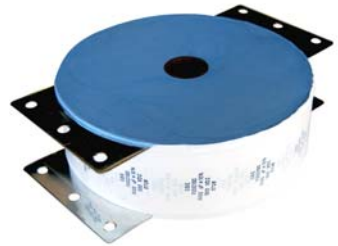
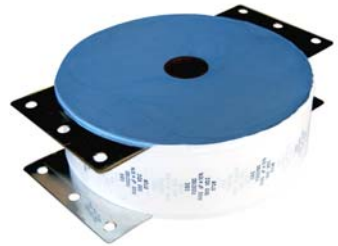


"A High Temperature, High Ripple Current DC Bus Film Capacitor in an Annular Form Factor"

Presented by:
Terry Hosking, V.P. Engineering
SBE Inc.
Power Ring Division

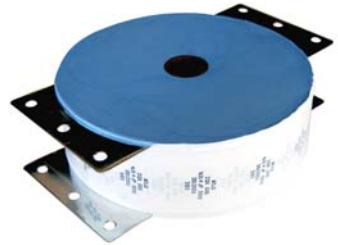
February 14, 2008 • Atlanta, Georgia

Areas of Discussion



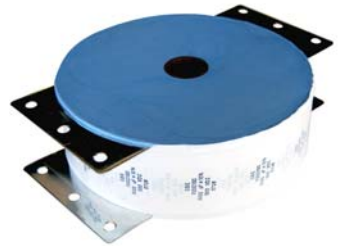
- Review 2007 presentation of thermal issues, simulation & testing results
- Dielectric choices, why Polypropylene?
- Recent R&D focus on Polypropylene film
- Findings, summary and direction of future work

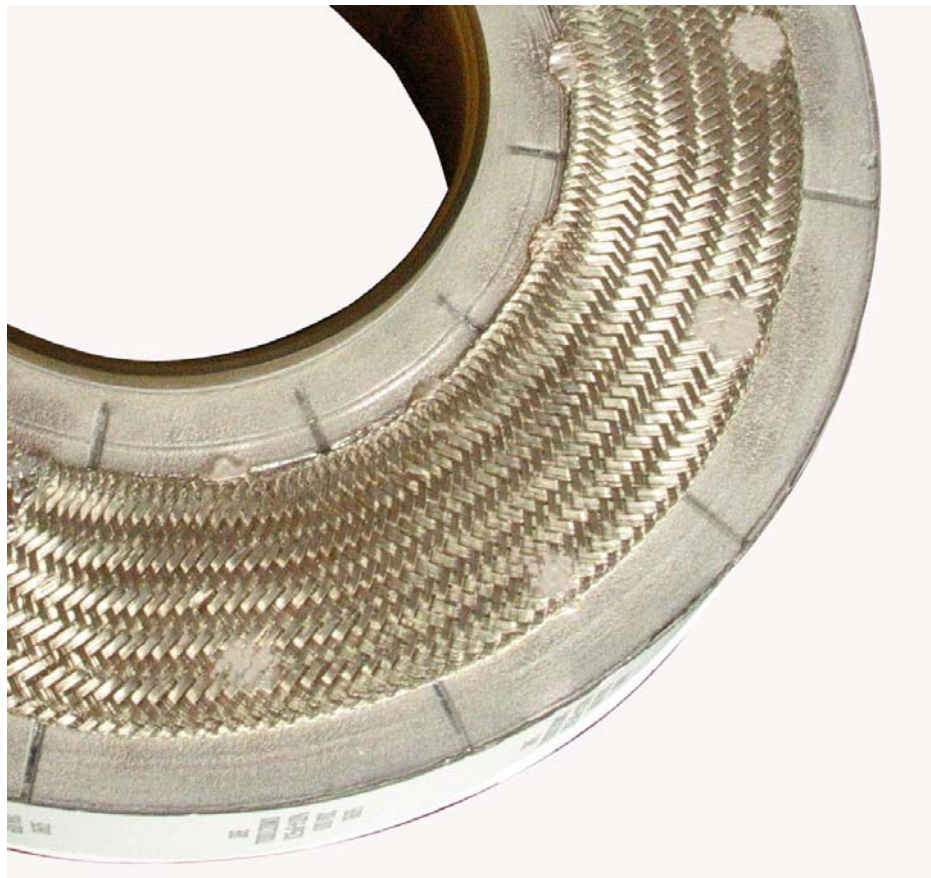
2007 Motor & Drives Review



- In 2007 we described thermal considerations for using the Power Ring in high ripple current inverter applications:
  - Advantages of a thin ring form factor; low losses, low T rise
  - Optimize interface between capacitor and bus structure
  - SBE's segmented end spray approach to mitigating thermal mismatch of metal end spray and plastic film

Power Ring's Segmented End Spray

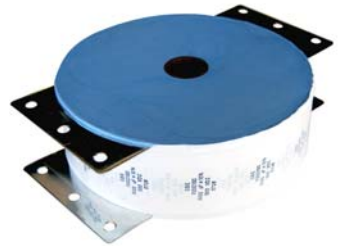


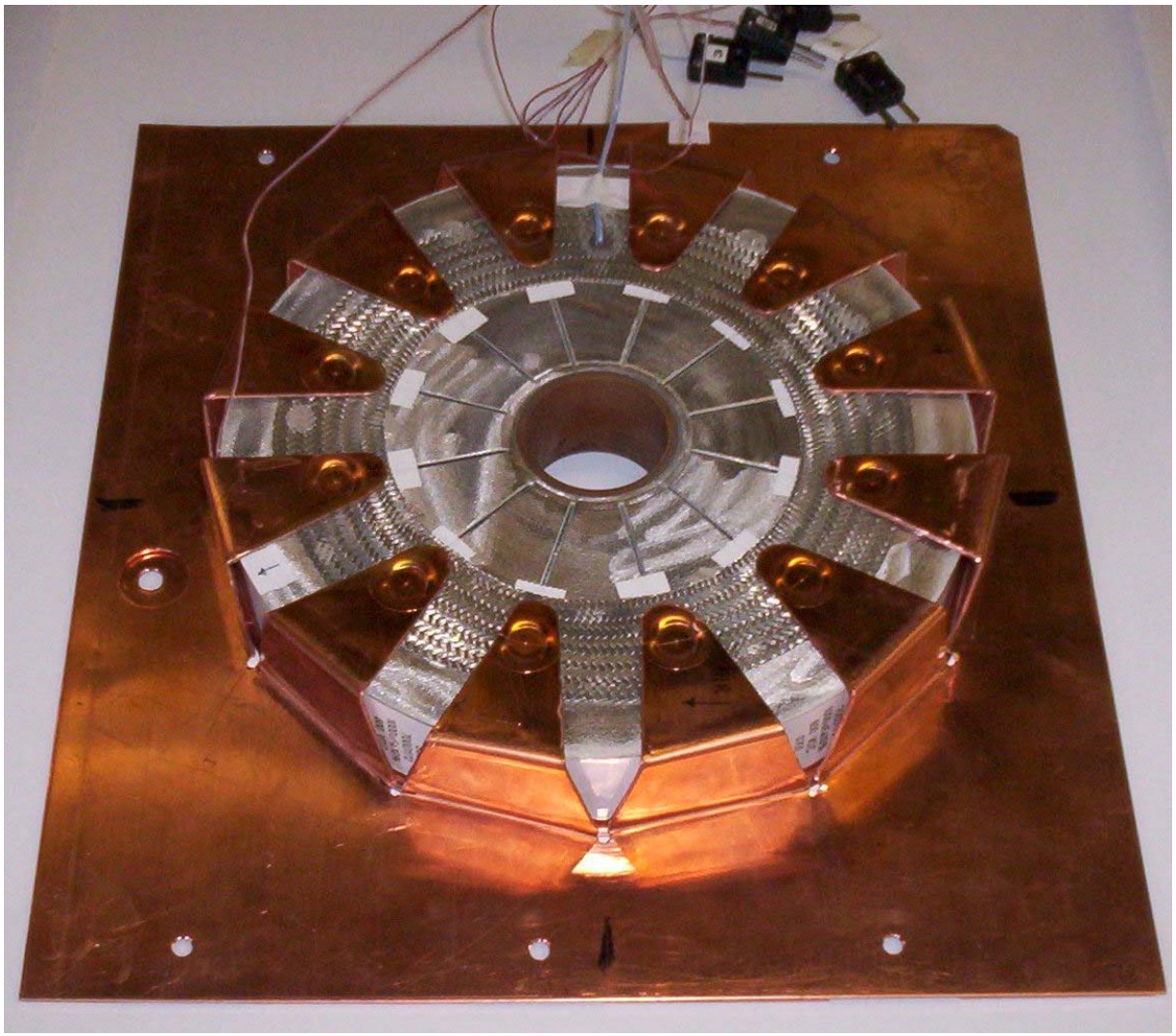


2007 Motor & Drives Review
Findings, Summary

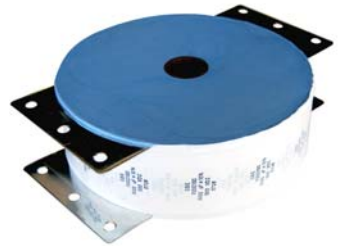
- Confirmed FLUX 2D simulation with test results:
  - T rise and thermal profiles for various film metallization resistances and cooling conditions
  - 1000 µF, 600 VDC unit built and tested
  - 100 KHz/240 Amp RMS test indicated only a +2°C temperature rise, surface to hot spot
  - Test data confirmed modeling accuracy

2007 Test Unit





So What is Driving the Choice of Dielectric Film?

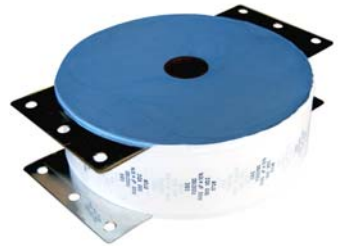


- DoE's FreedomCAR program outlines the demand for low cost, high temperature capacitor technology
- Upper temperature limit goal of +150°C
- Rationale for +150°C rating was to use +105°C engine coolant for inverter thermal management, and allow for a +45°C capacitor T rise

Why Polypropylene?

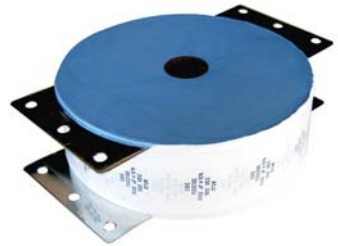
- High temperature films are available, but all are EXPENSIVE
  - PPS, 10x the cost of Polypropylene, self-healing issue
  - Polyimide, varied electrical performance over frequency and low dielectric strength
  - Teflon, difficult to metallize, has low dielectric strength and is difficult to wind in large capacitor sections
- In all cases there is a size penalty to pay when compared to Polypropylene

Why Polypropylene?



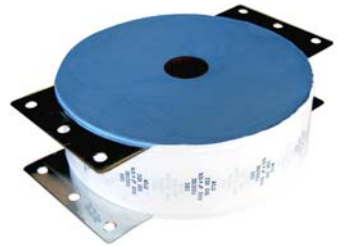
- Polypropylene presents best overall value
  - Plentiful, Generally Inexpensive
  - Long proven history of reliability
  - Excellent electrical characteristics
- The combination of these attributes, and the minimal temperature rise of the ring form factor, has led SBE to further research the limits of Polypropylene

Polypropylene



- Polypropylene resin is composed of 2 parts:
  - Atactic material which is non-crystalline (amorphous)
  - Isotactic material which is crystalline
  - Highly isotactic material has a higher melting point
- Highly isotactic polypropylene is referred to as High Crystallinity Polypropylene (HCPP)
- All capacitor grade polypropylene film, including HCPP, is produced by stretching in two directions, Biaxially Oriented Polypropylene (BOPP)

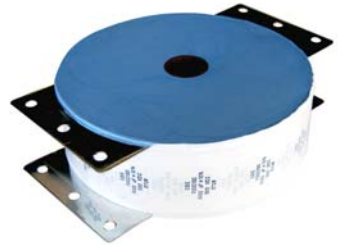
BOPP vs. HCPP



- HCPP is alleged to have improved performance at high temperature relative to BOPP

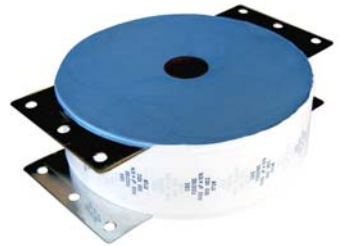
- Does it?

Polypropylene Characteristics



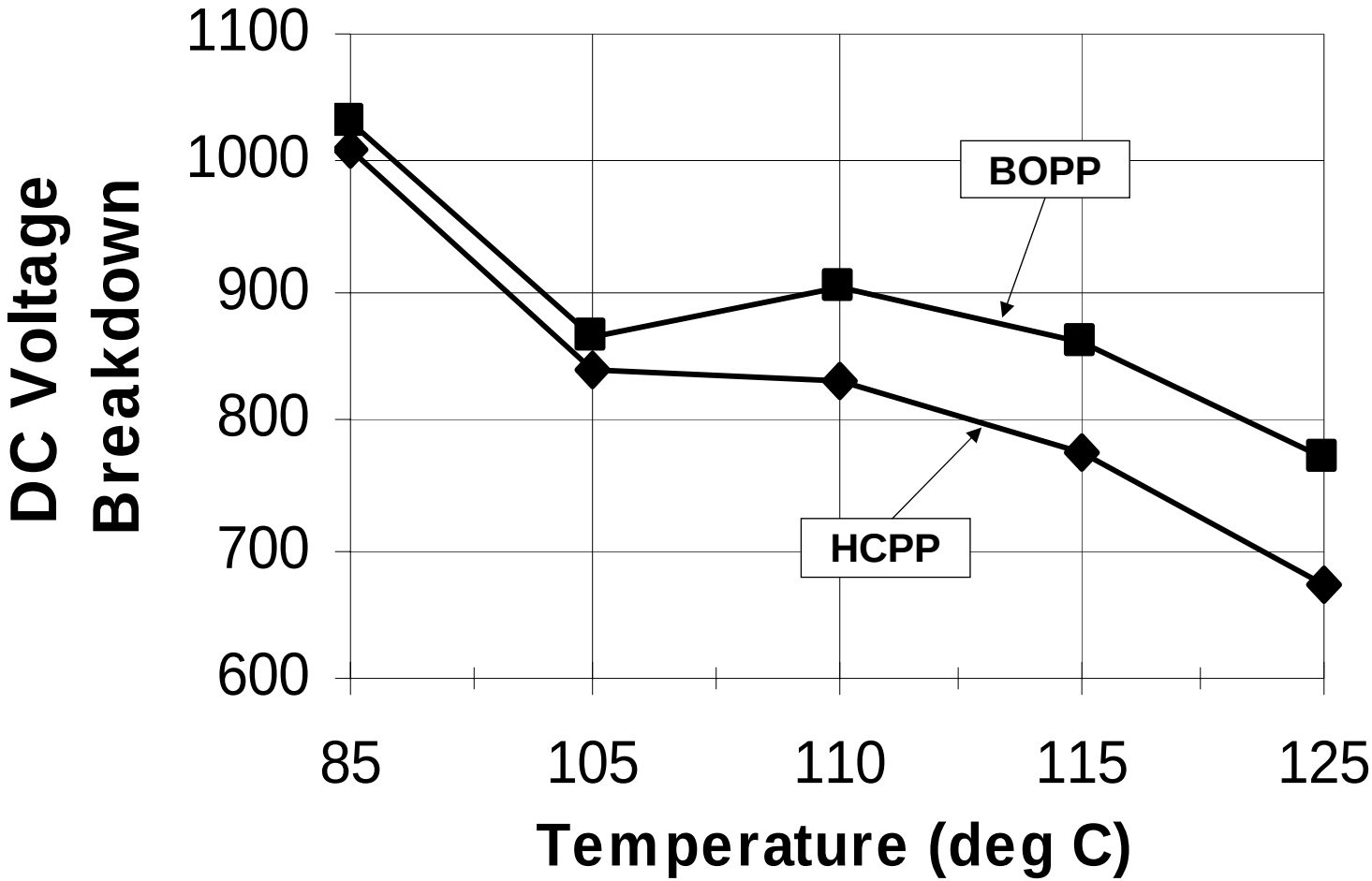
- Test data presented here on both BOPP and HCPP for:
  - Dielectric strength vs. temperature
  - Relative leakage current vs. temperature

Dielectric Stress

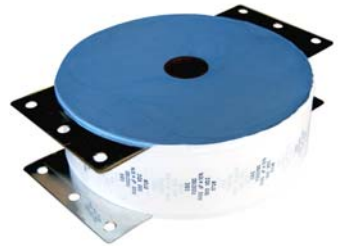


- Test data for dielectric strength vs. temperature
  - **Test data results not as expected!**
  - Data taken twice with same results
  - 3.8 micron film thickness

Dielectric Stress

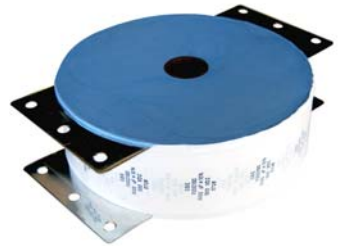


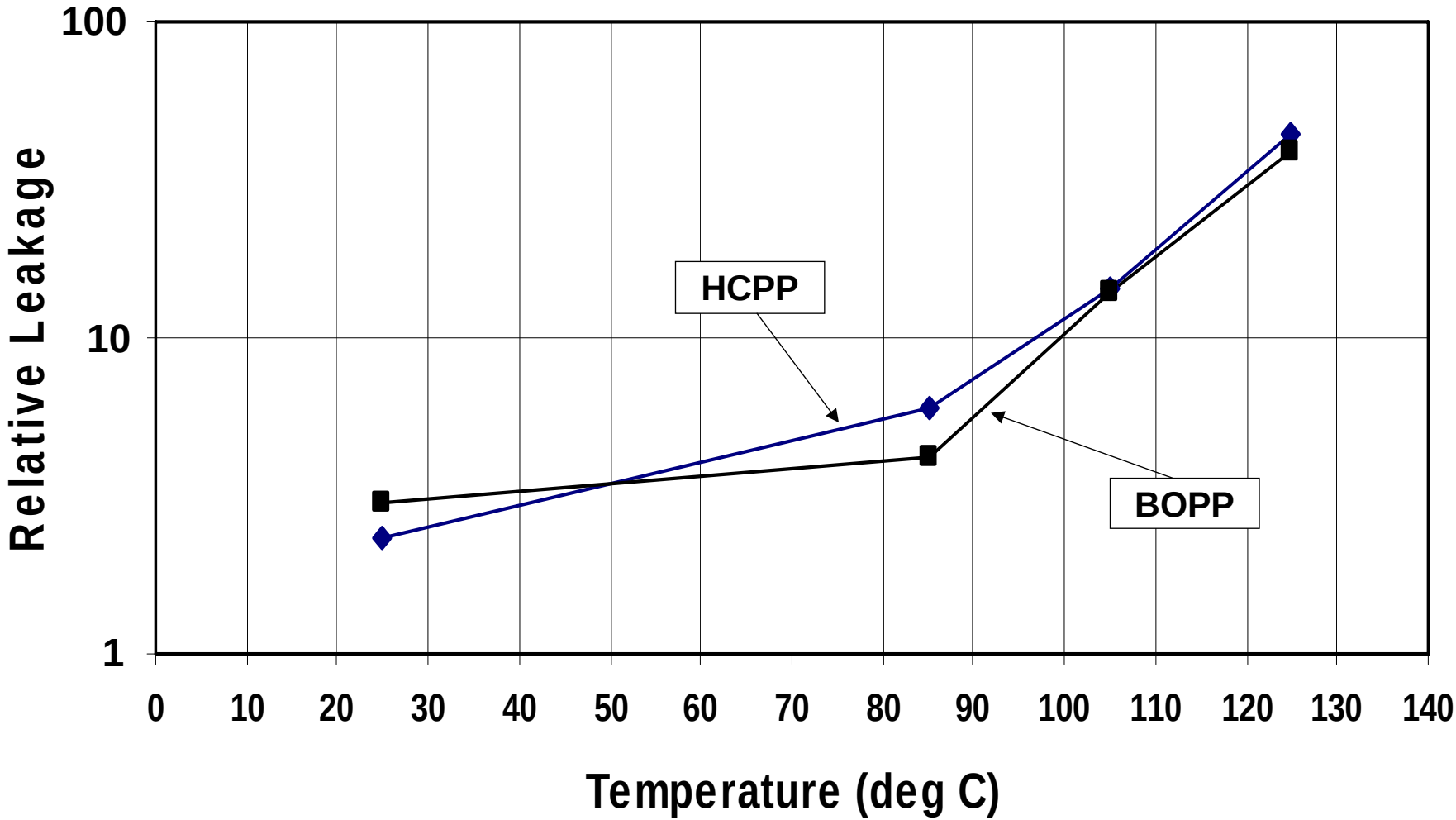
Leakage



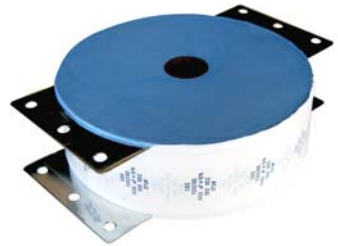
- It was expected that HCPP would have lower leakage
- Essentially no difference, although BOPP was slightly lower

Relative Leakage



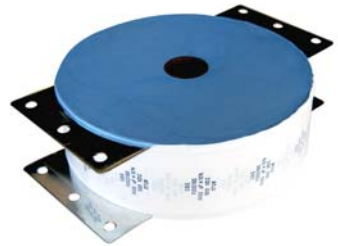


Capacitor ESR at High Temperatures

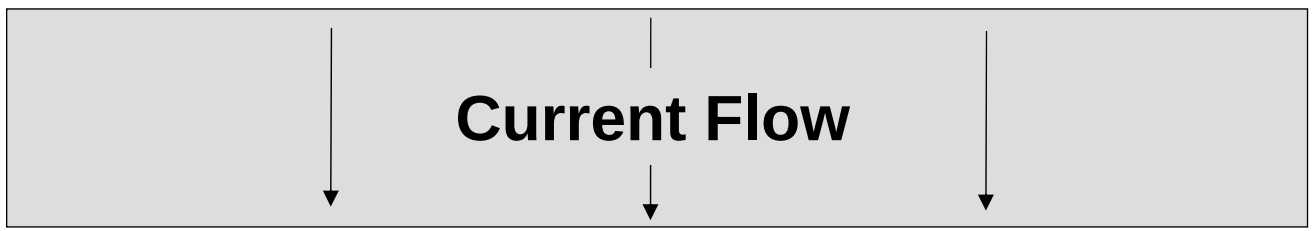


- Capacitor Temperature Coefficient of Resistance (TCR) vs. Temperature
  - TCR is a characteristic of the metallization on the film
  - Relates to ESR increases at higher temperature

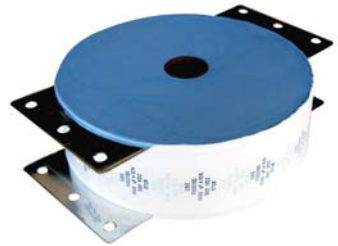
Capacitor Metallization TCR



- Metallization is Aluminum
  - TCR of bulk aluminum is ~3400 ppm/°C
- Current flow in a capacitor is across the film (Transverse)

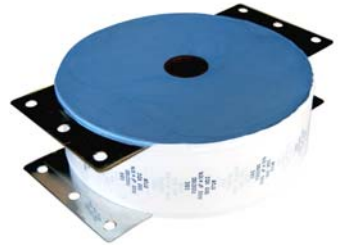


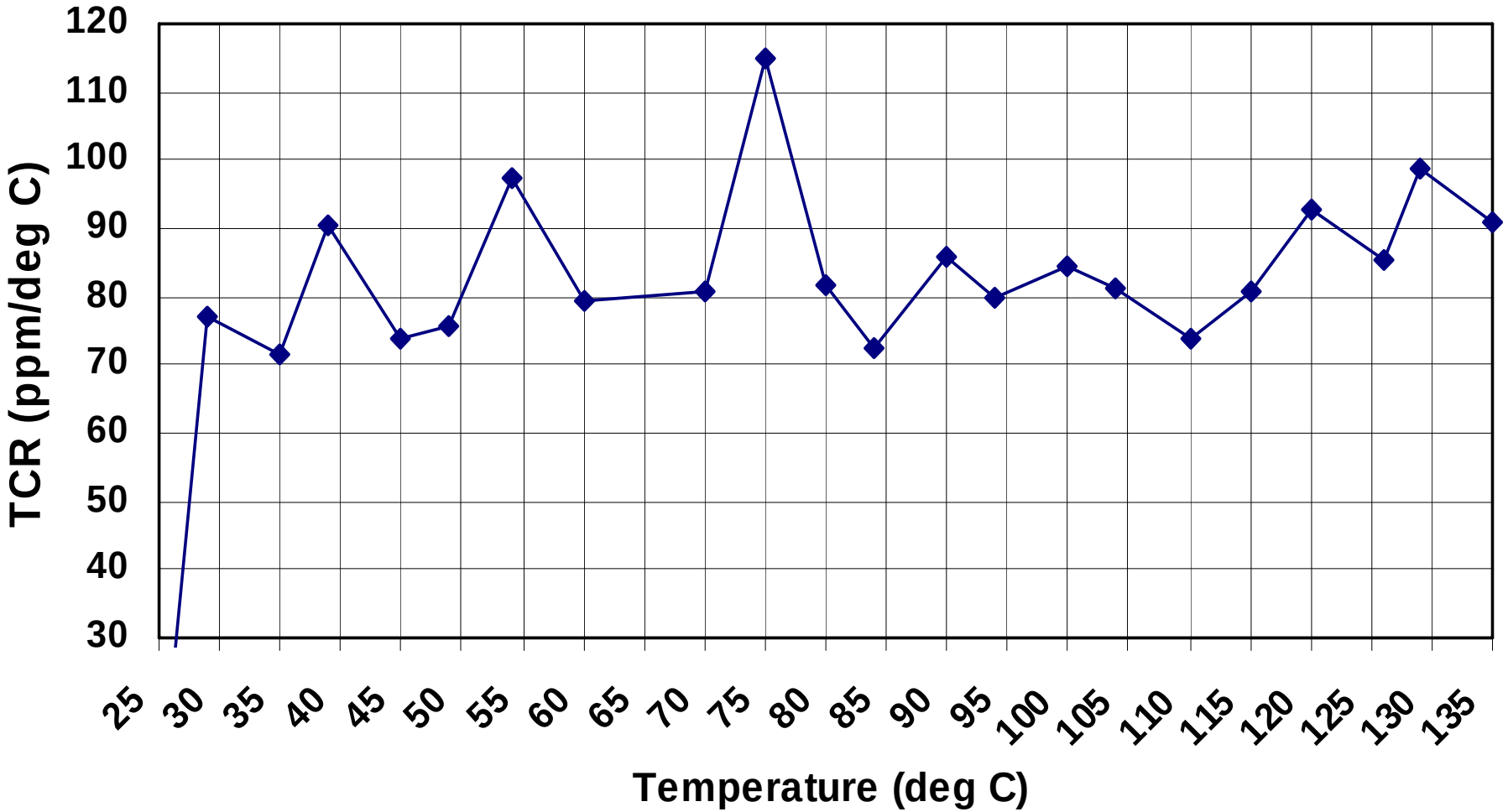
Capacitor Metallization TCR



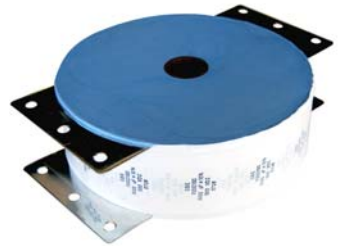
- Transverse TCR test data gathered
  - Capacitor-like device constructed to measure TCR using DC source
  - Expected TCR was ~3400 ppm/°C (one would expect ESR to behave the same)
  - SURPRISE, SURPRISE, SURPRISE!!
- Test data indicates TCR ~80-90 ppm/°C
  - Consistent from run to run
- ESR will rise less than expected at high temperature

TCR




TCR (ppm/deg C)
120
110
100
90
80
70
60
50
40
30
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
Temperature (deg C)

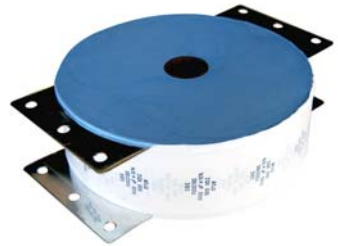
Implications of Test Data

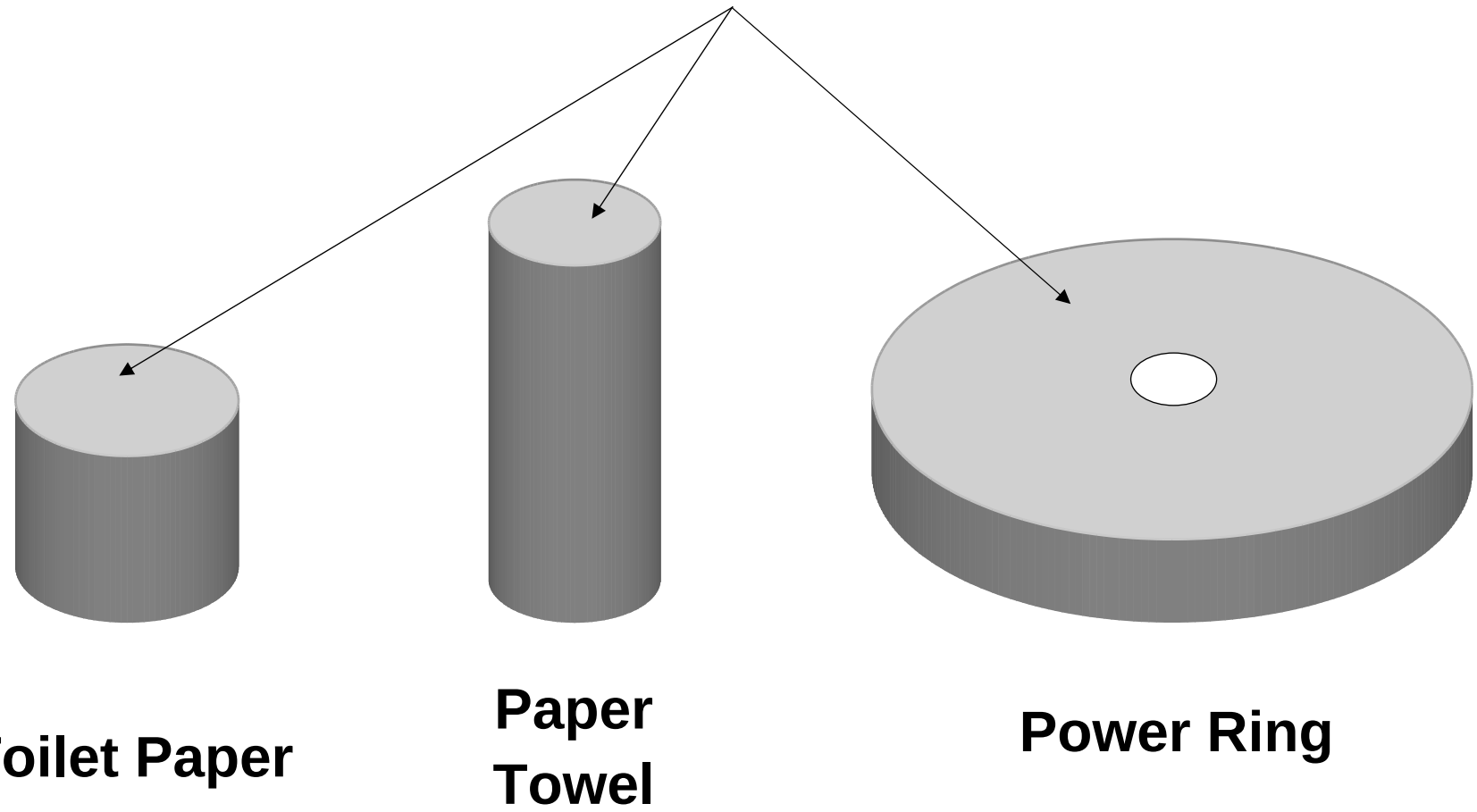


- Advancements in quality of base polypropylene resin has closed the gap between BOPP and HCPP as shown by data

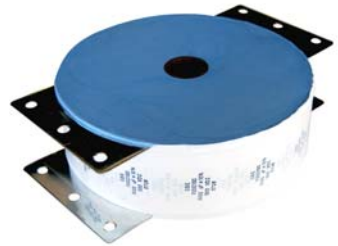
- The form factor of the wound capacitor section has surfaced as a critical parameter in the design regardless of choice of Polypropylene grade!

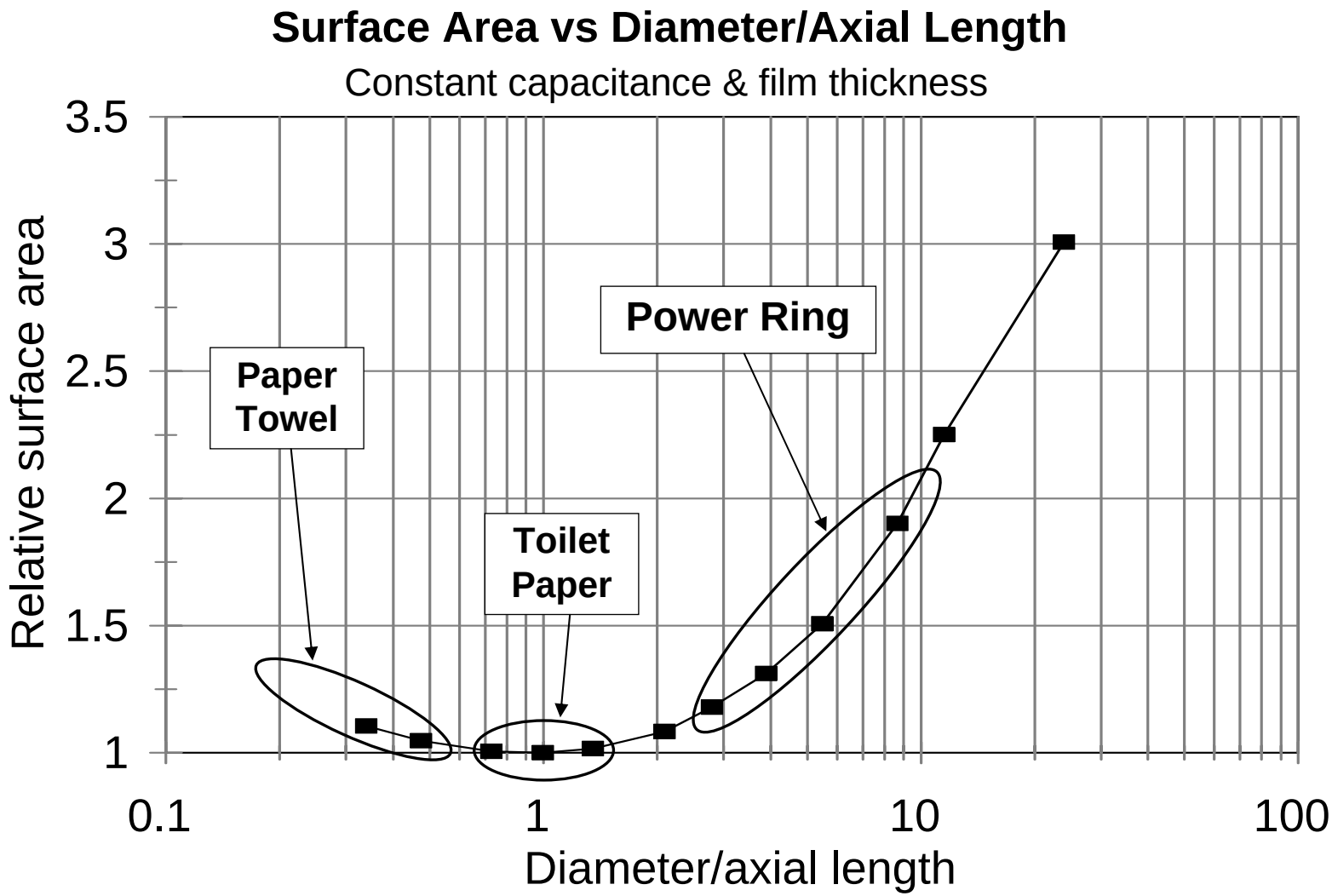
Capacitor Form Factors



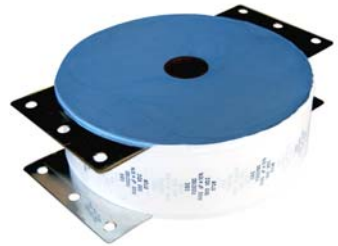


Capacitor End Spray Surface Area



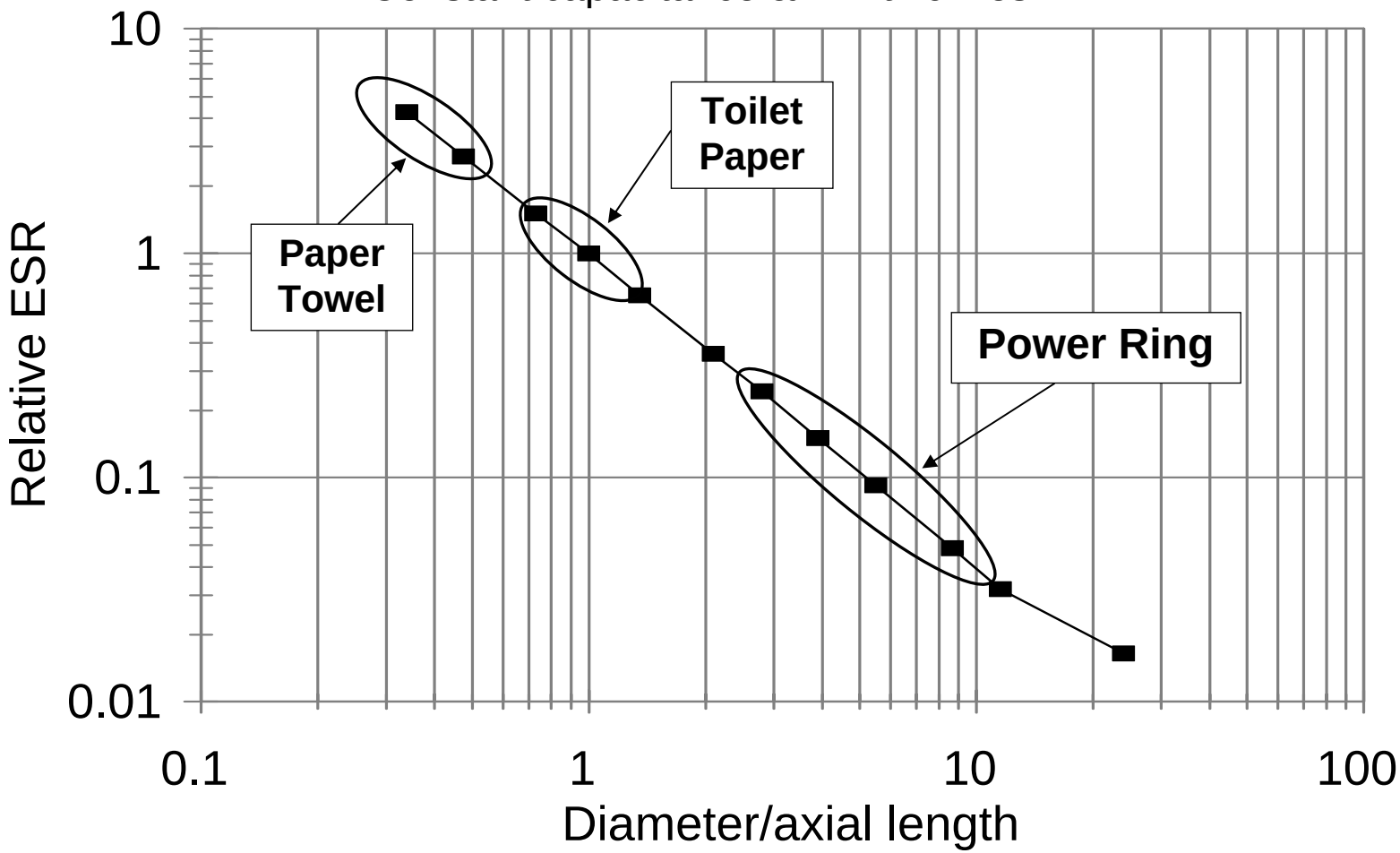


ESR

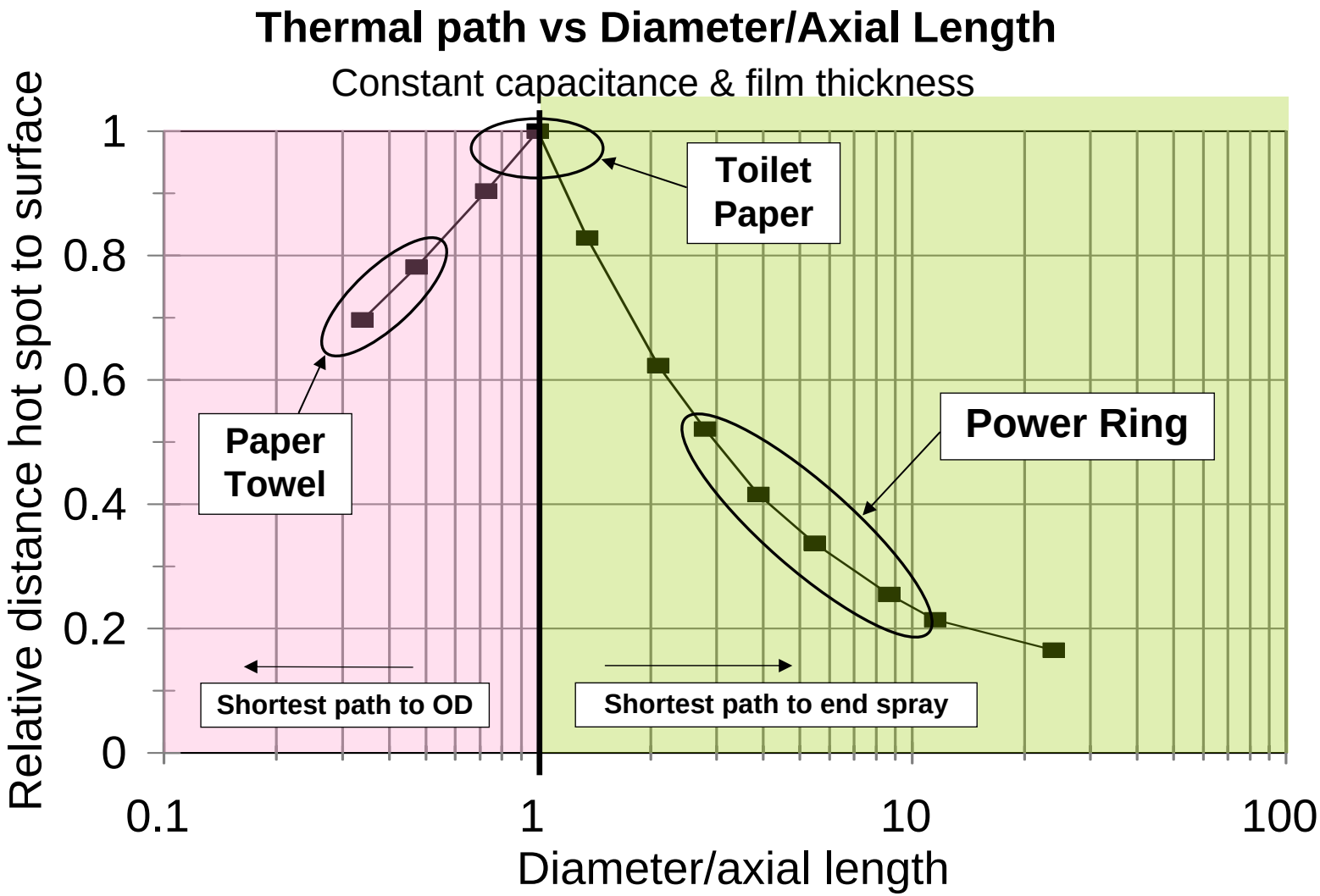


ESR vs Diameter/Axial Length

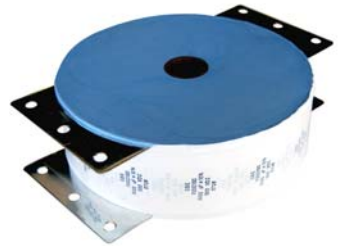
Constant capacitance & film thicknes



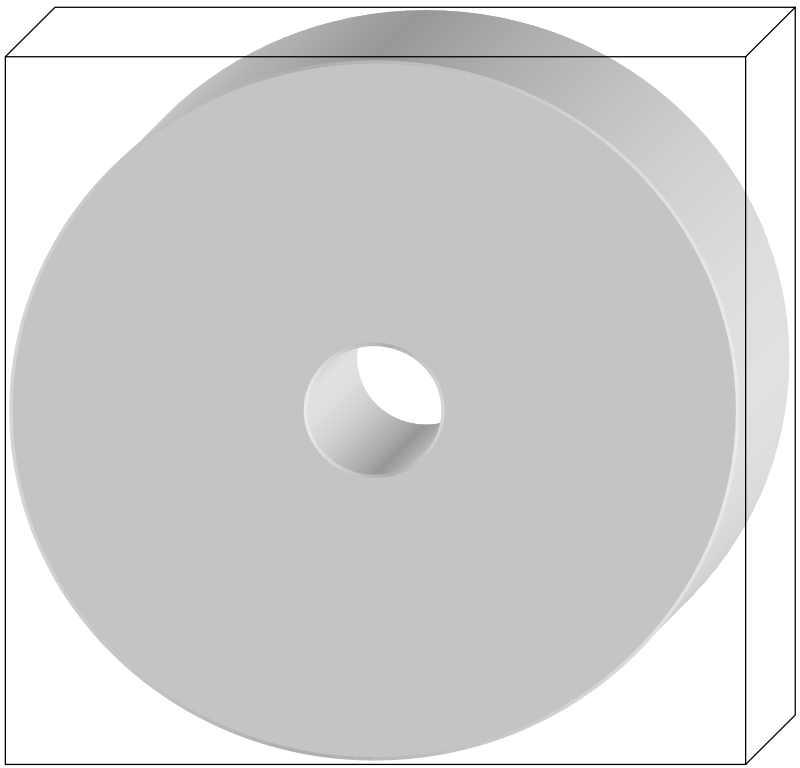
Thermal Path Length

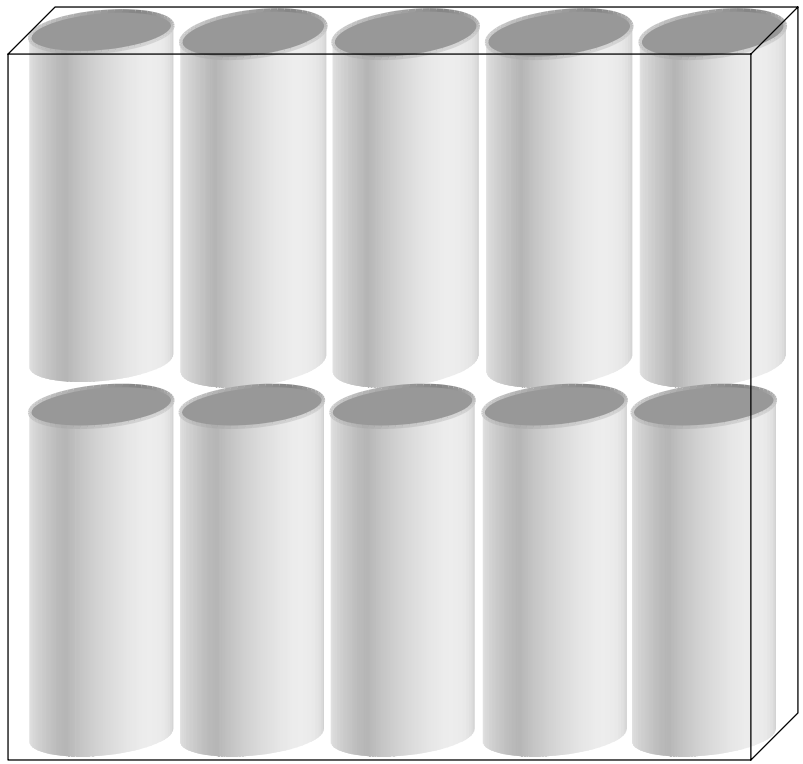


End Spray Surface Area

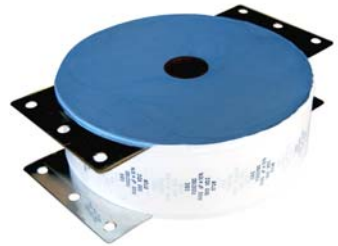


- **The Thermal Advantage**





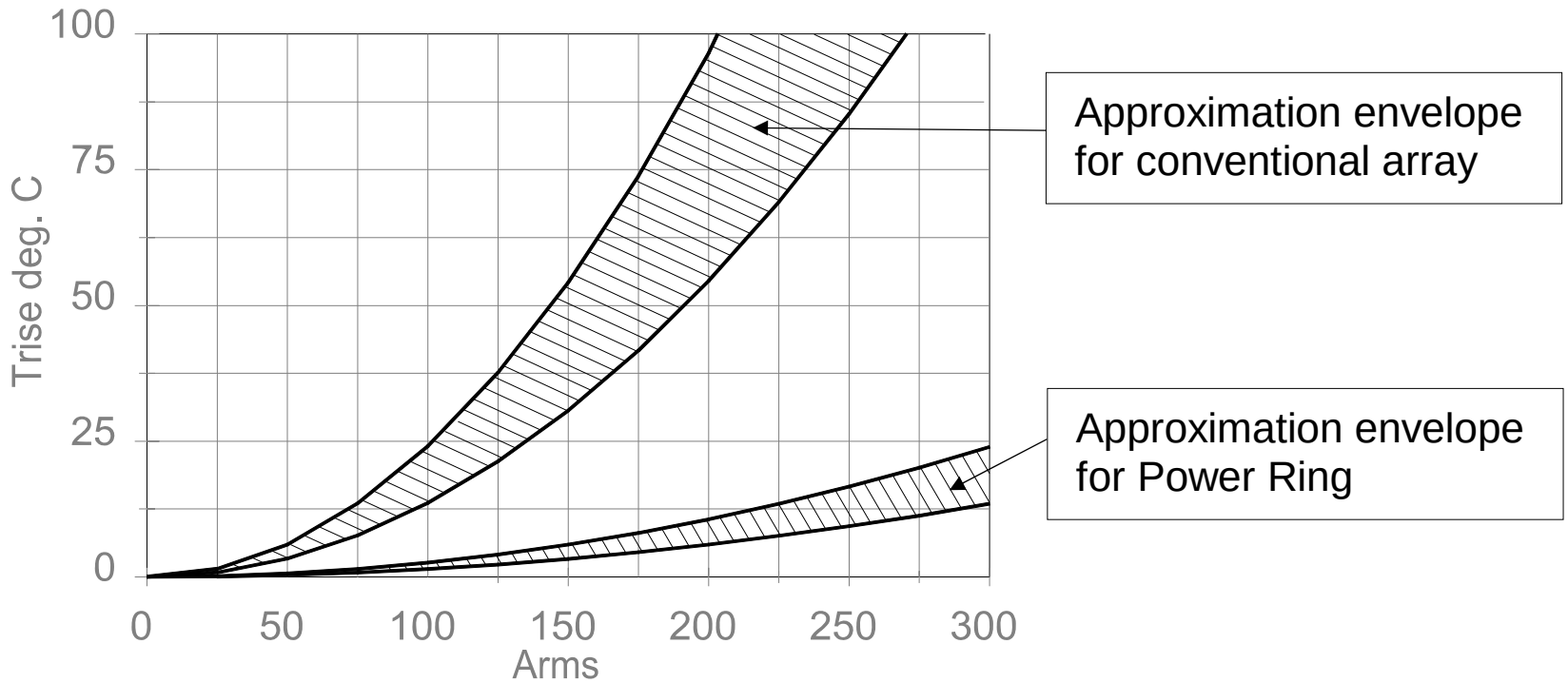
The Thermal Advantage



- Temperature rise of conventional array greater than 5 times that of the Power Ring for a given ripple current
- Power Ring's large, flat surface area allows for greater connection area and short thermal path to heat sink, chill plate, etc.
  - Thus further reducing temperature rise

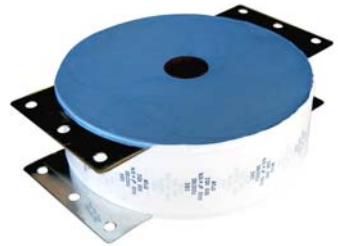
Comparative Temperature Rise Envelopes

Temperature Rise (°C) vs. Ripple Current (Amps)



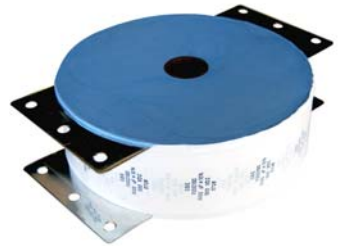
Data assumes both sides of the capacitor held at the same temperature

Findings, Conclusions



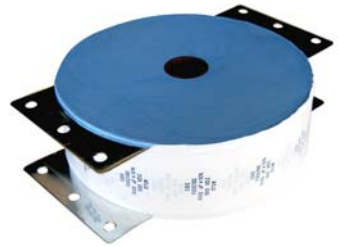
- No significant performance observed between BOPP and HCPP. DAMN!
- Polypropylene film capacitors will not be rated to operate at +150°C, HOWEVER, the ring form factor improves performance as temperatures elevate
- Functional upper temperature limit not easily defined, BUT….Power Ring's low T rise allows higher system temperature for a given capacitor hot spot temperature

Future Work



- Continued research of High Crystalline Polypropylene mechanical and thermal behavior
- Interconnect and Packaging options

Thank You!



Thank you!

Please visit us

in Booth #303