

2015 Applied Power Electronics Conference

1

Film Capacitors For High Temperature Switches And Power Electronics Applications Above 125°C

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March 2015

PSMA Capacitor Committee

Presentation Flow

2

- The industry need for high temperature caps
 - Wide Band Gap (WBG) semiconductors
 - Department of Energy (DOE) objectives
 - Other applications
- Standard available dielectric options
 - Overview of characteristics
 - The bi-axially oriented polypropylene (BOPP) benchmark
- Barriers to high temperature dielectric development
- Previous dielectric development
- Electronic Concepts Inc. (ECI) dielectric development and product series
- ECI continuing development goals for 2015-2017

Industry needs for high temperature capacitors

3

Wide Band Gap (WBG) Semiconductors

- North Carolina State University is leading Wide Band Gap (WBG) development for the Energy Department
- New SiC and GaN semiconductor switches operate at higher temperatures and voltages
- Capacitors complementing these switches needed
- Present plastic dielectric options limited to 125C

Industry needs for high temperature capacitors

4

- Wide Band Gap (WBG) semiconductors
- Band gap refers to the energy (eV) required to move an electron from the valance to the conduction band.
- Wide Band Gap Materials:
 - Operate at higher temperatures
 - Operate at higher voltages
 - Eliminate up to 90% of present technology loses

Wide bandgap semiconductors (shown in green) are materials that possess bandgaps significantly greater than those of silicon.

Semiconductor Materials		
Material	Chemical Symbol	Bandgap Energy (eV)
Germanium	Ge	0.7
Silicon	Si	1.1
Gallium Arsenide	GaAs	1.4
Silicon Carbide	SiC	3.3
Zinc Oxide	ZnO	3.4
Gallium Nitride	GaN	3.4
Diamond	C	5.5

Industry need for high temperature capacitors – DOE traction inverters

5

- Remove electronics cooling
- Run off engine coolant 90-105C
- 140C non-energized
- Higher switching frequencies and temperatures (WBG semiconductor incentives)
- High energy density of 4 joule/cc (65.5 joule/cu.in)
- Low cost (similar or lower than standard BOPP)

DOE Goals

6

Traction Drive Requirements: 55 kW peak power for 18 sec; 30 kW continuous power; 15-year life

Traction Drive System					Power Electronics		
Impacts →	Reduce Cost	Reduce Weight	Reduce Volume	Reduce Energy Storage Requirements	(\$/kW)	(kW/kg)	(kW/l)
Year	Cost (\$/kW)	Specific Power (kW/kg)	Power Density (kW/l)	Efficiency	7.9	10.8	8.7
2010*	19	1.08	2.60	>90%	7	11.2	10
2012	17	1.12	2.86	>91%	5	12	12
2015	12	1.17	3.53	>93%	3.3	14.1	13.4
2020	8	1.44	4.00	>94%			
					Electric Motors		
					(\$/kW)	(kW/kg)	(kW/l)
					11.1	1.2	3.7
					10	1.24	4
					7	1.3	5
					4.7	1.6	5.7

* 2010 traction drive cost target achieved with development of the GM integrated traction drive project

Vehicle Technologies Program – Advanced Power Electronics and Electric Motors

eere.energy.gov

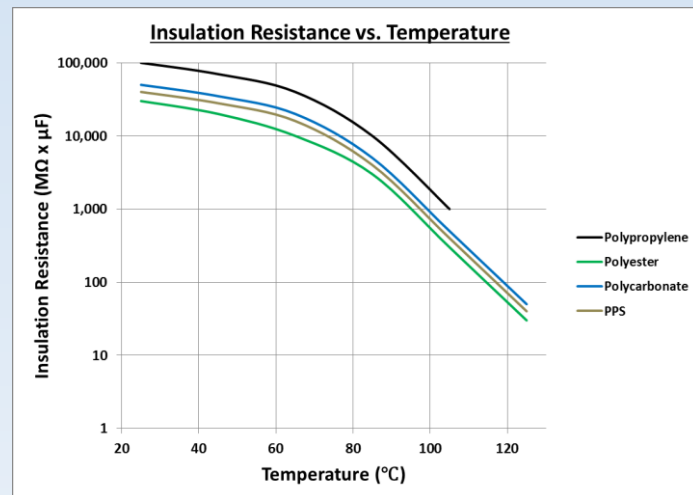
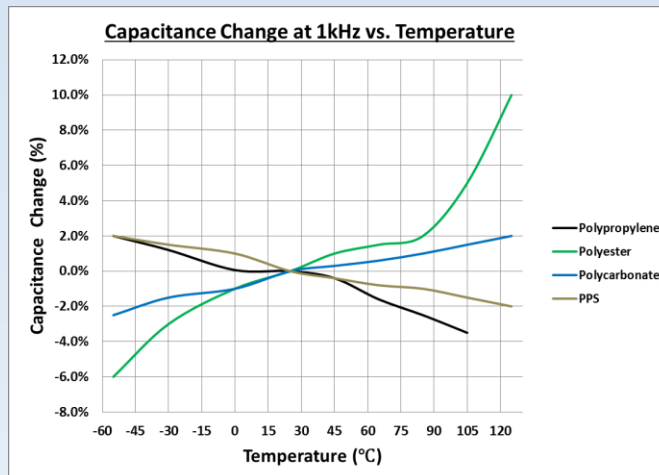
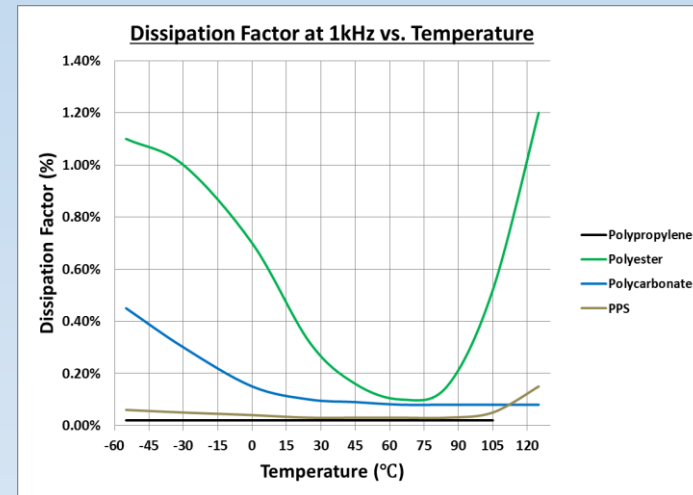
EV Everywhere Target Analysis		Current Status	PHEV 40	AEV 100	AEV 300
System Cost	\$/kW	20	5	14	4
Motor Specific Power	kW/kg	1.2	1.9	1.3	1.3
PE Specific Power	kW/kg	10.5	16	12	16.7
System Peak Efficiency	%	90	97	91	98

Standard available dielectric options

7

Market available dielectrics

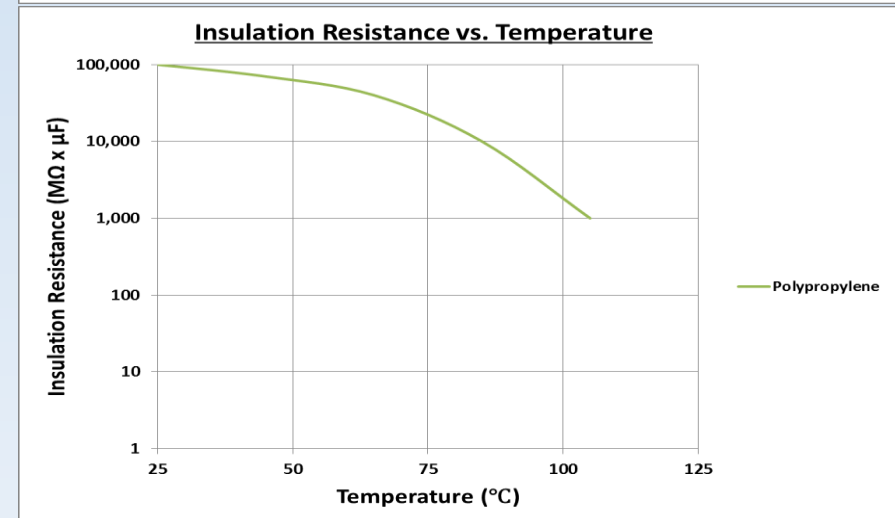
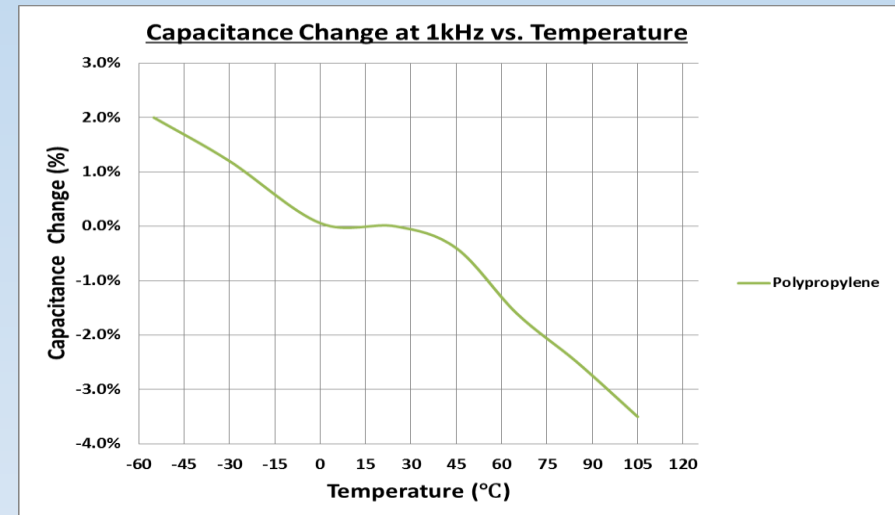
- BOPP – Bi-axially oriented polypropylene
- PET – Polyester
- PC – Polycarbonate
- PPS – Polyphenylene sulfide



The polypropylene benchmark

8

- Light weight – specific gravity 0.91
- Low DF – 0.02% through 100kHz
- Highest DC Link energy density (3-5 j/cu.in.) of standard dielectrics
- Stable capacitance vs. temperature
- Lowest cost dielectric option
- Excellent self-healing ability



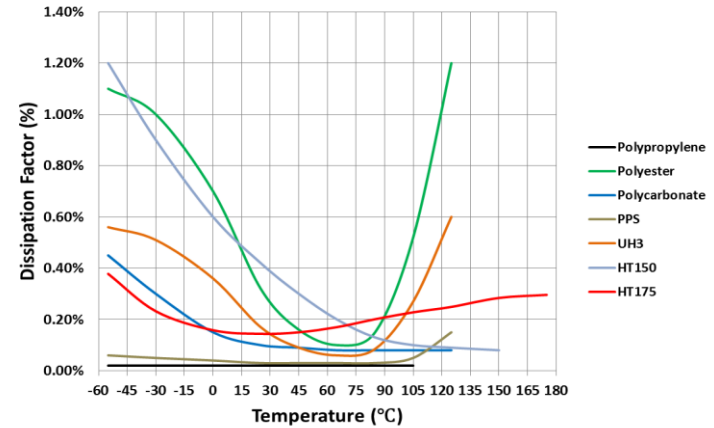
Overview with high temperature film

9

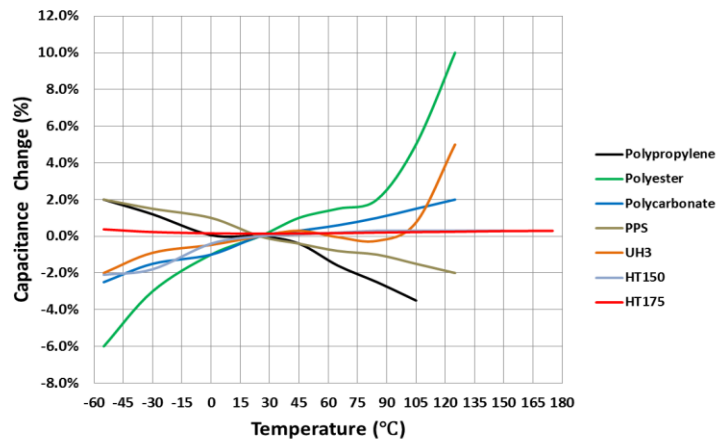
Market available dielectrics

- BOPP – Bi-axially oriented polypropylene
- PET – Polyester
- PC – Polycarbonate
- PPS – Polyphenylene sulfide
- UH3, HT150, and HT175 ECI proprietary dielectrics

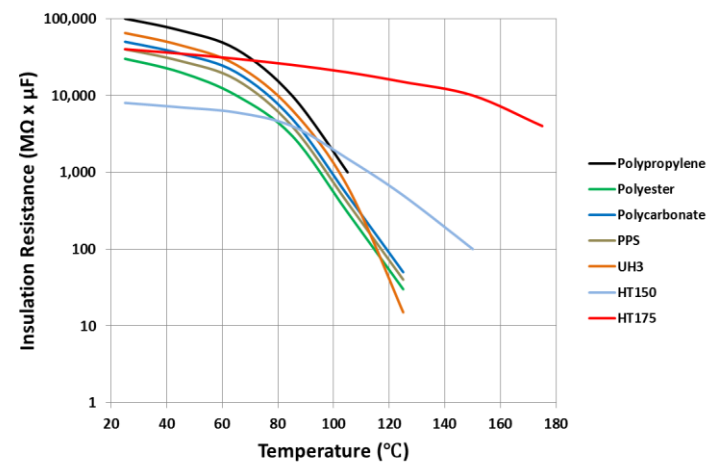
Dissipation Factor at 1kHz vs. Temperature



Capacitance Change at 1kHz vs. Temperature



Insulation Resistance vs. Temperature



Dielectric comparisons

10

Notes to following comparison slides

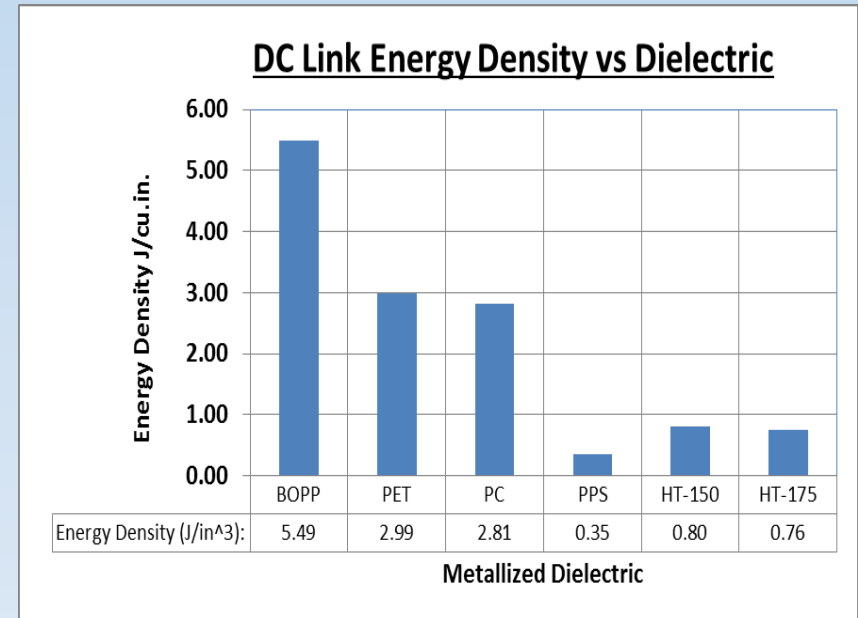
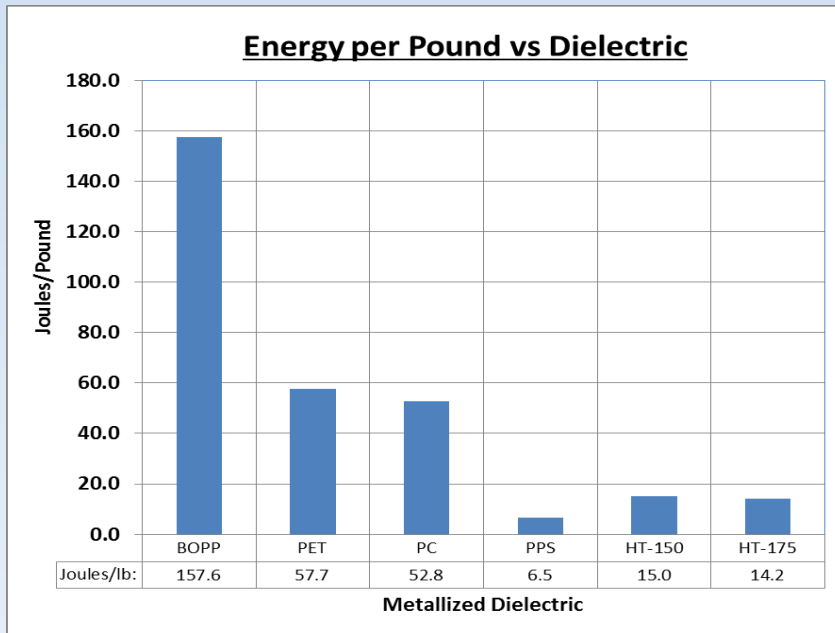
- 1,000 μ F, 1000VDC varied by dielectric
- Basic winding volume and weight without packaging
- Data based on present state-of-the-art for DC links

Present DC Link Energy Densities

11

Graphic represents DC link energy densities

Important to note that energy density of BOPP in snubbers ($\sim 0.7 - 1 \text{ j/cu. in.}$) is already available for HT150 and HT175



2014 HT150 & HT175 energy density enables direct size replacement of snubbers mounted to high temperature switches!

ECI Available high temperature dielectrics

12

- Polycarbonate (125C) – QPL 83421, 55514, several industrial series under MC and 5MC
- PPS (125C) – QPL MIL-PRF-83421/06 (hermetic seal), MU series (wrap & fill)
- UH (125C) – UH3 series (plastic case - ripple filter)
- Teflon (200C) – MT1 series (wrap & fill – down hole)
- HT-150 (150C) – HT1 series (plastic case - snubber)
- HT-175 (175C) – 5HT46 series (plastic cased - resonant supplies)
- Application specific designs using any of the above dielectrics (metallized or film-foil)

High temperature dielectric barriers

13

- Present demand too small to motivate resin manufacturers
- Most resin reactors look for 100 ton markets
- Present alternatives do not approach BOPP benchmarks (energy density, low losses, cost)

ECI UH3 Capacitors

14

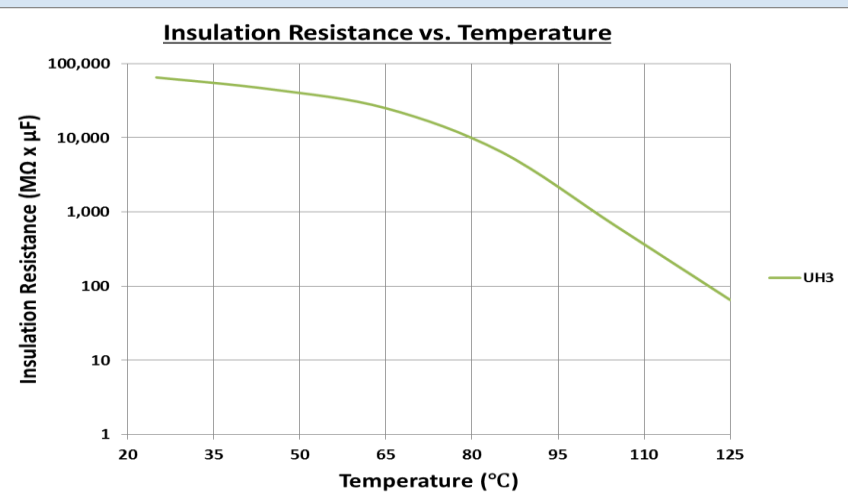
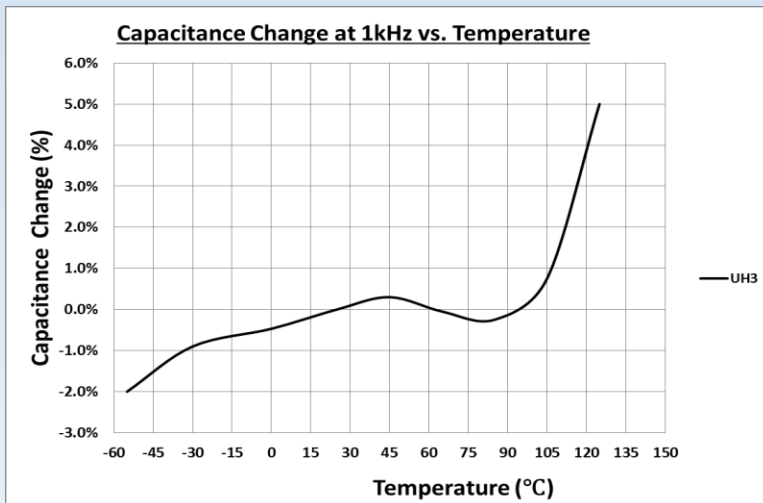
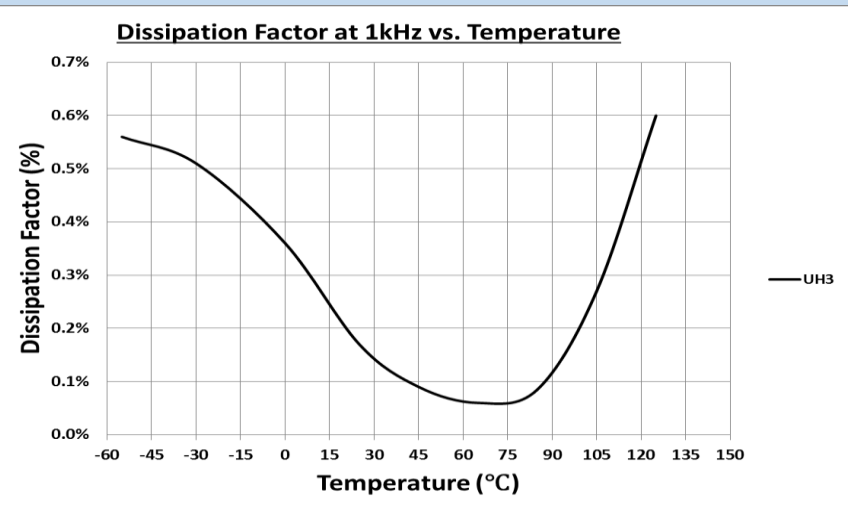
UH3 – Proprietary metallized dielectric

Lower cost than PPS or PC.

Lighter than PET or PPS.

Lower losses than PET.

Life Tested 2000 hours at 130% Vr at 125C



ECI UH3 Capacitors

15

- **Capacitance Range**
15.0 μ F to 120.0 μ F
- **Operating Temperature Range**
-65°C to +125°C
- **Voltage Rating**
450VDC to 1200VDC

FEATURES

- Continuous operation at 125°C
- Lower cost than PC or PPS
- Long term available resin
- UH3 offered with stud or threaded bushings
- Integrated mechanical mounting
- Ultra low ESL < 10nH available



ECI HT-150 dielectric (150C capacitors)

16

HT-150 – Proprietary metallized dielectric

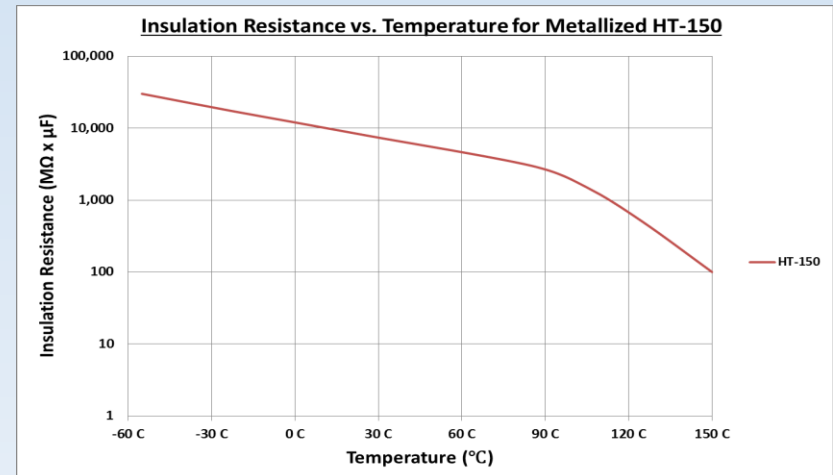
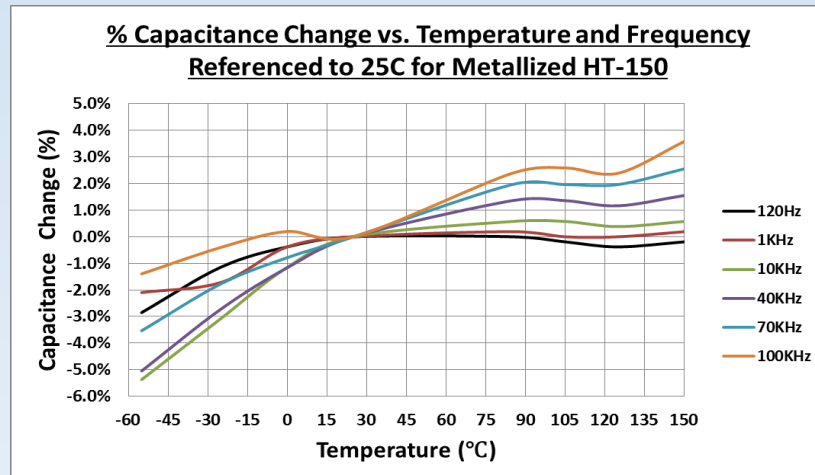
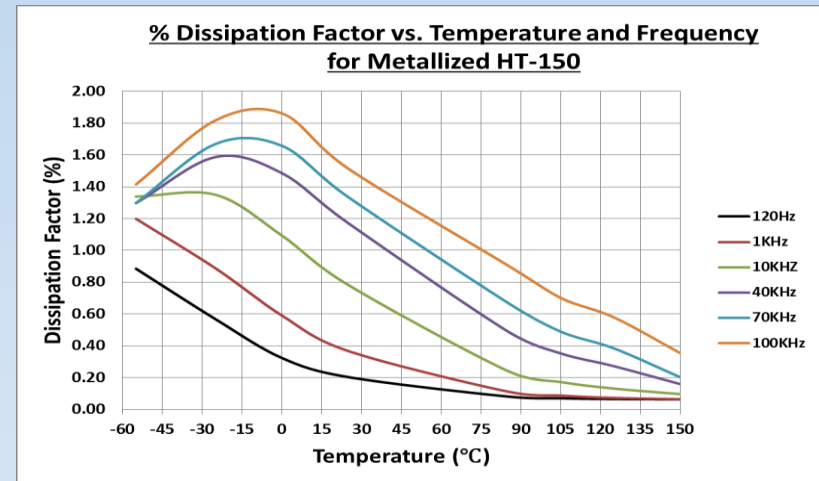
Stable Capacitance Change vs. Temperature and Frequency;
-5.5% to +3.5%

Low Dissipation Factor vs. Temperature and Frequency; <2%

Very high peak current (>10 x BOPP)

Life Tested 2000 hours at 130% Vr at 150C

*Metallized versions available for snubbers and resonant caps
at BOPP energy density at >10x I-pk of BOPP



ECI HT1 Series snubber - 150C capacitors

17

- **Capacitance Range**
0.12 μ F to 2.2 μ F
- **Operating Temperature Range**
-55°C to 150°C
- **Voltage Rating**
600VDC to 2400VDC



FEATURES

- Continuous operation at 150°C
- Highest peak current capabilities of any metallized film capacitor technology
- Low loss factors that decrease with temperature
- Tight capacitance stability versus temperature between -55°C and +150°C
- Volume efficiency comparable to 85°C polypropylene snubber capacitors like ECI series MP88

ECI HT1 Ripple current power test

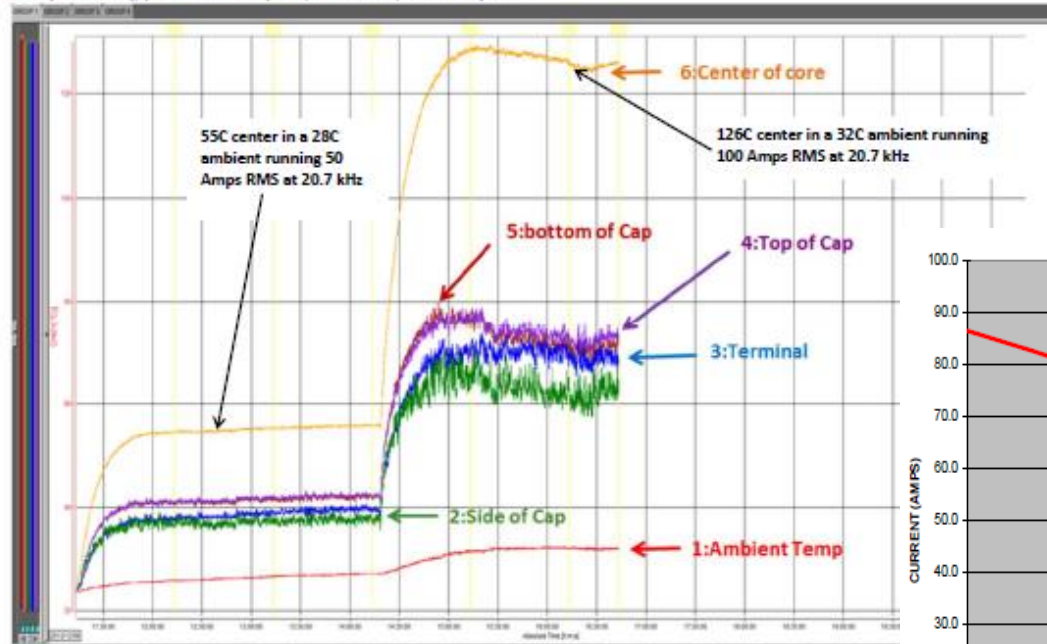
18

Electronic Concepts Incorporated

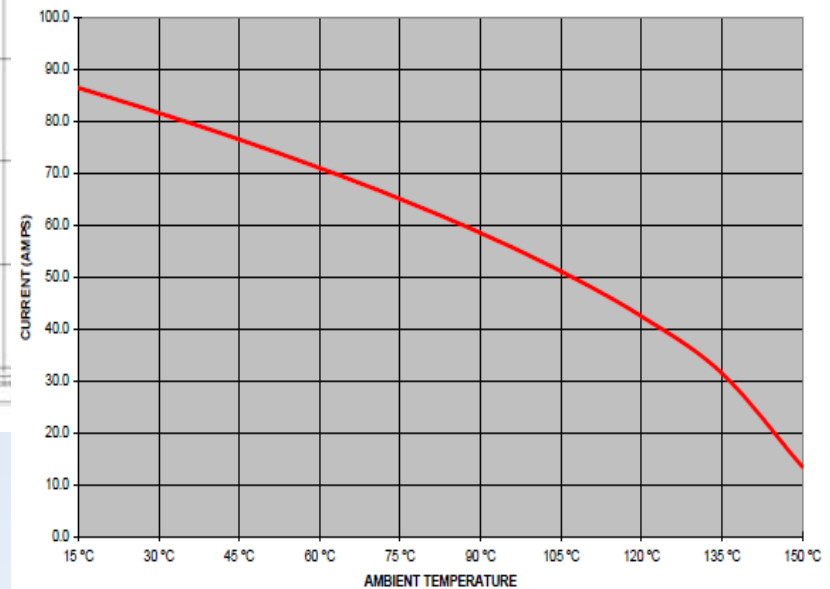
HT1 150C Power Capacitor Testing

SHT-30036J, 60uF +/-5%, 400VDC, Ripple Current Testing

$$R_{th} = (126C - 32C) / (100^2 \times 0.00247) = 94 / 24.7 = 3.8 \text{ C/Watt-Dissipated}$$



- -55C to 150C
- 60uF / 400vdc
- 50 A-rms & 100 A-rms at 20kHz
- $R_{th} = 3.8 \text{ Deg-C/Watt-dissipated}$



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ECI HT-175 dielectric (175C capacitors)

19

HT-175 Proprietary dielectric and foil high-current resonant caps

Stable Capacitance Change vs. Temperature and Frequency

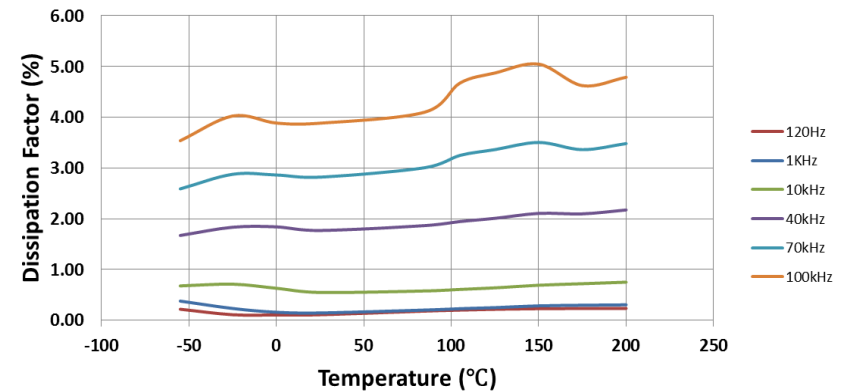
Low Dissipation Factor vs. Temperature and Frequency (high temp AC filter capacitors possible)

Very high peak current (>10 x BOPP)

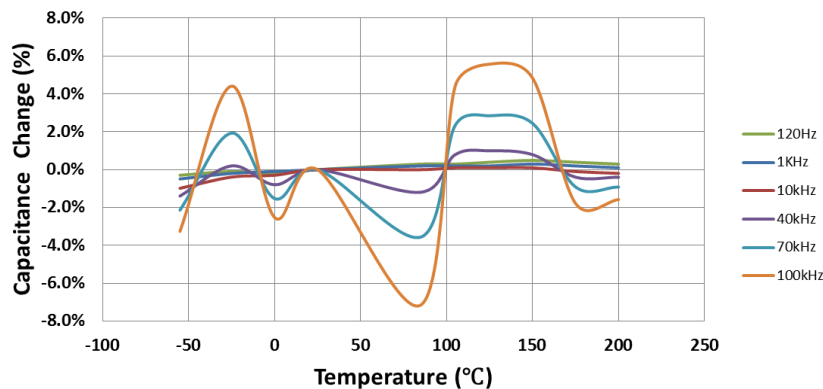
Life Tested 2000 hours at 130% Vr at 175C

*Metallized versions available for snubbers and resonant caps at BOPP energy density at >10x I-pk of BOPP

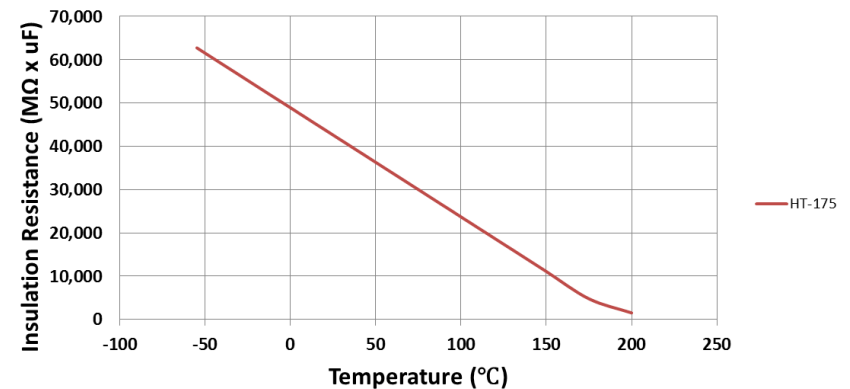
% Dissipation Factor vs. Temperature and Frequency for Metallized HT-175



% Capacitance Change vs. Temperature and Frequency Referenced to 25C for Metallized HT-175



Insulation Resistance vs. Temperature for Metallized HT-175



ECI 5HT Series resonant – 175C capacitors

20

- **Capacitance Range**
0.010 μ F to 0.100 μ F
- **Operating Temperature Range**
-55°C to 175°C
- **Voltage Rating**
400 VDC, 230 VAC

FEATURES

- Continuous Operation at 175°C
- Compact Configuration
- Direct Plug-in Spade Lugs
- Low ESL
- Low ESR
- High dv/dt
- High Peak Current



ECL continuing R&D

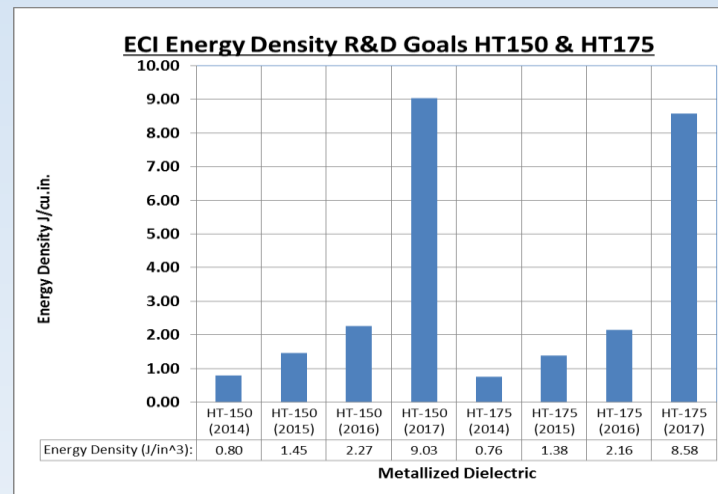
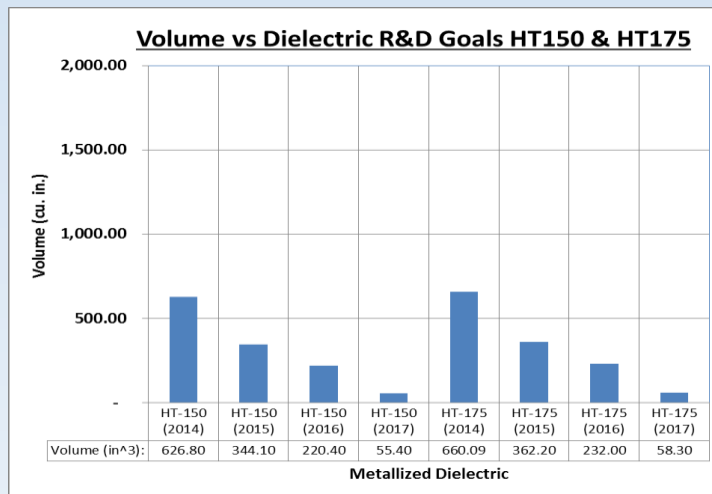
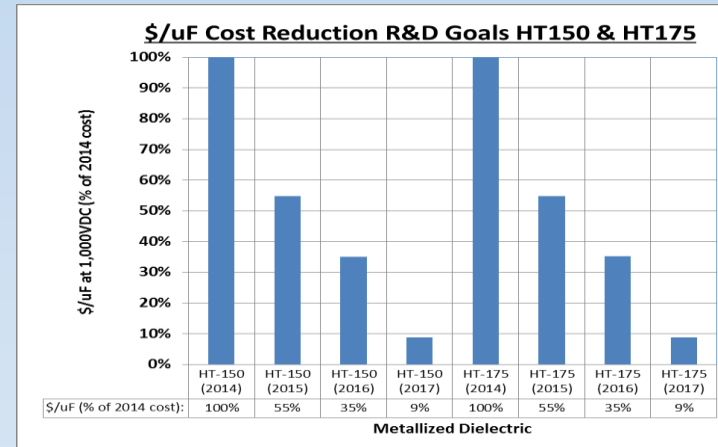
21

- Increase energy density on HT-150 and HT-175
 - ▣ Define stress curve through life
 - ▣ Goal to double voltage stress (4x energy density)
- Continue working with resin manufacturers
 - ▣ Studying new dielectrics in film labs
- Continue working with universities
 - ▣ NCSU, VT, PSU,...
- Continue working with government labs
 - ▣ Support DOE projects

ECl continuing high temperature R&D 2015-2017

22

- Continuing development of HT150 and HT175
- 2014 energy densities equivalent to BOPP snubber lines MP80, MP88, 5MP2 (direct replacements at higher temperature)



Other ECI High temperature research

23

- FPE (>200C) – ECI solvent cast and successfully tested to 300C, resin cost prohibitive (>> PPS)
- PEEK (175-200C) – lacks self-healing similar to PPS, ECI stretched and characterized
- PTFE (>200C) – heavy, low voltage stress, research on-going by resin manufacturer
- PEN HV (150-175C) – limited availability, problems with ESR over life in multiple trials
- Other polymers actively under research with universities, government labs, polymer groups, and private companies

End of Presentation

24

Contact Electronic Concepts Incorporated for more information or application assistance.

Visit our website at ecicaps.com

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Revisions

25

- Final 1 – released to APEC for print
- Final 2 – after release corrections made to slides:
 - #2 – correct date range to 201-2017
 - #7 – correct graphs showing PET twice
 - #12 – expanded series with description
 - #15 – correct temperature range from 150C to 125C
 - #20 – correct temperature range from 150C to 175C