High Performance DC Bus Film Capacitor

Daniel Tan (PI)

GE Global Research
June 7, 2016

Project ID:
EDT060

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Project start: October 2013
- Project end: Sept. 2016
- Percent complete (75%)

Barriers

- Temperature limit >140ºC
- Volume down by 25-50%
- Cost reduction to $30

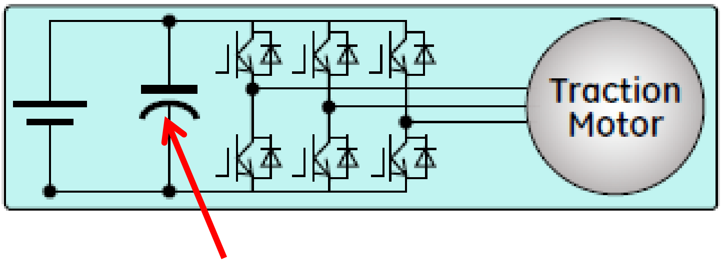
Budget

- Total funding: $2646k
  - DOE share $1750k
  - Contractor share $896k
- Funding received in F15 - $1,623k
- Funding for FY15/16 - $1,023k

Partners

- Delphi / subcontractor for capacitor specification and testing
- Film processing and capacitor suppliers

Relevance and Objectives



- **Largest component**
- **<125ºC**
- **Expensive**

DC Bus Capacitor Targets	DOE Metrics
Temperature range of ambient air, °C	-40 to +140
Volume requirement, L	≤ 0.6
Cost ($)	≤ 30
Failure mode	Benign
Life @operating condition, hr	>13,000

Objectives:

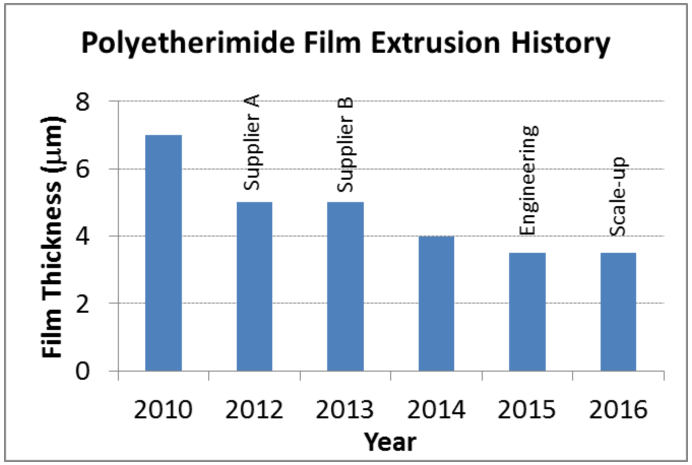
- Develop high temperature polymer film capacitors of >150ºC rating
  - Develop melt extrusion process for 3-5 μm thick polyetherimide (PEI) films to overcome volume and cost barrier
  - Develop nanocoating process for dielectric strength and self healing.
- Extrude <5 μm PEI films and demonstrate nanocoating process
- Validate roll-to-roll film coating process and capacitor manufacturing
- Design and prototype inverter-specific capacitor

Milestones

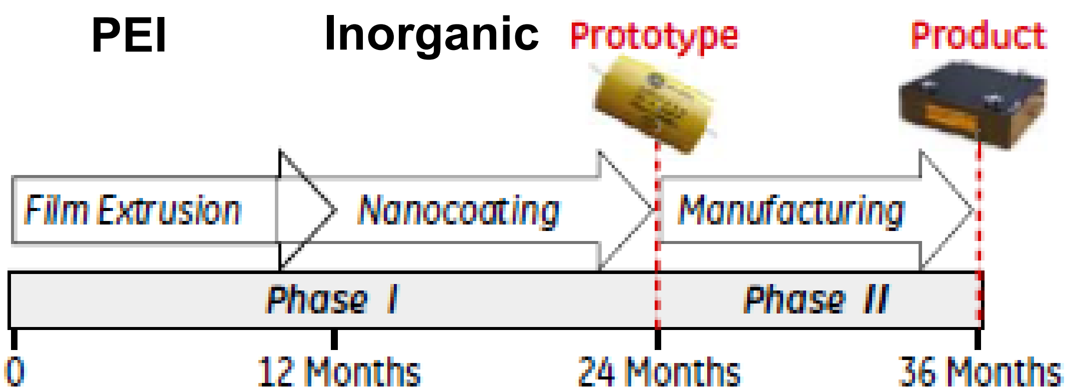
Month/Year	Milestone or Go/No-go Decision	Status
Mar. 2015	Milestone: - Test mechanical and dielectric properties of 3-5 μm films - Develop 3 μm film with minimal defects	Complete
Jun. 2015	Milestone: - Scale up 3-5 μm PEI films and downselect thickness - Properties of nanocoating films	Complete
Sept. 2015	Milestone and Go/No go decision: - Scale-up nanocoating on 3-5 μm film - Build and test prototype capacitor (25 μF)	Complete
Dec. 2015	Milestone: Scale up 4 μm PEI film and designed 100/300 μF prototype capacitors for Phase 1	Delivery delayed
Mar. 2016	Milestone: Build assembled 100/300μF capacitors and tested capacitor performance	Delivery delayed
Jun. 2016	Milestone: Design packaged capacitor and build multiple capacitor units Test assembled capacitor performance	Ongoing

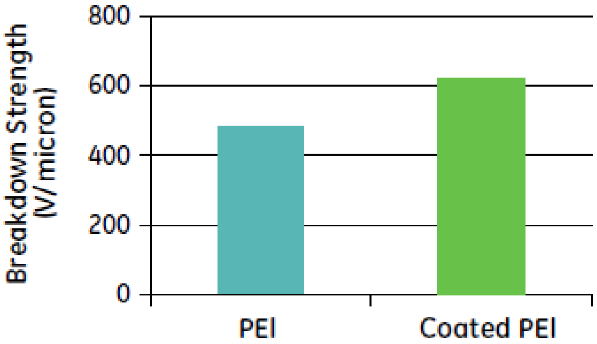
Approach/Strategy

- **Extruded <5 μm PEI film to overcome the shortcomings of BOPP and cooling system.**
- **Leverage higher dielectric constant and thinner film for lower volume and cost than state-of-the-art.**
- **Enhance dielectric strength via inorganic coating of PEI films for operating voltage and smaller volume.**



$$D = \varepsilon_o K E_{BD}^2 / 2$$

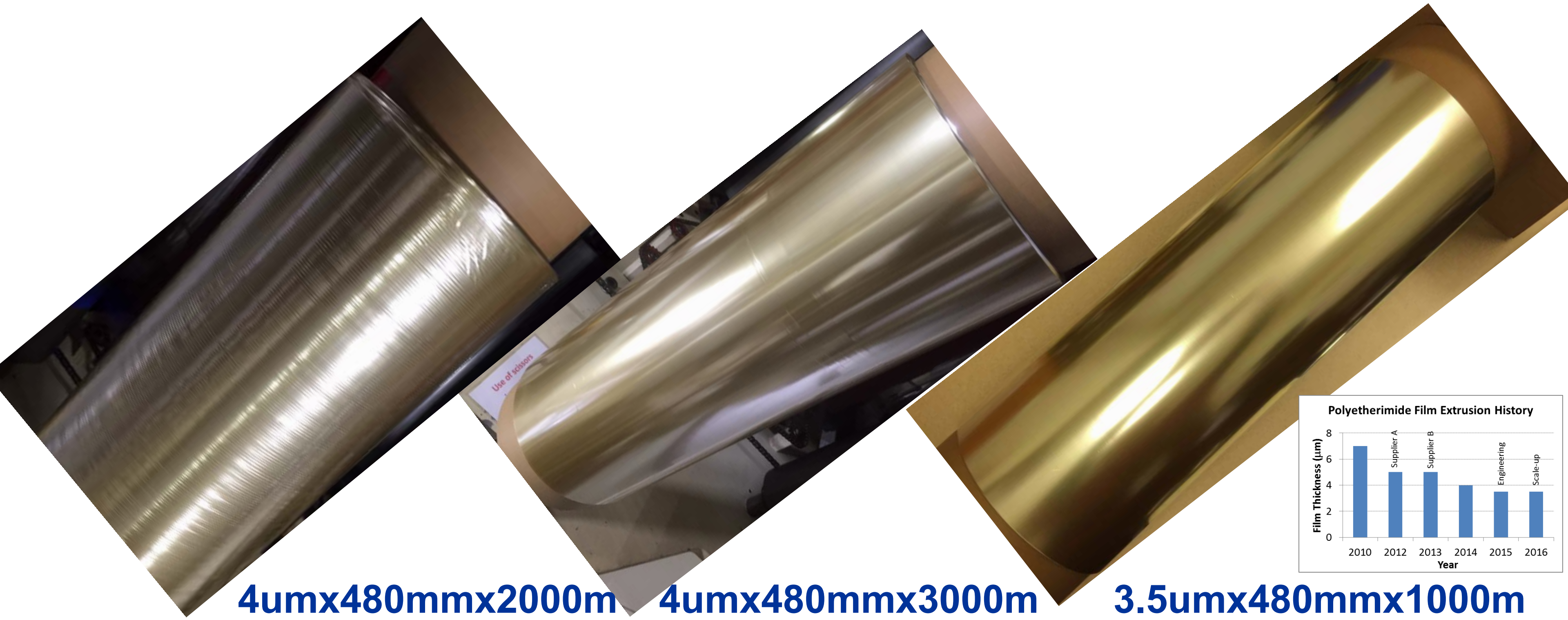




High temperature extruded polymer film capacitor

Technical Accomplishments/Progress: 3.5 μm PEI Film Produced by Extrusion

2014: Tin-canning → 2015/2016: Wrinkle-free

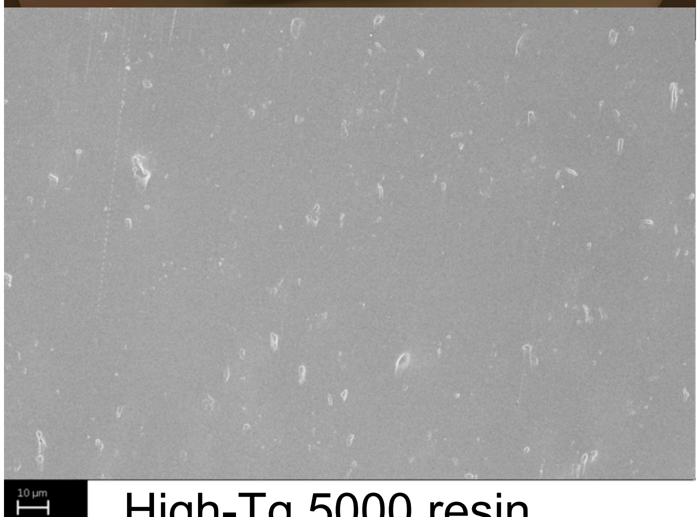


4umx480mmx2000m **4umx480mmx3000m** **3.5umx480mmx1000m**

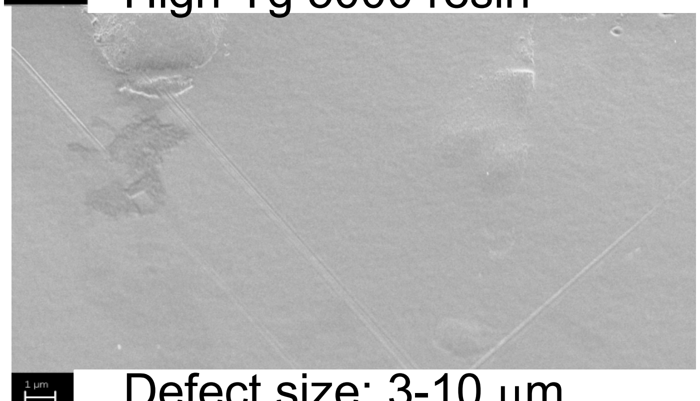
Wrinkle-free PEI films scaled-up and ready for capacitor prototyping

imagination at work

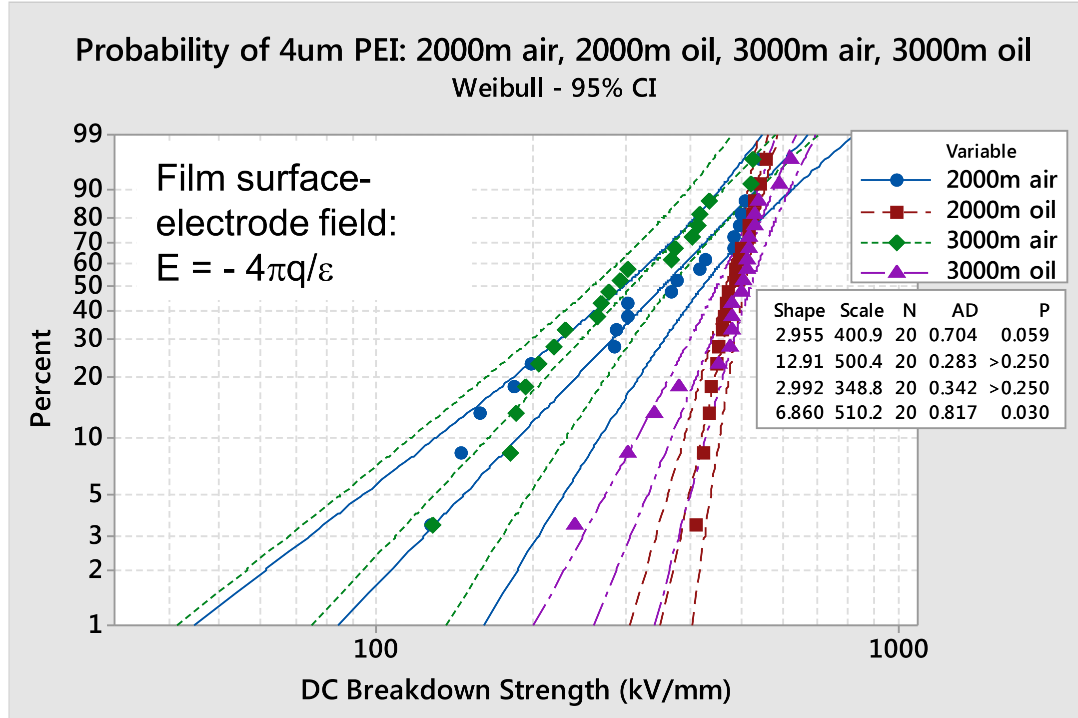
Film Surface Defects Account for Lower Breakdown Strength



High-Tg 5000 resin



Defect size: 3-10 μm

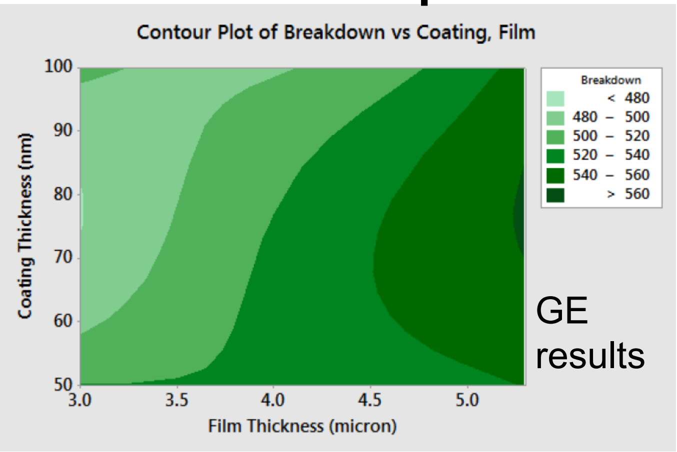


- When tested in oil (dielectric constant similar to PEI), local breakdown occurs at higher electric field.
- Air trap/sharp edges related to surface defects can easily induce breakdown of films and then adversely affected wound capacitor performance.

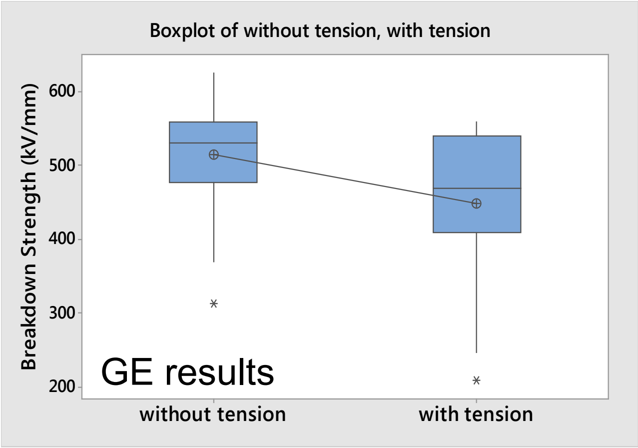
Roll-to-Roll Oxide Coating Demonstrated on 5 μm PEI Film

E-beam coater

Thickness dependence



Film tension effect



Challenges remained for oxide coating improvement and adoption:
1) Coater availability 2) Thinner film constraint 3) Film tension constraint

- Enhancement in breakdown strength in films thinner than 4 μm is overshadowed by the film tension in roll-to-roll winding process. Adjustment of the coater system set-up required in the future effort.
- Considering the discontinuity in coating, time pressure and cost increase, the oxide coating method will not be utilized in this program.

imagination at work

Metallization: Aluminum Deposition Parameters and Surface Resistance Designed

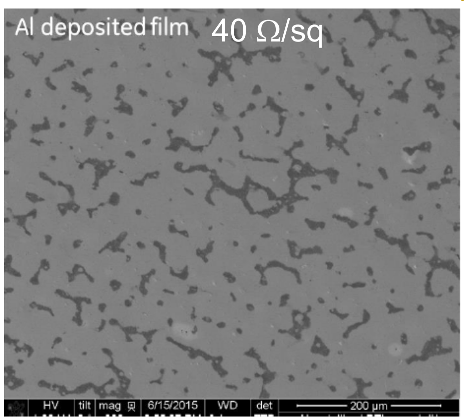
Vacuum deposition:

- Power & vacuum
- Plasma treatment
- Winding tension
- Cooling roll temp.
- Margin design
- Heavy edge resistance
- Surface resistance

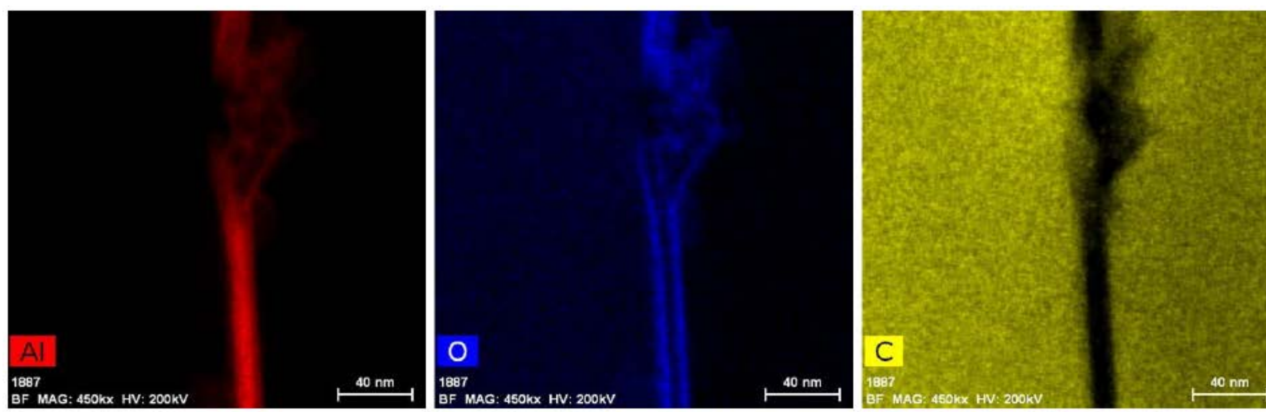
Relationship between Al thickness and surface resistance on PEI films.

Resistance (Ω/sq)	40	20	12.7	3.2	1.8	0.4
Al thickness (nm)	<10	<10	10	16	33	101
Remarks	Unstable and self-healing	Stable and self-healing	Self-healing concern	Heavy edge	Heavy edge	Too thick

Error: +/-8%



Oxidation of aluminum (<10 nm) occurs at 160ºC.

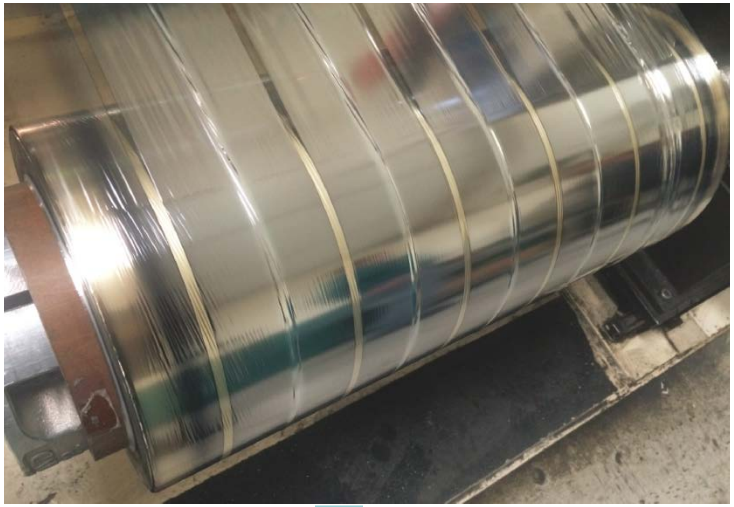


Images of the elemental analysis of the metallized PEI film.

Improper Al deposition leads to instability in capacitor film and performance.

Surface Resistance and Slitting Process Defined

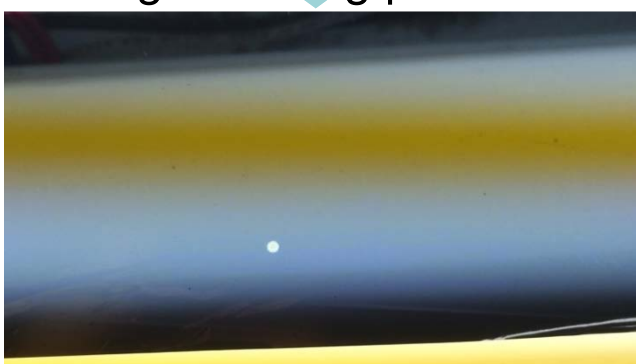
Master roll after metallization



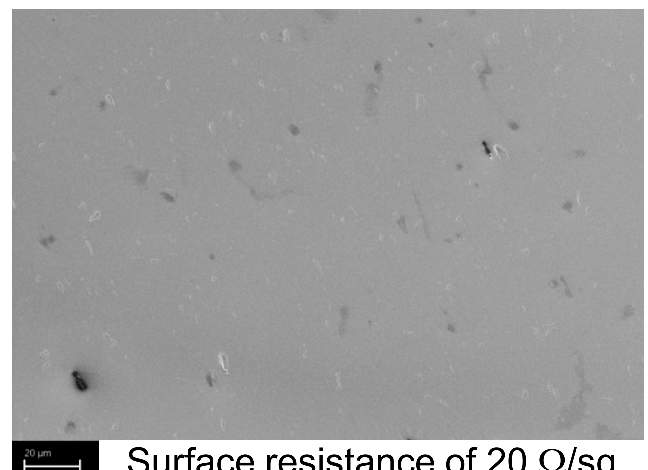
Slitting

Metallized rolls for capacitor

Low voltage clearing performed at slitting



Clearing sites of defect areas (Al removed)

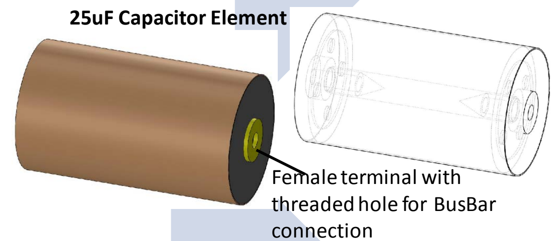


Surface resistance of 20 Ω/sq

Metallization processes well determined and ready for scale-up

Capacitor Winding Process Flow Under Evaluation

- Winding:
  - -proper tension
  - -PPS plug
  - -Kapton tape
- Vacuum-bake capacitor@ 25~160°C overnight
- Cool down capacitor in dry-box
- End-spray Preparation
  - End-spray Zn & Babbitt
- Cleaning End Spray
- End-spray cure, 70°C overnight & 140°C for xx hours



- Cool down capacitor in dry-box (25°C)
- Initial electrical tests: Cap, DF (25°C)
- Dump test @ 50VDC (25°)
  - Electrical test: Cap, DF, ESR (25°)
- Short Conditioning/ Burn-in: 140°C, 50VDC up to 600VDC for xx hrs
- Voltage Test:
  - Flash test @ 600 VDC (140 °C)
- Electrical test:
  - Cap, DF, IR @ 400 V (140 °C)
- Electroding and potting, Cooling down capacitors in dry-box (25°)

Passed capacitor units selected for assembly

imagination at work

Capacitor Winding: High Sheet Resistance Appears to Cause High Breakdown Voltage

25 μF capacitor units: surface resistance dependence of breakdown

Sheet resistance (Ω/sq)	Winding tension (g)	DF, % at 1 kHz	Film breakdown (V)	Capacitor flash (V)	Capacitor breakdown (V)
13	150	0.6 (0.21-1.9)	470-760	500 pass	600
20	50	6.9 (5.6-9.0)	530-1000	700 pass	1000

Good DF and ESR achievable below using films with 13 Ω/sq, however, they failed at lower voltage (600V).

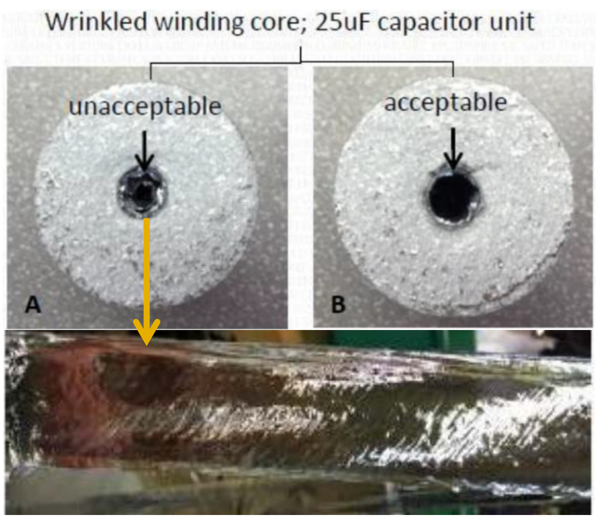
Winding Tension (g)	Dump/Flash at 50V/400V	DCL at 250VDC	Cap at 1kHz	DF at 1kHz	ESR, mΩ		
					1kHz	10kHz	100kHz
150	Pass	.07 μA	24.54μF	.22%	14	8	14
150	Pass	.03 μA	23.76 μF	.27%	18	13	14
150	Pass	25 μA	23.72 μF	.21%	14	8	9
150	Pass	.05 μA	24.64 μF	.93%	60	12	10
150	Pass	.06 μA	24.66 μF	1.94%	126	40	13
150	Pass	.05 μA	25.24 μF	.22%	14	7	8
150	Pass	.01 μA	24.96 μF	.22%	14	9	9

Achievable voltage for 4 μm film capacitor is 1 kV now.

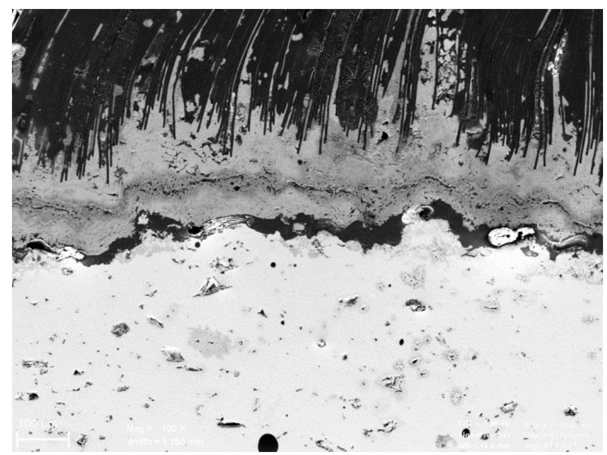
Capacitor Winding Parameter Effect on DF and ESR

- Higher DF and ESR can be resulted when metallized films were wound on its own using a smaller mandrel
- End-spray metal delamination also contributes to high DF and ESR.

Vacuum bake at 70-140ºC and Cure at 110ºC	DF, % at 1 kHz	ESR (mΩ) at 100 kHz
Automatic (Stella 703) with bigger mandrel and higher tension	0.25 Min:0.21 Max: 1.94	11 Min: 8 Max: 14
Automatic (Stella 706) with smaller mandrel and lower tension	4.5 Min: 3.1 Max: 9.3	55 Min: 33 Max: 125



Severe wrinkling/crimpling of film close to the core of high DF units



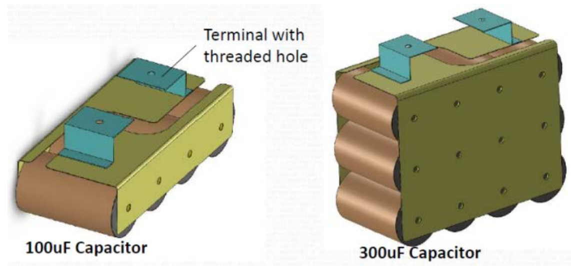
Capacitor processes needs further improvement to avoid Zn/Babbit interfacial delamination.

Capacitors Designed and To Be Delivered

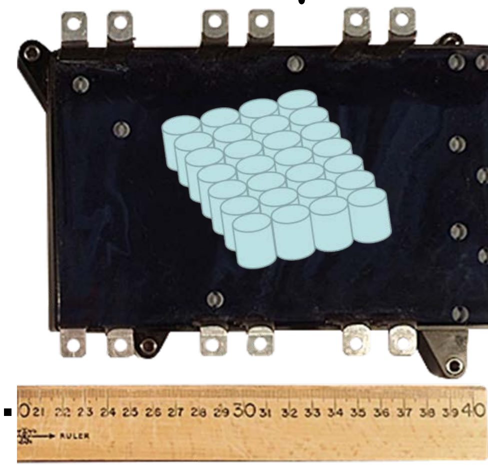
25 µF

1” diameter

100/300 µF



700 µF



700 µF capacitor using 4 µm film will be > 0.6 L.
3.5 µm film capacitor is <0.6L.

Capacitor fabrication and testing plan	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Extrude PEI films												
Procure 10 rolls of 4um												
Procure 6 rolls of 3.5um												
Milestone: Dowselected film thickness												
Metallization												
Produce multiple rolls with target Al												
Milestone: Metallized rolls with proper design												
Capacitor manufacturing												
Produce and package 300uF capacitor for Ph.1												
Design & Manufacture package, busbar, interconnect												
Build capacitor bank												
Milestone: Fabricated six 750uF for Ph.2												
Capacitor testing and delivery												
Test 300uF capacitor												
Test performance of 700uF capacitor												
Milestone: Test results for Ph.1 and Ph.2 capacitors												
Final Report												

Response to Reviewers Comments

AMR15 comments were positive with 6 reviewers posing 6 questions:

1. Invest more on film processing as film quality is a major limiting factor.

Yes, we ran multiple trials and succeeded in eliminating wrinkles. However, surface defects are associated with the intrinsic resin properties and cannot be avoided within the required time of this program. Future efforts will be needed.

2. Compare the state of the current material and the project requirements

Currently produced 4 μm films are sufficient to make 6 capacitor of specified requirements defined by GE team as shown in the table.

3. Reviewer is unsure if the schedule is met since lots of things to be done

GE worked with several vendors simultaneously on handling the thinner films. However, the vendors started over the learning curve due the change of engineering resource and delayed the Phase 1 delivery due to the processing issue with high DF and ESR. GE team has a plan to catch up in Phase 2.

4. Characterize the breakdown of interesting nanocoated PEI at 150° C

We didn't invest resources and budget to do it as we will not implement this method for the program due to timing and availability of e-beam coater.

5. List specific milestones including the fabrication & testing of capacitors

Shown on the previous slide

6. Provide more information to prove claimed operating life

Tests and modeling prediction are underway

7. Physical/Electrical/mechanical specs of capacitors for car inverters

800μF PP capacitor (1 kg/1 liter) consumes 25–40 vol% of an inverter requiring cooling system. Car customers define specs that vary with applications (<100kW).

Crite-ria	Require-ments	Thermal/ Mechanical
Capaci-tance	300 μF -10%/-0% 700μF -10%/-0%	AEC-Q200 REV D specification Mechanical Characteri-stics Require-ments TBD
ESR	≤0.3mΩ	
ESL	≤5nH	
Cont. Ripple current	300 μF – 97.5Arms 500μF – 293Arms	
Peak current	300 μF – 195Arms 500μF – 455Arms	
Vop Vpeak	270-430V 600V	

imagination at work

Collaboration and Coordination with Other Institutions

- Contract Collaborator
  - Capacitor specs definition and testing (Ralph Taylor / Delphi)
- Extruded Film Suppliers
  - Supplier B downselected to produce free-standing thin films
- Other Service Suppliers
  - Amcor downselected to produce inorganic coating (e-beam)
  - Bollore and Steinerfilm for metallization
  - DEI, ECI, Kemet for capacitor winding, packaging and testing

Remaining Challenges

- Commercial scale 3.5-4 μm PEI films exhibit surface defects that are possibly associated with high-Tg 5000 resin. These defects were not observed in film from 1000 type of resin that may be leveraged in the later time.
- Capacitor manufacturing process needs more improvements to minimize DF and ESR.
- Ultimate cost of extruded PEI film is difficult to control, and depends on film manufacturing process and market demand.

Future Work: Design & Build Capacitors

FY2016

- Scale-up metallization of the thinner films (Q2).
- Design capacitor package and build bus bars (Q2).
- Build PEI capacitors using 4 μm films (Q2)
- Build and test specified capacitor assembly (Q3)
- Final report (Q4)

Summary

- **Scaled up production of 3.5 ~ 4 μm thick PEI films**
  - Extruded wrinkle-free PEI films of 3000 m in length.
  - Downselected 4 μm PEI film for capacitor prototyping.
  - Extruded wrinkle-free 3.5 μm film of 1000 m in length.
- **Developed nanocoating process on PEI films.**
  - Demonstrated R2R coating feasibility on thin PEI film
  - Terminated coating due to limited experience and time
- **Developed metallization recipe suitable for PEI film capacitors**
- **Prototyped 25 μF capacitor showing the feasibility of PEI capacitors.**
- **Capacitor manufacturing processes are yet to be improved to deliver DOE-specified capacitors.**

Acknowledgement

•"This material is based upon work supported by the Department of Energy under Award Number DE-EE0006433.“

•GE Aviation Systems are greatly appreciated for their cost share and business support.