High Performance DC Bus Film Capacitor

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GE Global Research

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Imagination at work.

Overview

Timeline

- Project start: October 2013
- Project end: Sept. 2016
- Percent complete (50%)

Barriers

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

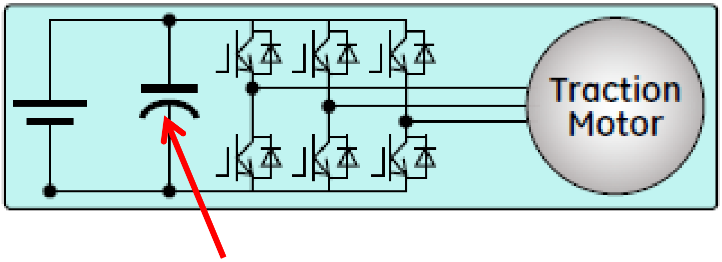
Budget

- Total funding: $2646k
  - DOE share $1750k
  - Contractor share $896k
- Funding received in FY13/14 -$698k
- Funding for FY14/15 - $925k

Partners

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

Relevance



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

DC Bus Capacitor Targets	DOE Metrics	GE technology
Temperature range of ambient air, °C	-40 to +140	PEI (-40 to +180)
Volume requirement, L	≤ 0.6	3-5 μm film (0.3-0.5)
Cost ($)	≤ 30	≤ 30
Failure mode	Benign	Self-clearing (Benign)
Life @operating condition, hr	>13,000	200,000

<u>Objectives</u>:

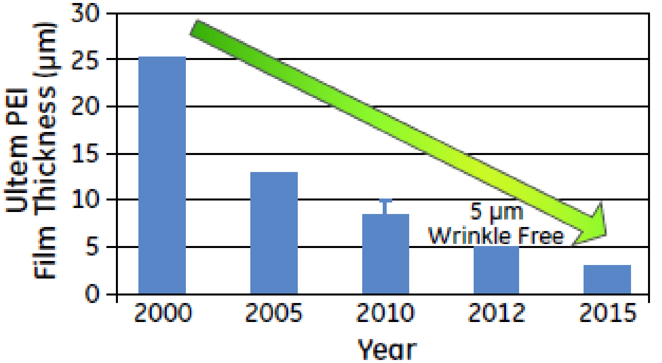
- Develop high temperature polymer film capacitors of >150ºC rating
  - Develop melt extrusion process for 3-5 μm thick polyetherimide (PEI) films to overcome volume and cost barrier
  - Develop nanocoating process for dielectric strength and self healing.
- Extrude 5 μm PEI films and demonstrate nanocoating process in Budget Period 1
- Validate roll-to-roll film coating process and capacitor manufacturers for inverter-specific capacitor in Budget Period 2

Milestones

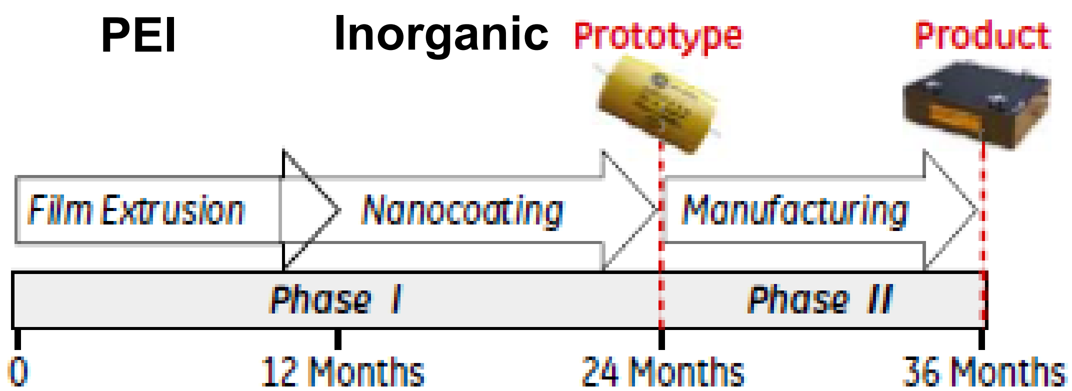
Month/Year	Milestone or Go/No-go Decision	Status
March 2014	Go/No-go decision: Validate extrusion process for 5 μm PEI film. Is film thickness variation <10% and wrinkles-free? Yes	Complete
Sept. 2014	Go/No-go decision: Demonstrate 5 μm film rolls (500 meter). Check film properties, thickness variability and cost model.	Complete
Dec. 2014	Milestone: - Identify nanocoating vendors and test R2R coating feasibility - Scale up 5 μm PEI film (2000 meter)	Complete
Mar. 2015	Milestone: - Test mechanical and dielectric properties of 3-5 μm films - Develop 3 μm film with minimal defects (film with support)	Complete
June. 2015	Milestone: - Scale up 3-5 μm PEI films and downselect thickness - Properties of nanocoating films	On track
Sept. 2015	Milestone and Go/No go decision: - Scale-up nanocoating on 3-5 μm film - Build and test prototype capacitor	On track

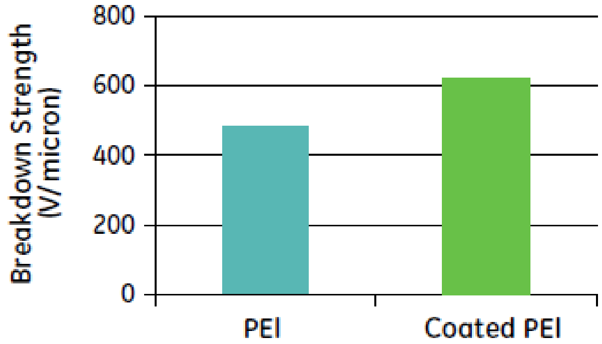
Approach/Strategy

- Develop extruded high temperature 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: PEI Film Extrusion Process

Barrier: Scaled-up extrusion process

Supplier A&B

Free-standing

Carrier-assisted

Supplier C

Wrinkle minimi-zation methods

Process control

Imprinted

Slip agent

Surface adhesion

Film thickness achieved

Wrinkle minimization methods	Film thickness achieved
Process control	25, 13, 10, 7, 6, 5, 4 μm
Imprinted	13, 10, 7, 5, 3 μm
Slip agent	4 μm
Surface adhesion	5, 4, 3 μm

High temp thinner PEI film successfully developed in production extruders. Two processes validated.

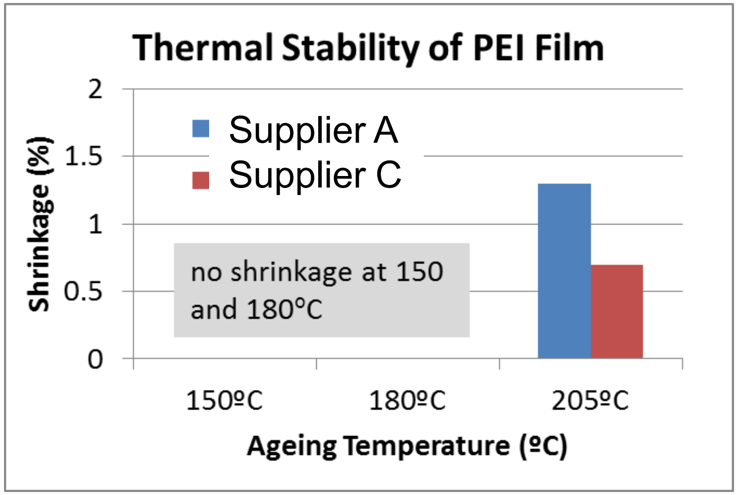
Scale-up Efforts for Free-standing Films

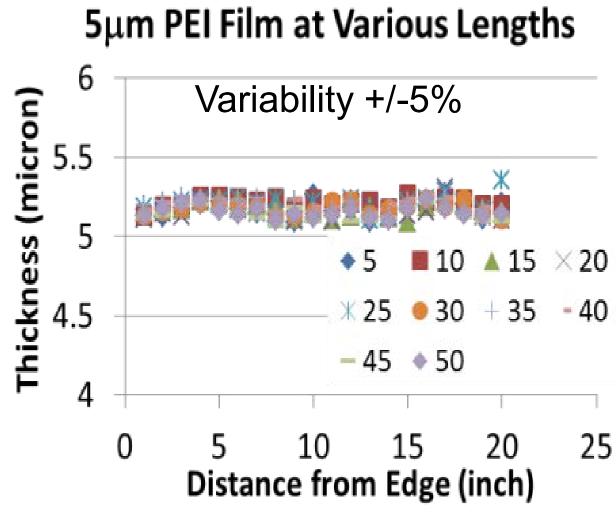
Supplier A
- Wrinkle-free film (3-7 μm)
- Uniform thickness (but higher roughness)
- DC dielectric strength (Weibull: 510-580V/μ)
- Good scalability (2000m x 530mm)
- Awaiting commercialization of 5 μm films

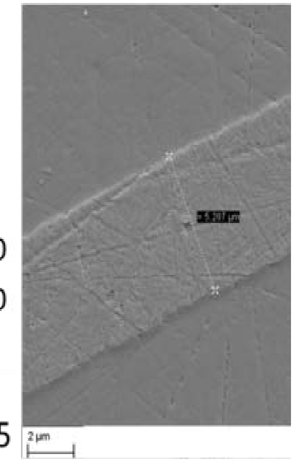
Supplier B
- Light crinkled film (5-7 μm)
- Uniform thickness (but some pits)
- DC dielectric strength (Weibull: 550-600 V/μ)
- Good scalability (2000m x 480mm)
- Awaiting production of 3 & 4 μm films

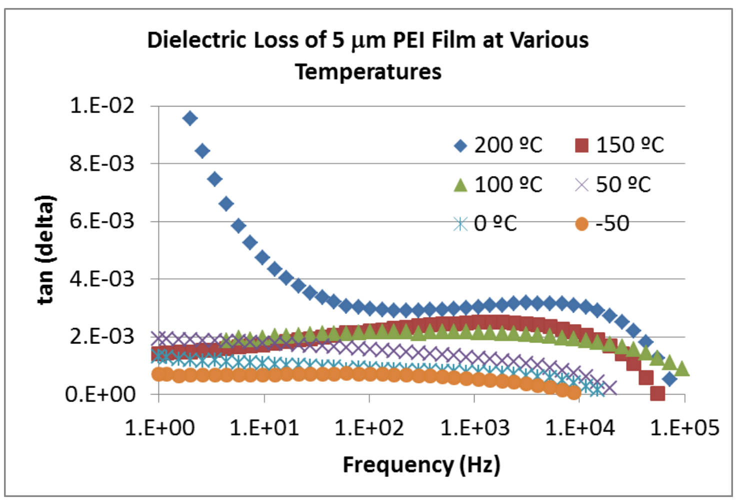
Developed working relationships, producing 4 μm films.

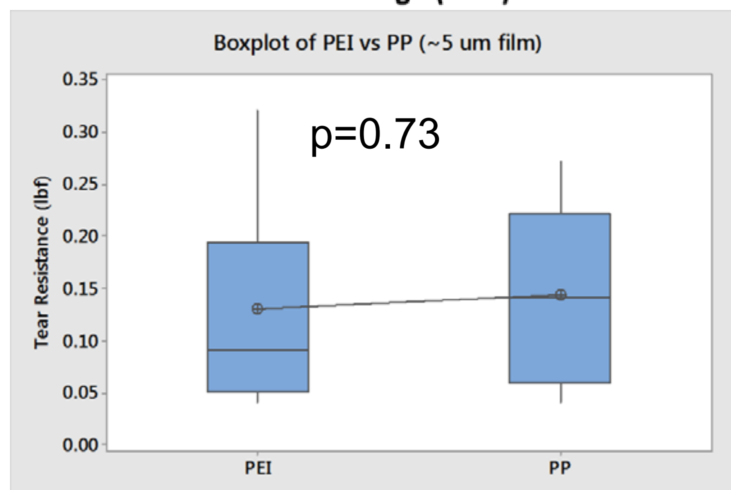
Properties of 5 μm PEI Films







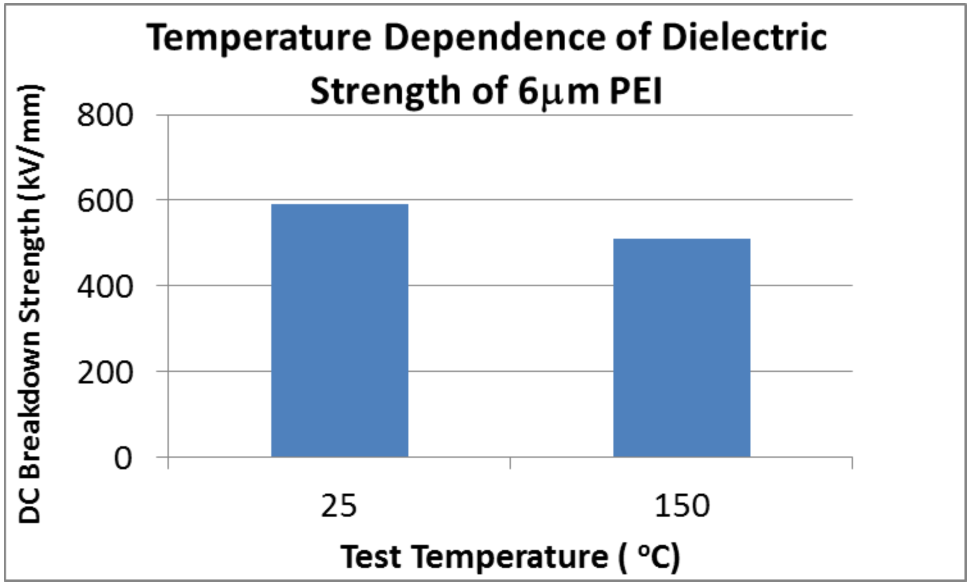




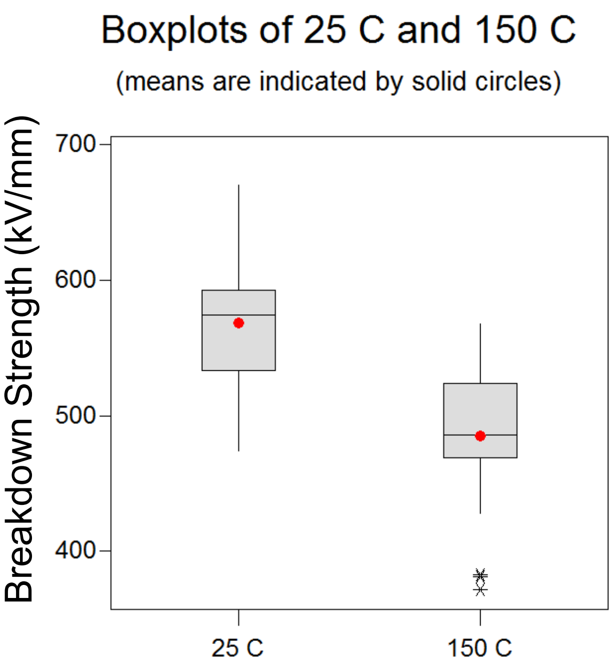
Stable properties up to 180ºC, adequate for capacitor.

Breakdown Strength at High Temperatures

Weibull distribution, shape factor =10



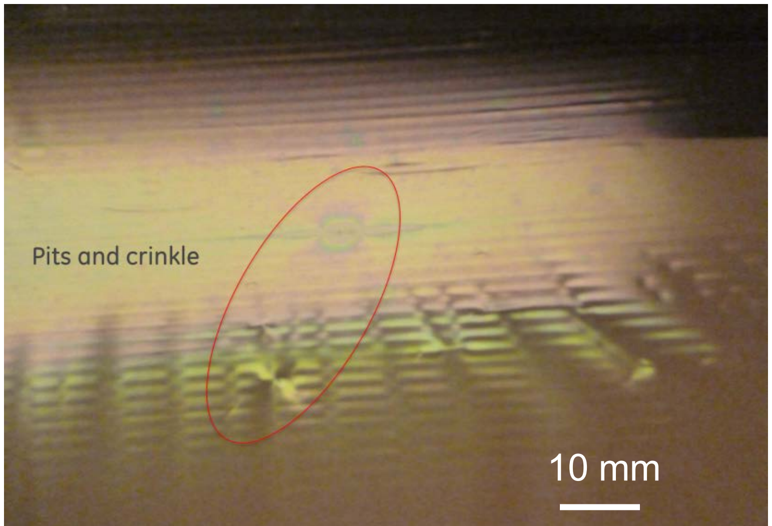
Normal distribution 2-sample t

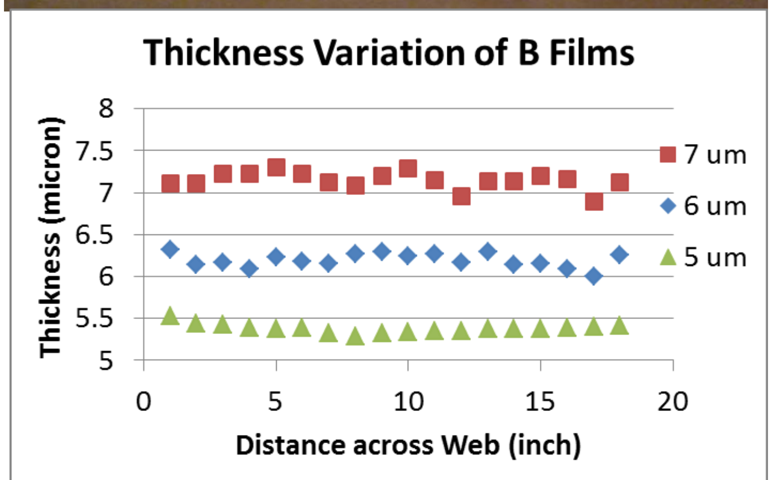


$p<0.05$, significant

Breakdown strength becomes lower at 150ºC.

Optical Analyses of PEI Films

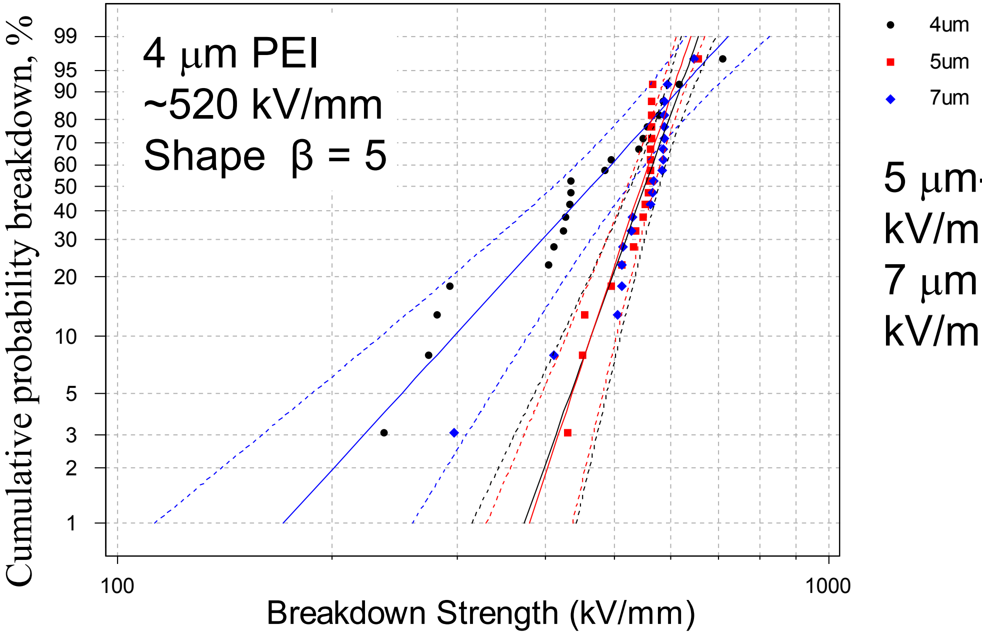




Defects on 5 µm extruded film (polarized optical microscopy)

Good thickness uniformity (+/-10% target) , but a little wrinkle and defects

Development of 4 μm PEI Film

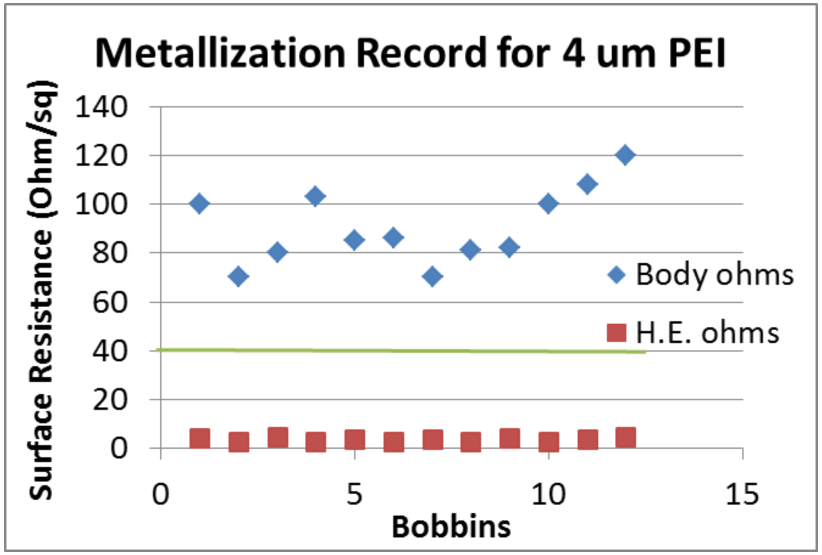


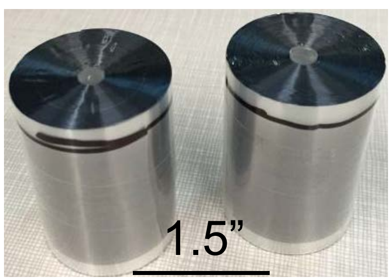
5 μm- 552 kV/mm
7 μm -577 kV/mm

Breakdown strength defined at 63% probability and the shape factor β measures the scatter.

4 μm films with slip additives (5 wt%) for wrinkle elimination produced, but exhibit lower breakdown strength and broad distribution.

Capacitor Winding Using 4 μm PEI Film



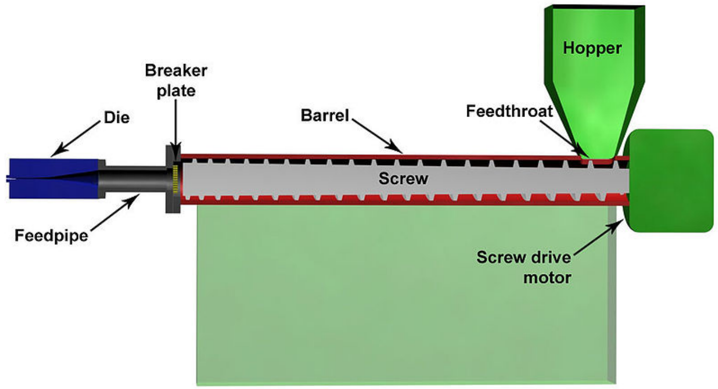


Unit #	600VDC Flash	DC current leakage (μA) @500VDC	IR @500VDC, MΩ	Capacitance (μF) at 1kHz	Dissipation Factor at 1kHz
1	Pass	0.091	5500	34.694	0.96
2	Pass	0.114	4400	37.922	0.95
3	Pass	0.086	5800	36.987	0.89
4	Pass	0.1	5000	38.713	0.93
5	Pass	0.187	2700	37.048	1.42
6	Pass	0.085	5900	37.237	1.4
7	Pass	0.083	6000	35.781	1.42
8	Pass	0.086	5800	36.993	1.42
9	Pass	0.214	2300	37.337	1.09
10	Pass	0.102	4900	40.082	1.01
11	Pass	0.11	4500	36.229	1.19
12	Pass	0.085	5900	36.402	1.01
13	Pass	1.06	4700	38.167	1.3
14	Pass	0.127	4000	35.572	1.15
15	Pass	0.094	5300	35.934	1.36
16	Pass	0.09	5600	35.272	1.31

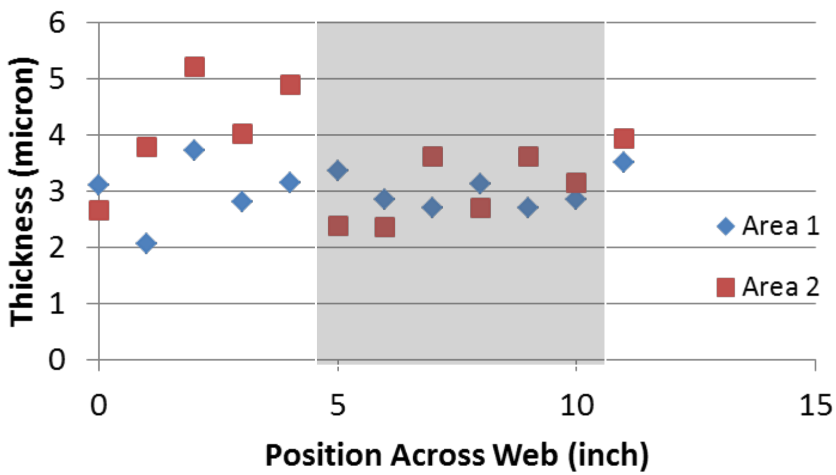
- Metallization off target due to low surface adhesion (excessive slip agent)
- High insulation resistance, but lower breakdown voltage
- New formulation and process underway.

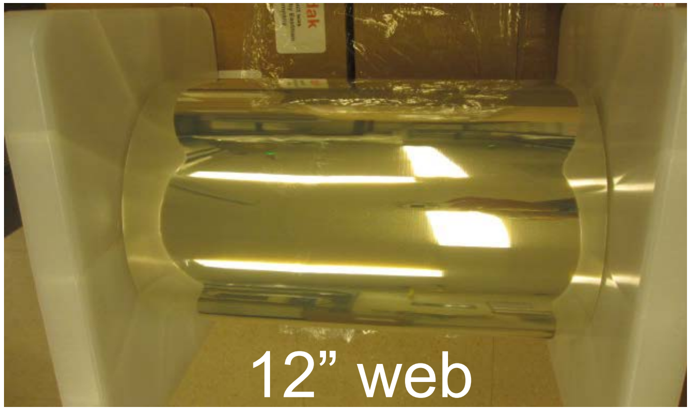
Development of 3 μm Films on a Carrier

- 6" wide uniform film roll produced at supplier C
- ~3 μm PEI produced on a carrier



http://commons.wikimedia.org/wiki/File:Extruder_section.jpg

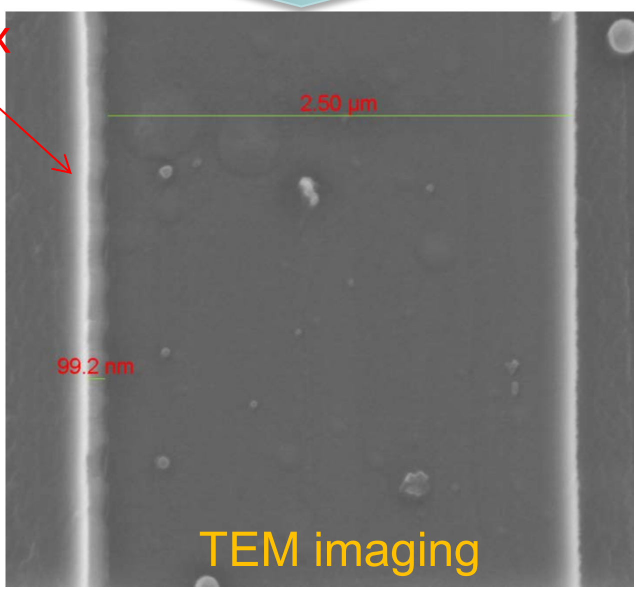




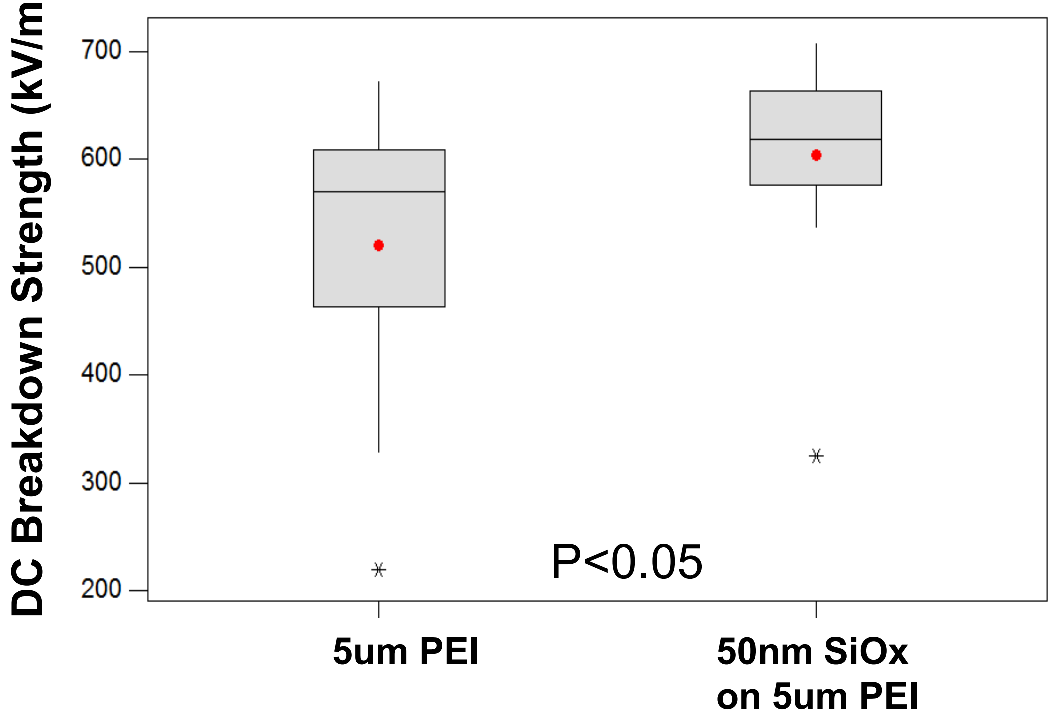
Thickness uniformity was constrained by die-lip flatness. There are some good and thin areas.

Roll-to-Roll Oxide Nanocoating on PEI Film

SiOx



Box plot for 5um PEI film with and without SiOx coating (means are indicated by solid circles)

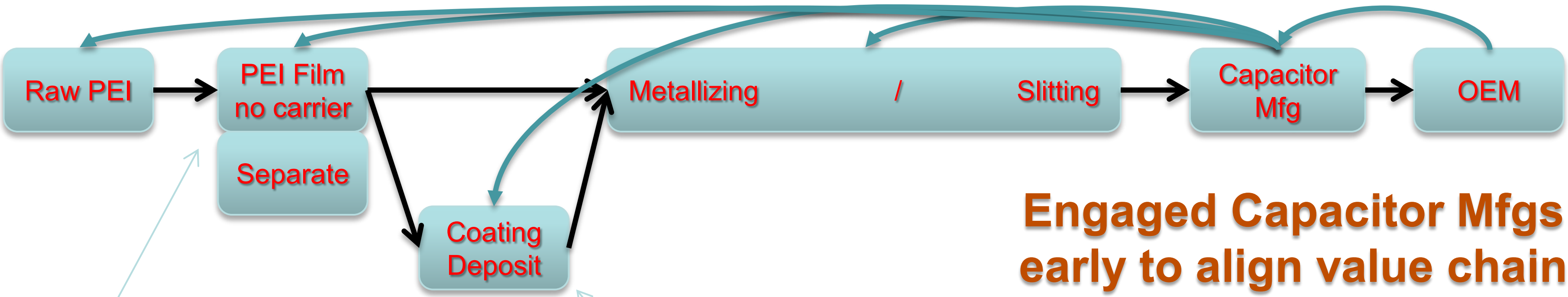


Sputter coating on free-standing film and faster e-beam coating feasibility underway

Feasibility proved, but coating on free-standing films need to be studied.

Technology-to-Market Development

GE design and coordinate capacitor manufacturing using high dielectric constant polymer films to achieve smaller volume units.



Engaged Capacitor Mfgs early to align value chain
Kemet
ECI
DEI
NWL
SBE

Extrusion of 3-5µm PEI films favorable for medium voltage and smaller capacitors.

Enhanced dielectric strength via nano-coating of PEI films to ensure voltage handling reliability.

Response to Reviewers Comments

AMR14 comments were generally positive with the reviewers posing three questions:

1. Be aware of the potential cost of the carrier film

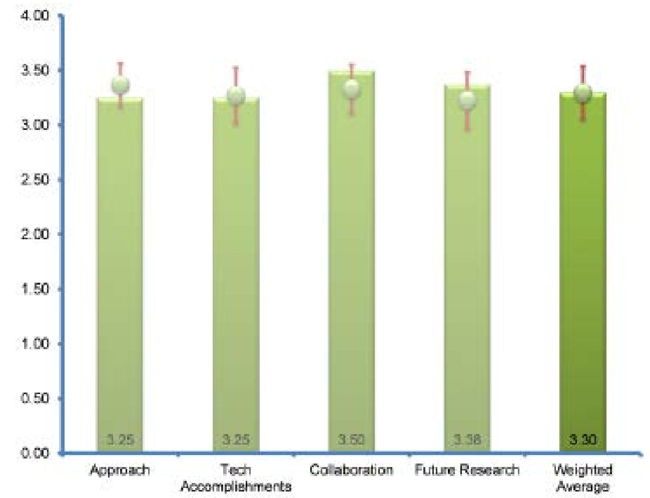
Yes, the team is aware of the cost of carrier and is working on minimizing carriers. Use of a carrier to support the very thin extruded film has the potential to improve the ease of handling and yield associated with various capacitor manufacturing steps, and the resulting process cost savings may help to offset the initial material cost of the carrier. The team will favor the free-standing film approach if high yield of 5, 4, and 3 μm films are gradually achievable.

2. Explain the approach from film to capacitors in more detail

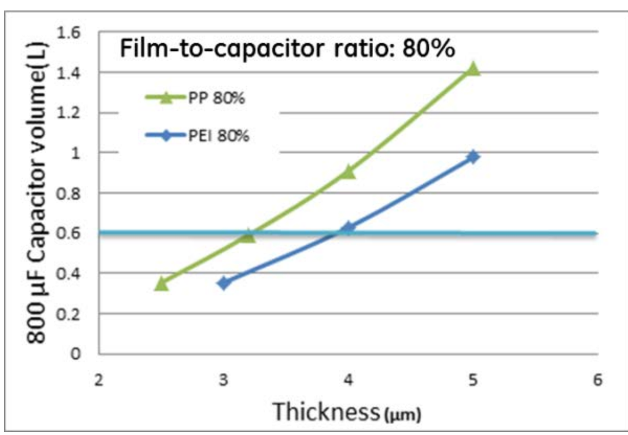
Taking into account both the film properties (*e.g.* dielectric constant, breakdown strength, and thickness) and capacitor design, 3-5 μm film was calculated to be able to meet DOE targets. The team is also considering the shape factor of different capacitor designs and packaging to minimize the volume, weight and cost (3 μm is ideal).

3. How much material production has contributed to achieving goals

Decreasing the film thickness is critical to achieving the DOE goals as shown in the figure at right. Producing films below 4 μm with minimal wrinkles is necessary and will lead to achieve DOE's unit volume target. High volume production of thin films may allow reduction of film manufacturing cost.



$C/N = \varepsilon_0 \varepsilon$ Area/thickness



Collaboration and Coordination with Other Institutions

- Contract Collaborator
  - Capacitor specs definition and testing (Ralph Taylor / Delphi)
- Extruded Film Suppliers
  - Free-standing film process (A, B)
  - Carried film process (C)
- Other Service Suppliers
  - Materion, Amcor, FEP for inorganic coating (sputtering, e-beam)
  - Bollore, Steinerfilm for metallization
  - DEI, ECI, SBE, NWL, Kemet for capacitor winding, packaging and testing

Remaining Challenges

- Commercial scale 5 μm PEI films exhibit minor wrinkles to be minimized.
- Scale-up extrusion of 3-4 μm free-standing film without wrinkles remains challenging.
- Nanocoating processing method needs improving.
- Ultimate cost of extruded PEI film is difficult to control, and depends on film manufacturing process and market demand.

Future Work: Validate Films & Capacitors

FY2015

- Extrude 3-5 μm film with minimal wrinkles from production line (Q2).
- Test and validate scaled-up films thinner than 5 μm (Q2).
- Optimize R2R nanocoating using e-beam tool at commercial vendors (Q3)
- Prototype PEI capacitors using films of 5 μm or thinner (Q3)
- Down select PEI film and nanocoating process (Q4).
- Verify film processing cost model (Q4)

FY2016

- Scale up PEI film and nanocoating (Q1)
- Design, deposit and verify metallization (Q2)
- Build and test specified capacitors using thinner films (Q3)

Summary

- **Scaled up production of PEI films of 3-5 μm in thickness, with minimal film wrinkling and thickness variability.**
  - Melt extruded wrinkle free PEI films (5 μm).
  - Developed the second supplier for 3-5 μm film with minor wrinkles.
  - Produced 3 μm PEI film supported by a carrier.
- **Developed nanocoating process on PEI films.**
  - Demonstrated breakdown strength enhancement on nanocoated film.
  - Demonstrated R2R coating feasibility on free-standing film.
- **Qualified film properties in terms of thermal, dielectric and mechanical characteristics.**
- **Developed a supply chain from film production to nanocoating to capacitor making.**
  - Established collaborative relationships with various suppliers.
  - Demonstrated the feasibility of winding the extruded films through various process steps.

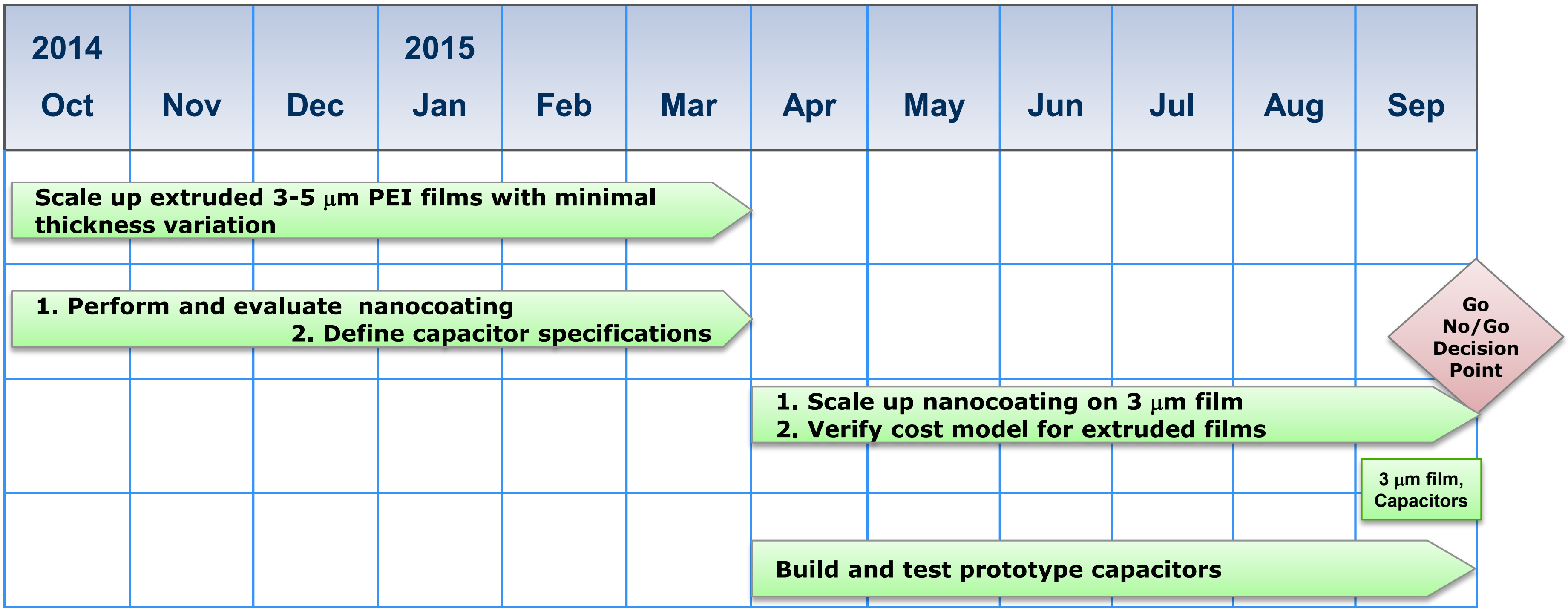
Acknowledgement

•"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.

Technical Back-Up Slides

BP2 Tasks to Achieve & Key Deliverable



Go No/Go Decision Point: Downselection of film thickness and coating process
Tear strength of nanocoating film

Key Deliverable: 3-micron film and nanocoating; Specified metallization design; 6 capacitors of specified requirements

Capacitor Volume and Cost Reduction

Volume: **40% (50% higher permittivity, capacitor factor, component number, potting and casing free)**

Weight: **40% (less connection, potting and casing free**

Cost: **$30 (less film~$24, less package)**

$$C/N=\varepsilon_0\varepsilon \ \text{Area/thickness}$$

800 µF capacitor	3 µm PEI	2.5 µm PP
Film volume (L)	0.254	0.257
Capacitor volume (L)	0.5	0.6
Capacitor shape	Flat/16 parts	Round/48 parts
Space fill factor	0.05	0.25
Potting casing (L)	No potting needed Casing optional	0.15
Final Volume (L)	**0.53**	1
Capacitor weight(g)	800-900	700
Overall weight (g)	**≤1000**	1800

Capacitor of $30 and 0.6L is possible.