Reliability Considerations of Inverter/DC Link Capacitor using PP Film and 105°C Engine Coolant

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Who is SBE?

- Formerly a Division of Sprague Capacitors
- The Barre, Vermont plant has been building film capacitors since 1946
- Polypropylene (PP) Film Capacitors built in Vermont since introduction of the Orange Drop® in 1959
- SBE is the recipient of a 2008 DoE SBIR Phase II award to develop a High Temperature PP DC Link Capacitor which is reliable using 105°C Cooling methods

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Statement of the Problem

- Nearly all PHEV, HEV, and EV applications use an inverter to convert DC from the battery/fuel cell to clean AC power for the Electric Motor
- Reliability is a major concern
- Engineering trade-offs for power density, cost, and packaging flexibility can greatly effect reliability
- Availability of creative solutions is limited in the industry, causing most system platforms to follow a “well beaten” path

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Inverters and the Engineering Trade-Offs

- Voltage – Inverters almost universally get more efficient with higher voltages
  - Batteries and Fuel Cell tend to be more expensive with higher voltages
  - Aluminum Electrolytic capacitors (the least expensive choice when usable) are VERY voltage sensitive and become unusable for long term reliability above 300V bus voltages - unless “heroic” and expensive protection mechanisms are employed

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Inverters and the Engineering Trade-Offs

- Temperature - Components inside the inverter must be kept within the material limitations for each component to insure good reliability
- This dictates low temperature cooling fluid for most inverters today
  - Typically 50 - 70°C liquid cooling in many applications
  - Air Convection Cooling common in Bus/Heavy Vehicle applications where sufficient surface area is available
- Cooling needs of the inverter are driven by the requirements of the semiconductor switching devices and that of the DC Link (Ripple) Capacitor(s).

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Inverters and the Engineering Trade-Offs

- Maximum reliable current density of the Inverter is essentially dependent on the Temperature Management Strategy (assuming appropriately-sized components are used).
- The designer has four knobs to turn:
  1) coolant temperature
  2) coolant efficiency
  3) sizing of components (the brute strength method)
  4) decrease current
- IT'S ALL ABOUT COMPONENT TEMPERATURE RISE IN THE INTENDED USE

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US Department of Energy's take on it

"Hybrid Electric Vehicles (HEVs) and plug-in hybrids (PHEVs) require advanced technology in the areas of Energy Storage and **Ripple Current Capacitors**. These technology areas represent some of the most critical barriers to the development and marketing of cost competitive HEVs and PHEVs."

Emphasis added

U.S. Department of Energy, October 2006

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US Department of Energy's take on it

"Currently, inverter technology used in hybrid electric vehicles uses 70°C coolant that is supplied via a separate cooling loop in the automobile. It is desirable to eliminate the need for an additional cooling loop to reduce cost and complexity in the vehicle."

U.S. Department of Energy, Freedom Car Program
Advanced Technology Solicitation, December 2006

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Interpretation

- There isn't much incentive to get too innovative on semiconductor solutions if the DC Link capacitors need 50 - 70°C coolant or are otherwise prohibitively expensive at 105°C (i.e. high current ceramic)
- Since 105°C engine coolant is readily available and must be sized for SIGNIFICANT heat transfer from an internal combustion engine, an inverter that could run reliably using it would have more or less "free" coolant use
- What is needed is an inexpensive DC Link capacitor that can reach automotive reliability goals using 105°C Coolant
  - Sidebar: or can accept extreme inefficiencies of cooling strategies inside the inverters using 50 - 70°C coolant

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The current goal of many HEV/PHEV/EV advanced systems

- Battery/Fuel Cell Voltages:
  - 325V – 500V (388V typical)
- Ripple Currents of 100 – 250Arms are the typical demands of a 50 – 90kW Electric Traction Motor
- It's the proverbial "gimmie more, for less, in no more than the current space occupied….oh ya, smaller would be good".
- But the reliability bar is not being relaxed
- There is almost universal agreement that Aluminum Electrolytic Capacitors do not solve this total inverter solution goal

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Enter Polypropylene (PP) Film

- Already used in many high power traction drives
- Decades of proven long term reliability
  (equal to and beyond automotive requirements when used within the appropriate component limits)
- Relatively low cost - although universally considered a “more expensive option” by the industry today
  - Comparing existing DC Link cost of 25 – 40kw inverters with those of the 50kw – 90kw class using traditional solutions
- Very low sensitivity to high voltage transients and brief high current events
  - Long term reliable in the “real world” when properly designed

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PP Capacitor Limitations

- The reliability of PP Film capacitors is determined by 3 things:
  - The Current Density passing through the electrode end area
  - The hot spot/region created in the capacitor due to resistive loss under the current imposed
  - The voltage applied and the ability of the capacitor to “withstand” the applied voltage at the instant it is applied

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PP Capacitor Limitations

- Current Density passing through the electrode area is a function of the total area and the connection method
- While this can also have a great impact on reliability in the DC Link solution, typical HEV/PHEV/EV requirements are not limited by this characteristic
- SBE has patented technology that addresses this particular area
  (visit www.sbelectronics.com)

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PP Capacitor Limitations

- SBE has performed extensive modeling and testing to prove exactly where the hot spot or hot region is in a film capacitor
- The farthest location from the terminals will have the highest temperature rise
  - Film resistive losses
  - Longest heat path to the “convection medium” (the terminals and end spray).
  - PP Film (any film really) is a terrible thermal conductor

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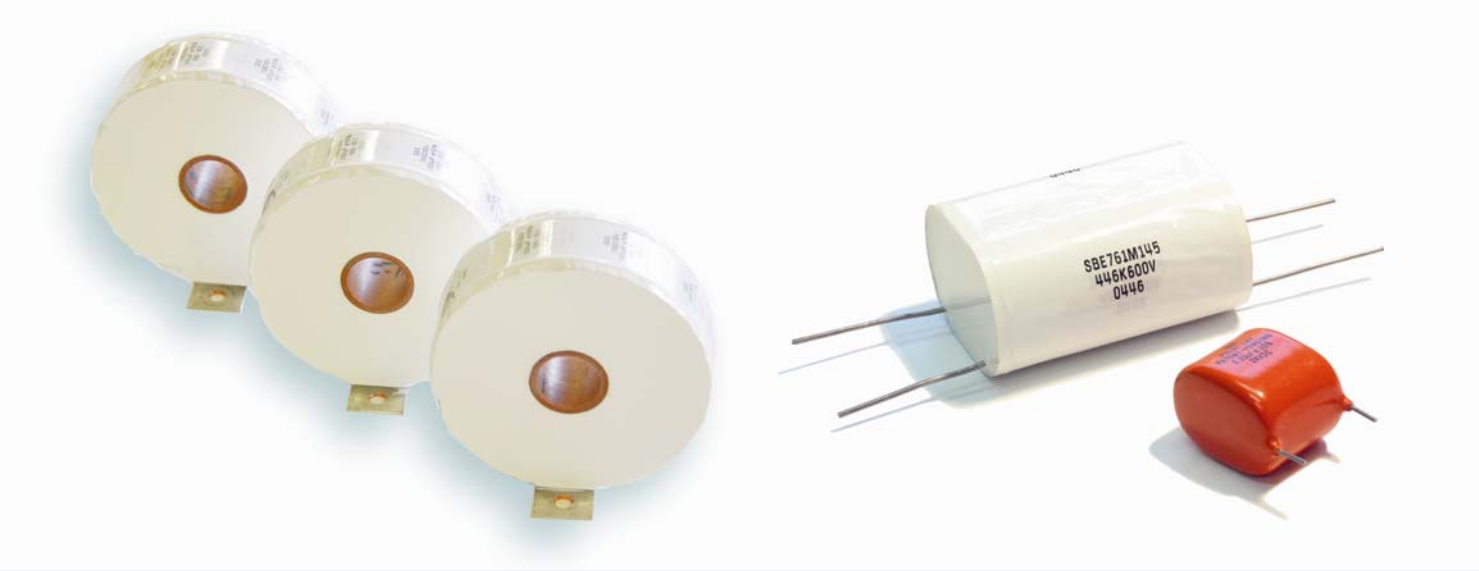
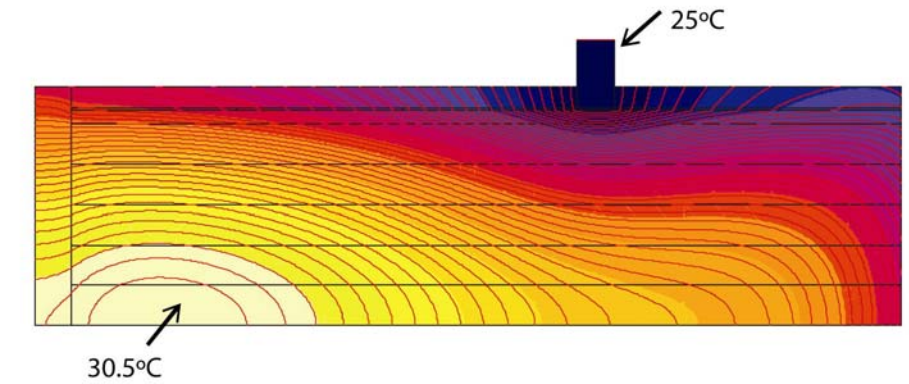
PP Capacitor Limitations





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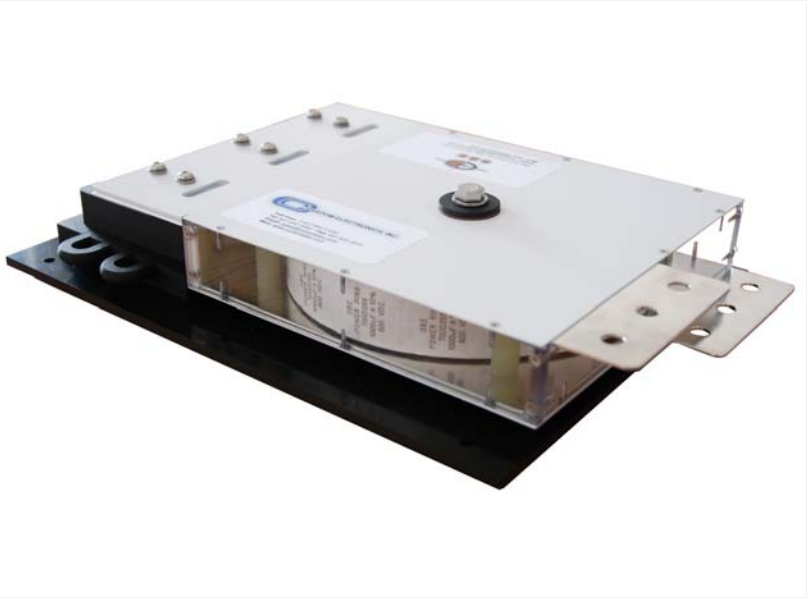
PP Capacitor Limitations



Conventional Inverter
vs. Power Ring

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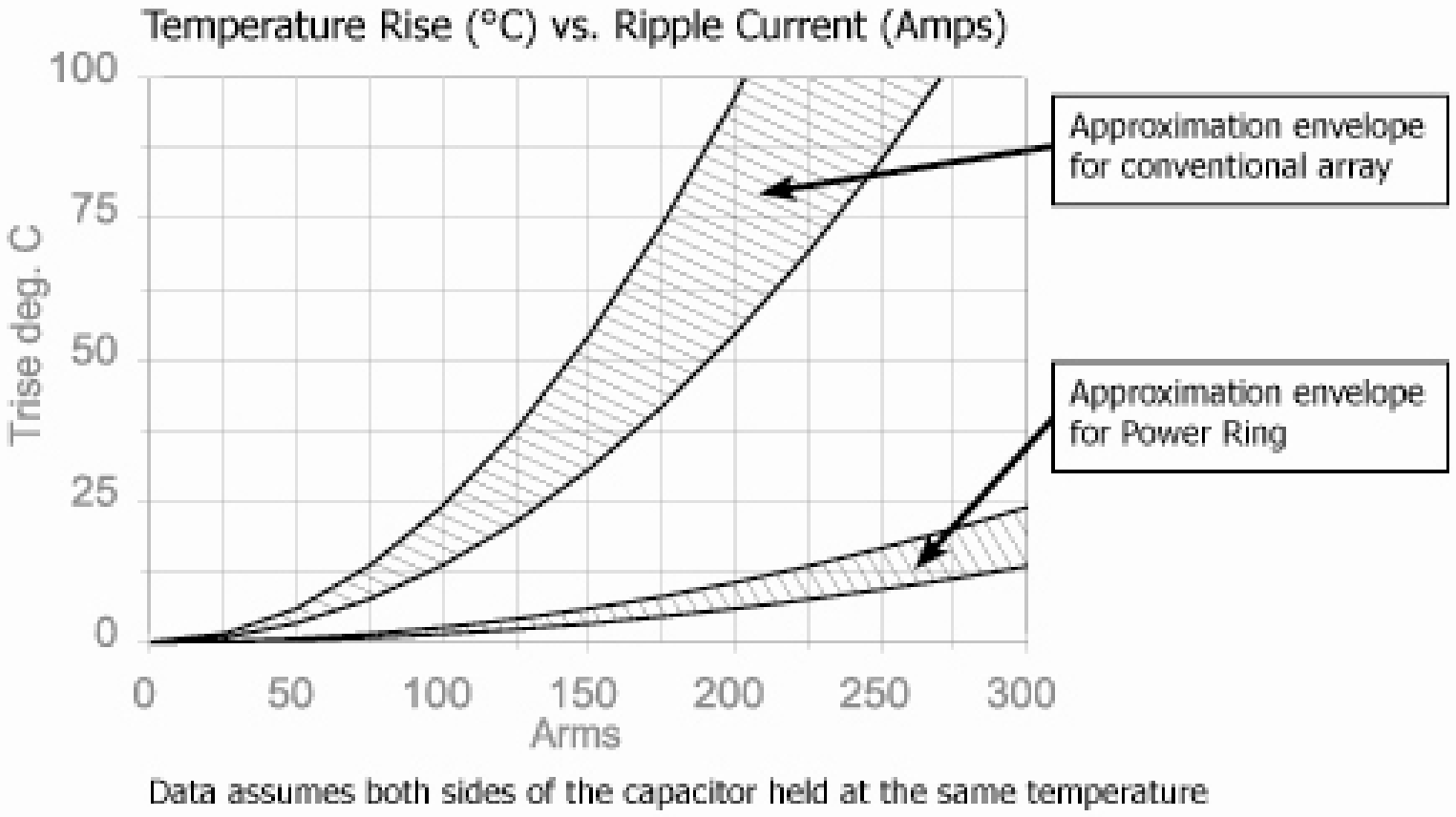
PP Capacitor Limitations



PP Capacitor Limitations

- In the DoE SBIR phase I, SBE performed material analysis and characterization on the base PP film material
- The PP Film was found to be stable into the 115 - 120°C region. This implies that 105°C cooling reliable operation is feasible as long as the hot spot temperature does not exceed 10 - 15°C.
  - Typical PP Film Capacitor shapes have 25 - 40°C temperature rise under desired current load conditions
  - The annular form factor “SBE Power Ring” has a demonstrated 4 – 10 °C temperature rise at 100 – 250Arms depending on size

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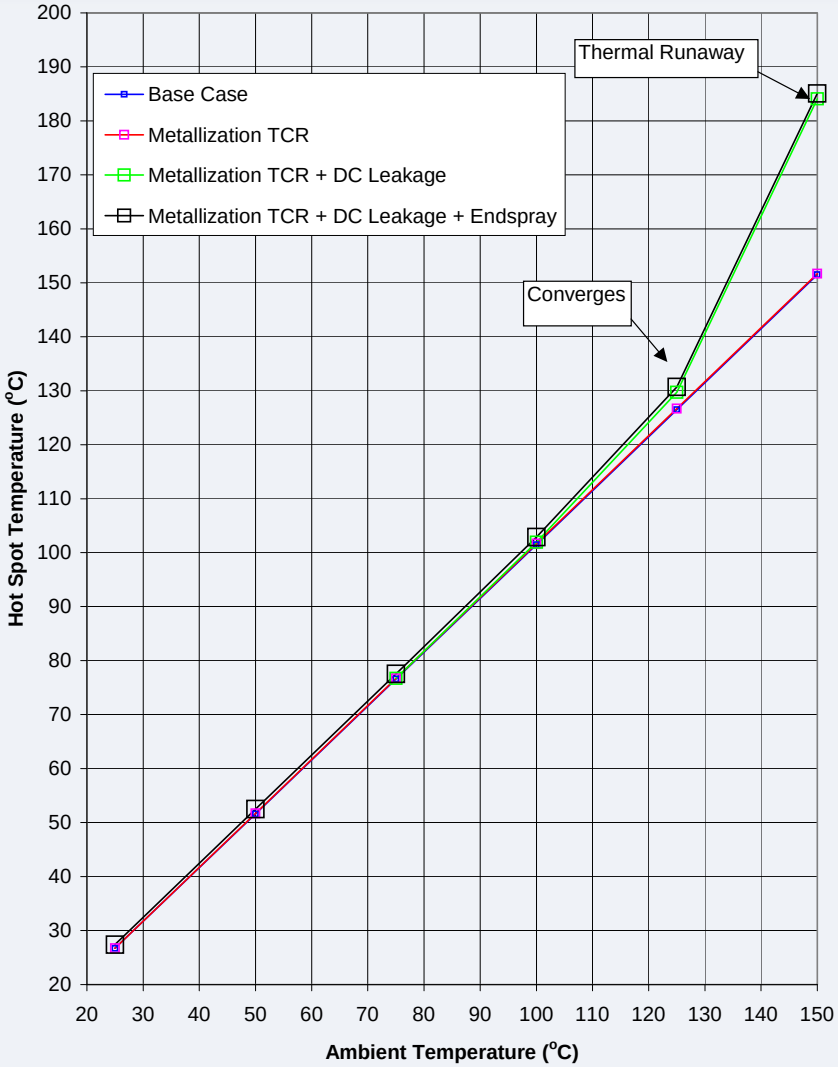
PP Capacitor Limitations



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PP Capacitor Limitations

- Voltage withstand is the ability of the capacitor dielectric, PP, to hold a specific voltage charge
- The voltage can be increased simply by using a thicker dielectric layer but this increases size, weight, and cost
- The desire is to use the thinnest material which can safely withstand 600Vdc at 25°C and still have the capacitor remain reliable
- How does PP behave up to the desired temperatures of 115 - 120°C hot spot?

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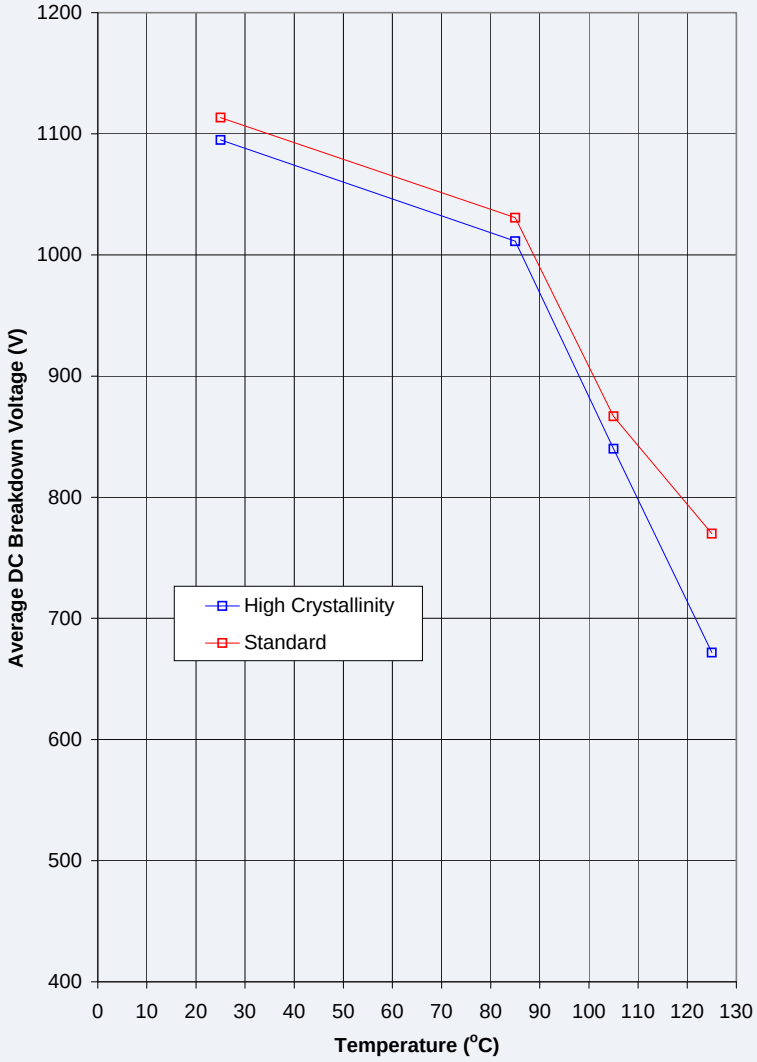
PP Capacitor Limitations



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Predicting Reliability

- Traditional methods of predicting reliability for capacitors involve voltage and/or temperature increase to invoke greater dielectric stress and potentially accelerate early failures
  - Voltage Acceleration: $FR@V2/FR@V1=[V2/V1]^{k}$
  - Temperature Acceleration: $FR@T2/FR@V1= 2^{[(T2-T1)/k]}$
- The problem in creating significant acceleration predictions is that significant differences are needed between T2 and T1 or V2 and V1
- The accelerated reliability method should not instigate its own unique failures due to overstress

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Predicting Liability

- DoE SBIR Phase II will be funding reliability testing and prediction results
- The voltage acceleration method has more promise for significant long term prediction results
- Many capacitors will have to log a heavy number of hours to give solid 10+ year lifetime predictions

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While we wait

- In the meantime, the Power Ring remains the lowest temperature rise DC Link capacitor in the market and will be more reliable at “normal” temperatures of 50 – 80°C coolant
- The lower coolant requirements compared to traditional capacitors gives much greater flexibility of placement within the “inverter box”
  - Significant increases in power density are possible

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Thank You

For more information on any of these topics, please contact SBE Engineering at PowerRing@sbelectronics.com