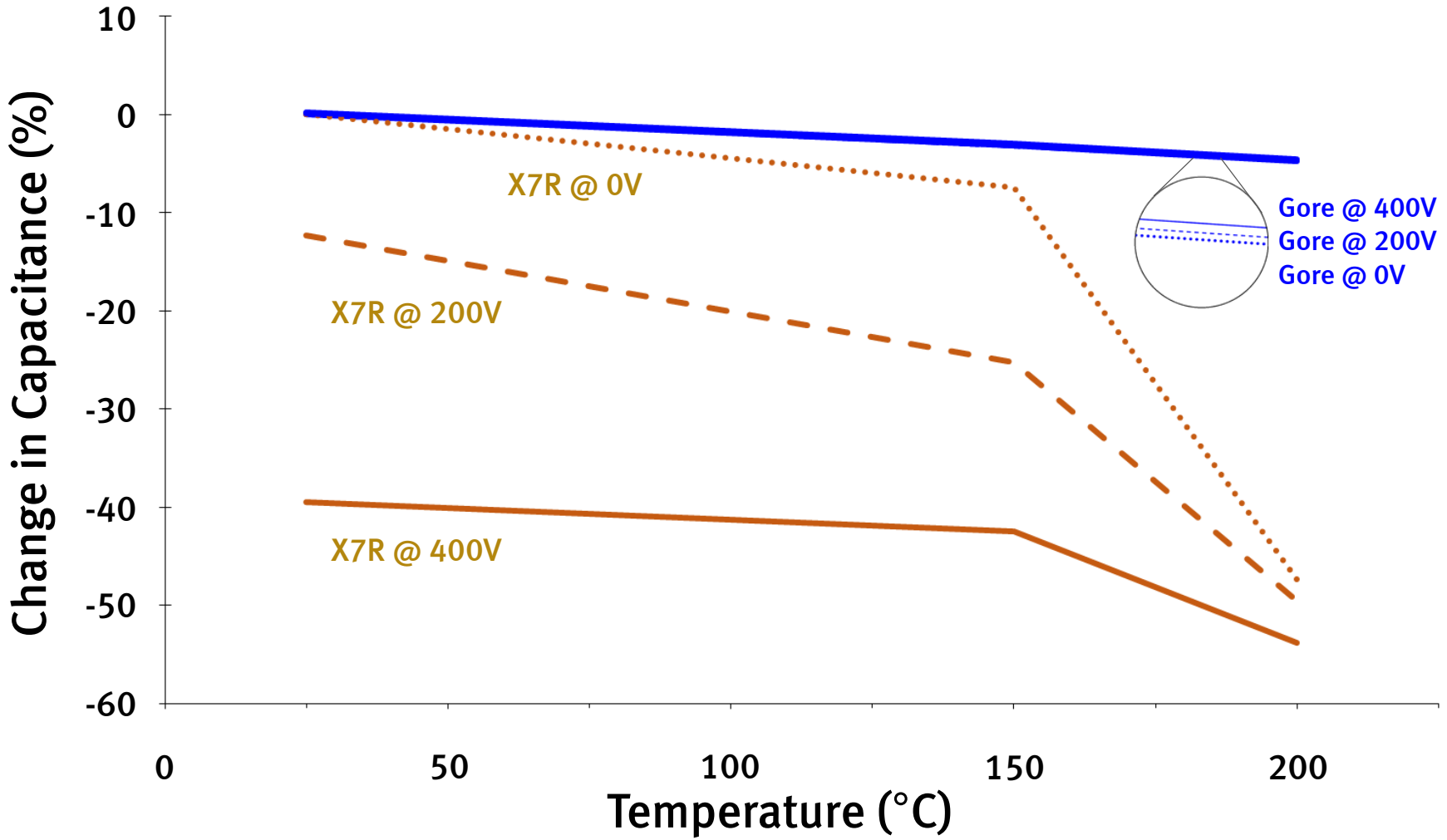
- GORE™ High Temperature Film Capacitors exhibit a 1-2% capacitance gain at -40°C and a 1% loss at 150°C
- PET and PEN film capacitors show large changes with a 10% or greater change in capacitance over the tested temperature range
- PPS film exhibit good stability up to the 150°C

Capacitance Change Over Temperature



- Wet tantalum capacitors technology suffer extreme changes in capacitance over temperature exhibiting a 20% gain at 125°C and nearly an 60% loss at -40°C

Capacitance Over Temperature & Voltage
(change from 25°C and 0 Volt reference)



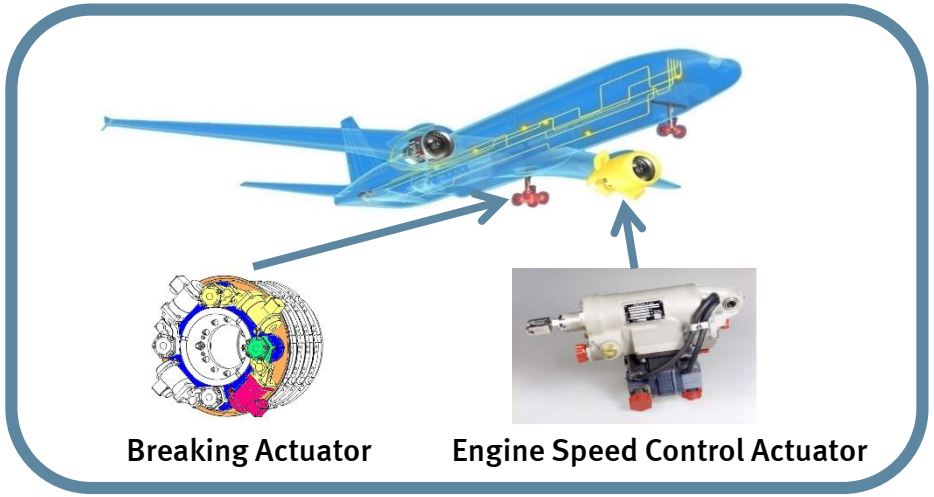
- GORE™ High Temperature Film Capacitors exhibit stable capacitance over a wide temperature and voltage range
- Typical X7R ceramic capacitors exhibit large drops in capacitance over the same temperature and voltage range
- Other ceramic dielectrics (e.g., C0G) are more stable over temperature but are only available in small capacitance packages (< 0.5 uF)

More Electric Aircraft Example Application:

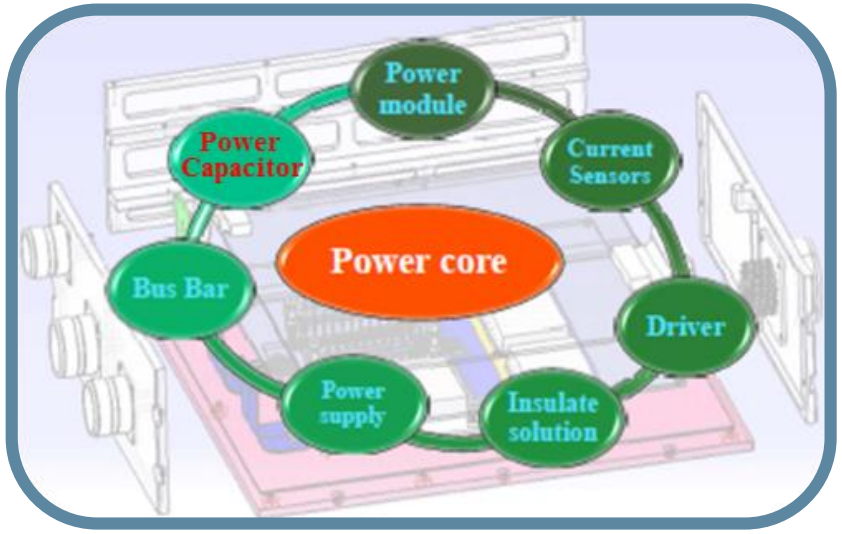
Safran Power Core Motor Drive for Aeronautics

Safran: Advanced High Temperature Power Electronic Inverter for Smart Actuator

- **Safran is also a major player in the current trend towards "more electric" aircraft**
- **Objective: Realize a 5kW Power Core demonstrator running at 200 °C to validate technologies**



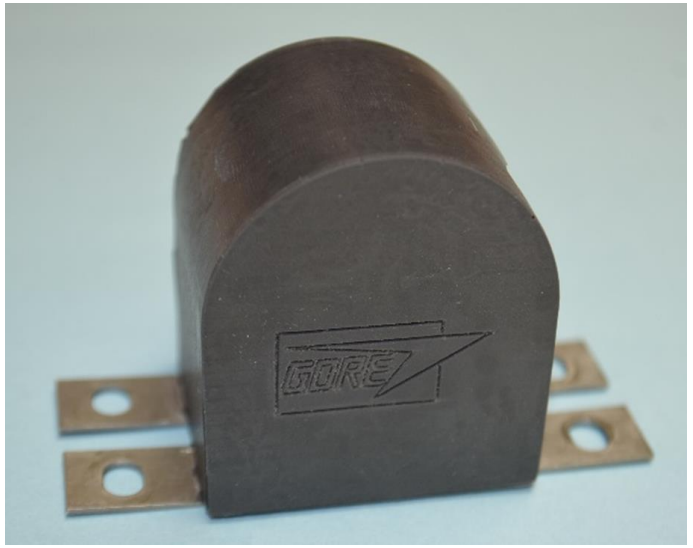
Example Application Areas



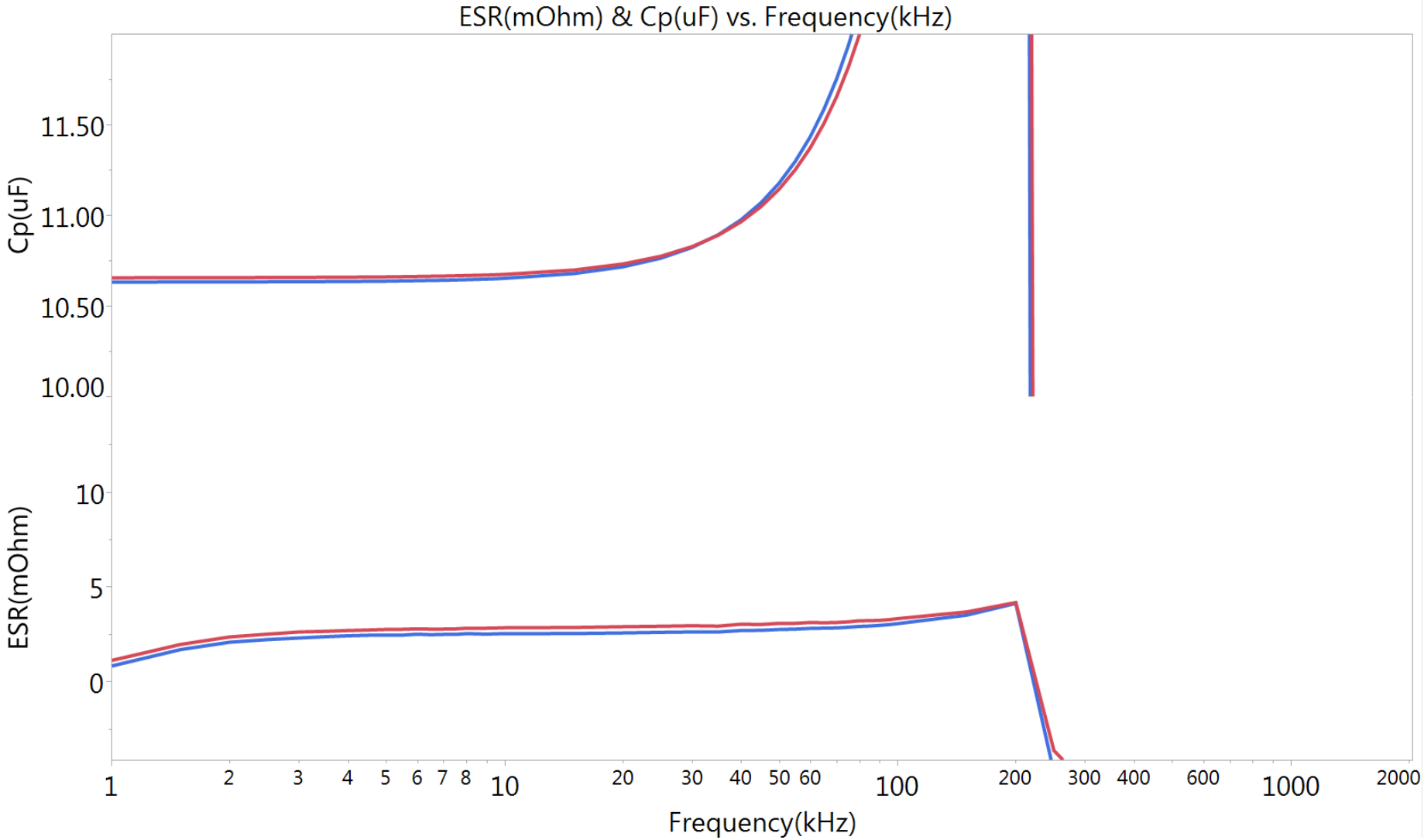
Power Core Technologies

Target Specification

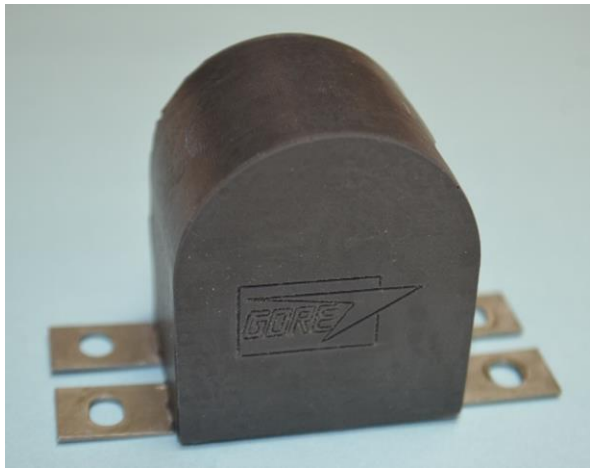
- Wide range temperature use: -63˚C to +200˚C
- Voltage DC: 600V/1000V peak
- Capacitance: 10µF
- Low inductance: ‹10nH
- Ripple current: ~10A_{rms}
- Long life: ›10,000 hours (90,000 Goal)
- Stable performance over entire temperature range and lifetime



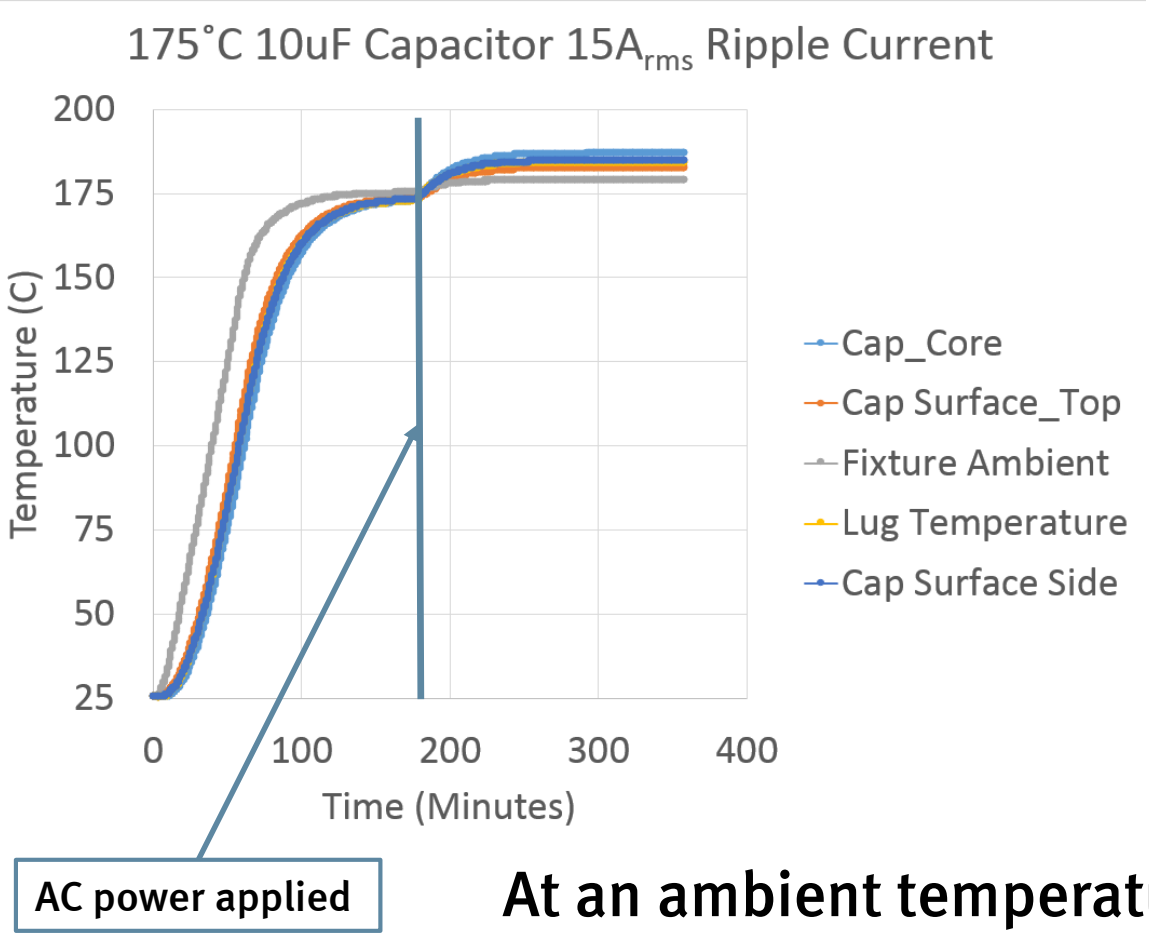
GORE$_{TM}$ Capacitor: Capacitance and ESR Data

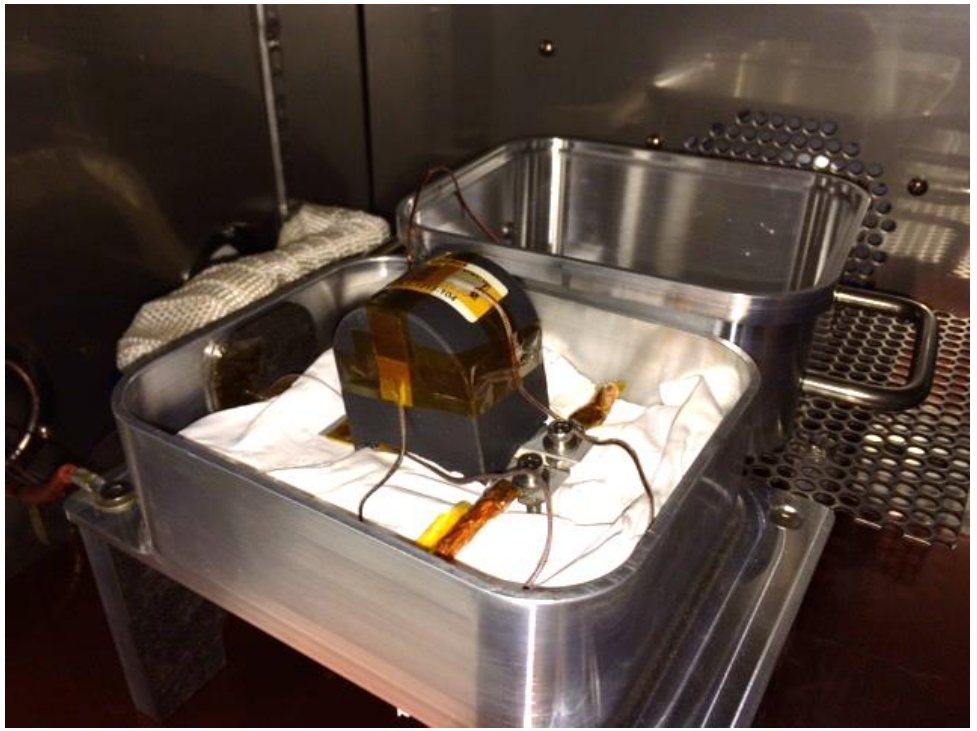


Capacitance: 10.6µF
ESR: ‹5mΩ
ESL(section): 8nH
Resonance Frequency: ~200kHz



GORE$_{TM}$ Capacitor: Ripple Current Data





At an ambient temperature of 175˚C and with 15A$_{rms}$ current applied, the maximum temperature rise for this design~8˚C with no heat sink and no forced air flow

Summary/Current Status

- **GORE$_{TM}$ Film Capacitors offer many technical advantages for use in high temperature power electronics for More Electric Aircraft**
  - Wide range of temperature use (-65˚C to + 200˚C)
  - Stable properties over temperature and voltage
  - Low loss and high breakdown strength at elevated temperatures

- **GORE$_{TM}$ Film Capacitors Status**
  - Continuing to develop lead applications in Oil & Gas and Aerospace markets that benefit from High Temperature film capacitor technology
  - Investing in additional film development, high temperature manufacturing techniques, and test infrastructure