Nature-Inspired Motivation for Developing Self-healable Electrical Insulation

Tiffany S. Williams, Ph.D.
Materials and Structures Division
NASA Glenn Research Center
Cleveland, OH

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Examples of Self-healing in Nature

Self-healing vs. regeneration?

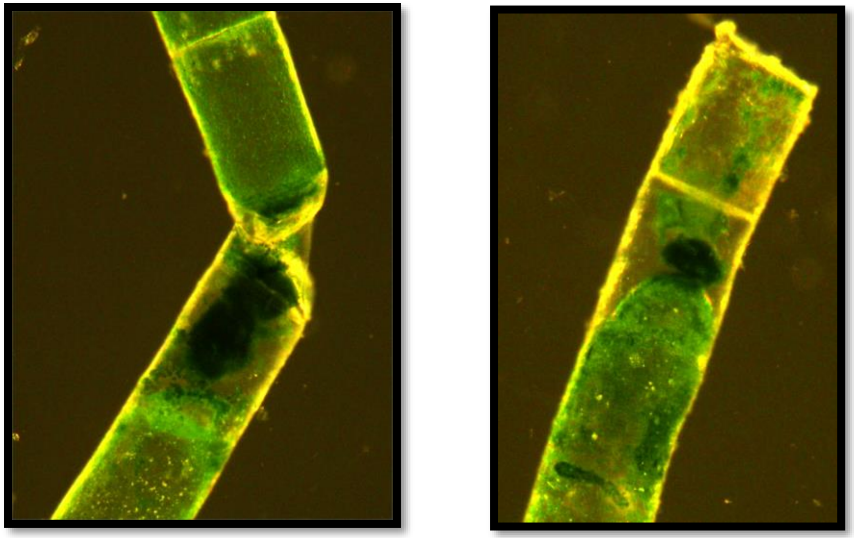
“Self-healing” to an engineer:

The ability for a material or structure to restore normal functions

Algae recovery in progress:
Formation of buds and nanofibrils

Living Things:

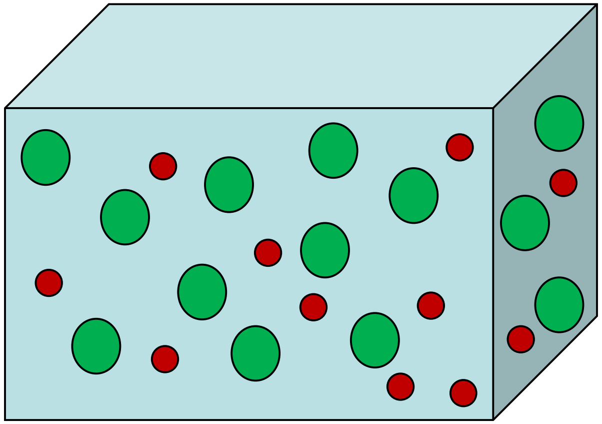
- Vertebrates
- Invertebrates
- Plants



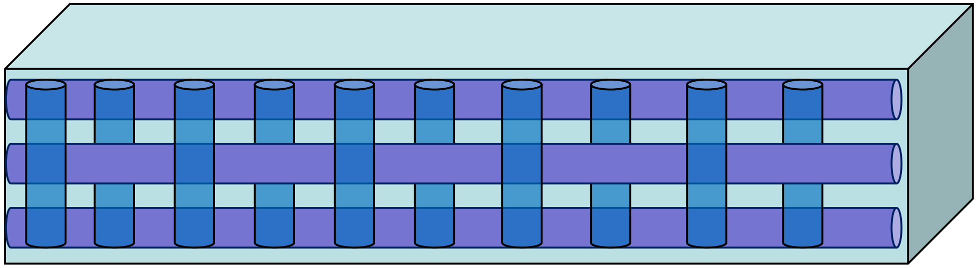
Regeneration in algae

Self-healing Mechanisms in Synthetic Materials

Extrinsic Healing

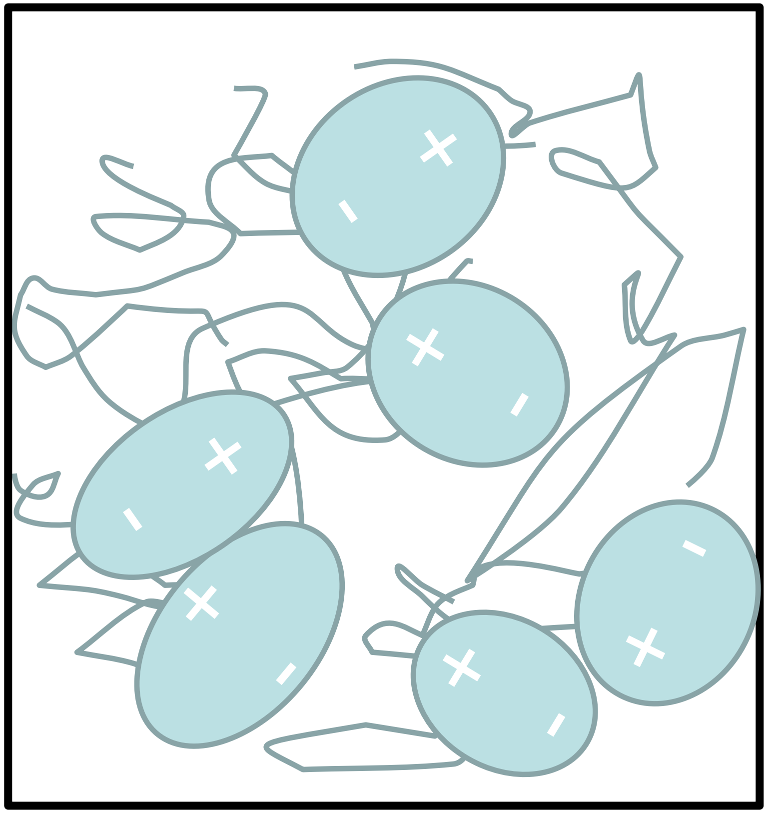


Embedded microcapsules filled with healing agents that flow and polymerize when cracks are formed.



Microvascular networks filled with healing agents that flow and polymerize when cracks are formed.

Intrinsic "Reversible" Healing



Ionic clusters and other bonds that can break and reform

The number of healing cycles is limited with extrinsic healing approaches

Motivation

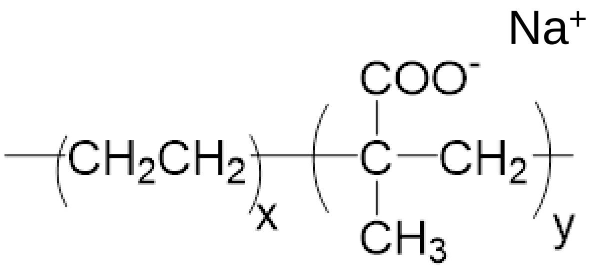
- **Problem:** Polymeric aircraft electrical insulation is highly prone to damage by:
  - Corona discharge at altitude
  - Abrasion and cuts (maintenance)
  - Damage to electrical insulation leads to electrical shorts and/or fires

- **Objective:** To increase aircraft safety and longevity of electrical insulation over state-of-the-art insulation through self-healing

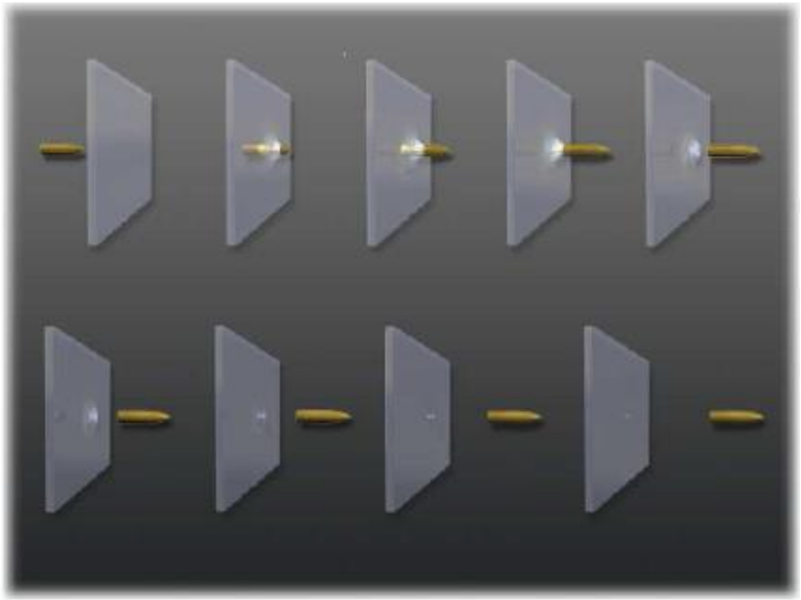
- **State-of-the-Art Insulation:** Polyimide
  - **Advantages**
    - Good dielectric properties
    - High thermal stability
  - **Disadvantages**
    - Moisture absorbance → Electrical fires

Surlyn ®

- Manufactured by DuPont. Ethylene methacrylic acid copolymer
- Commonly used as packaging materials – puncture resistance
- Previously investigated for impact-related healing.
- Thermal energy from impact believed to be high enough to initiate self-healing
- Ionic crosslinks thermally reversible
- Moisture absorption: < 1.3 % @ 70˚C, 85% R.H.



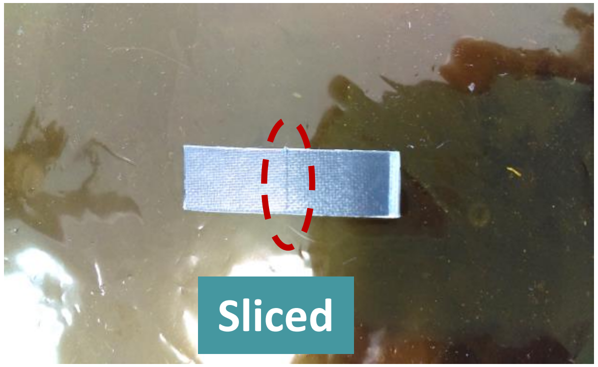
Sodium Ionomer

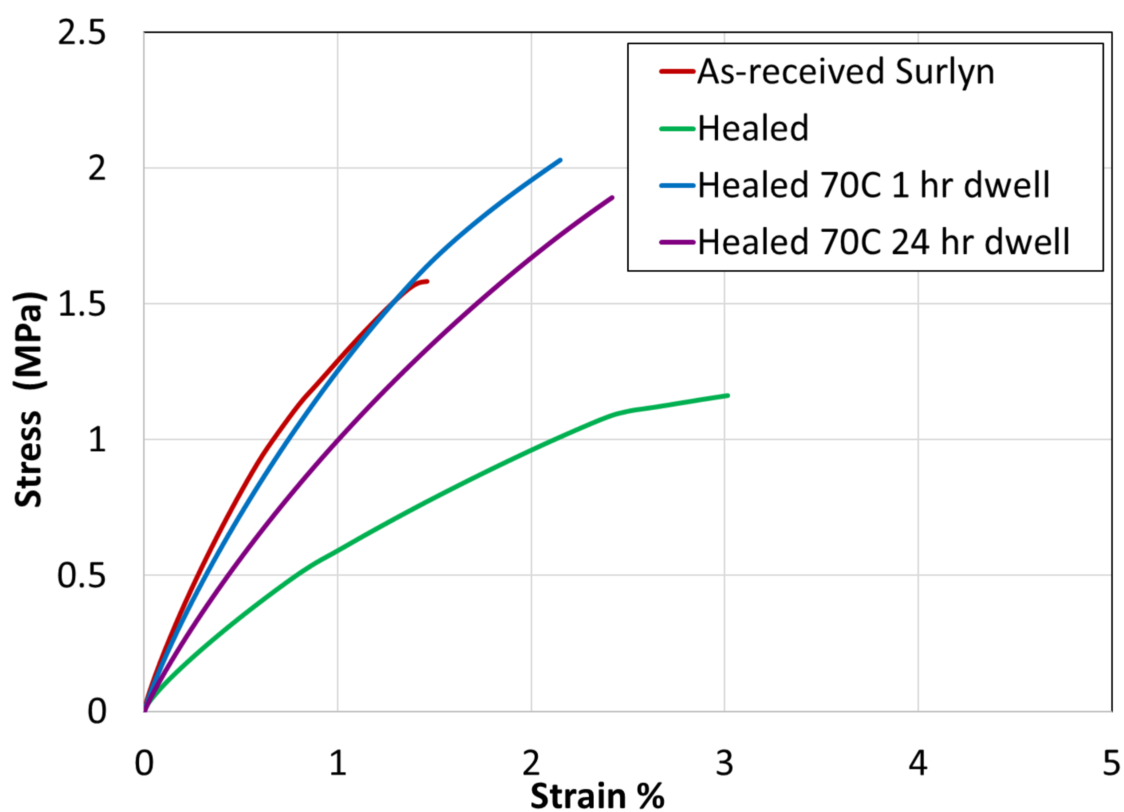


Bullet penetration and healing schematic for intrinsically healable materials

[K. Gordon et. al, Puncture Self-healing Polymers for Aerospace Applications, NASA Langley]

Recovery Strength Assessment





Surlyn film was cut and then heated to induce healing.

1st healing cycle → Only 67% recovery w/o additional heating

Elevated heating after mending is believed to activate ionic crosslinks.

Achieved 90-97% recovery when samples were dwelled at 70˚C.

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Dielectric Breakdown: Polyimide vs. Surlyn

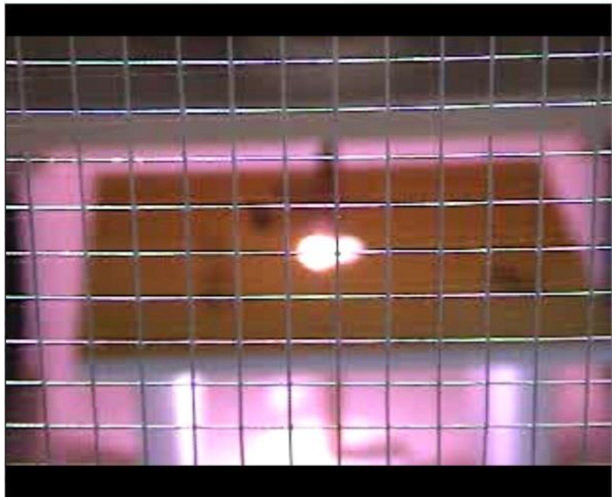
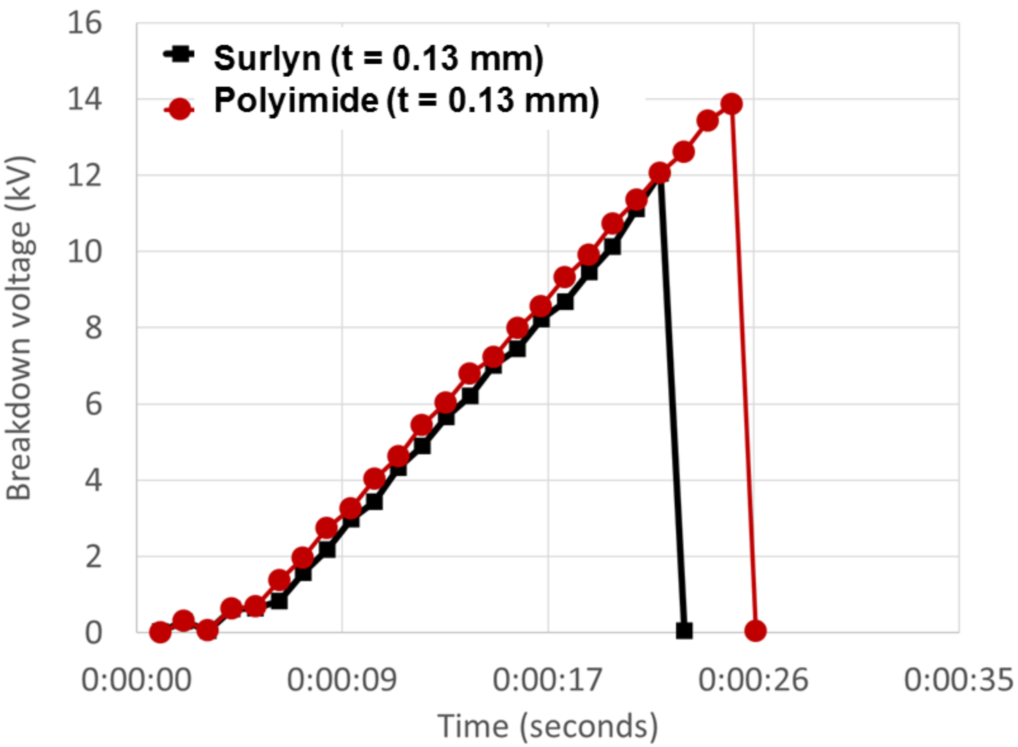


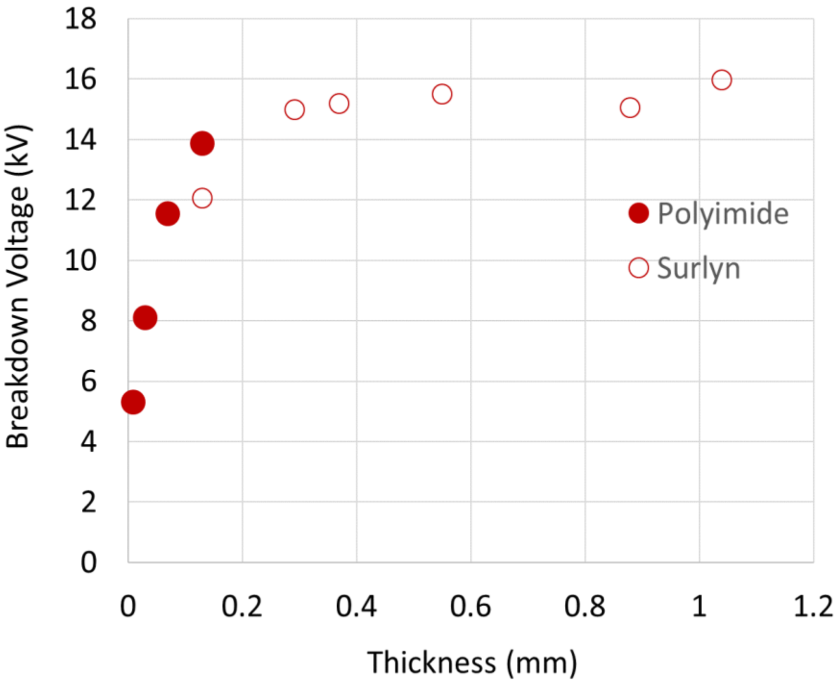
Image of arcing during breakdown.

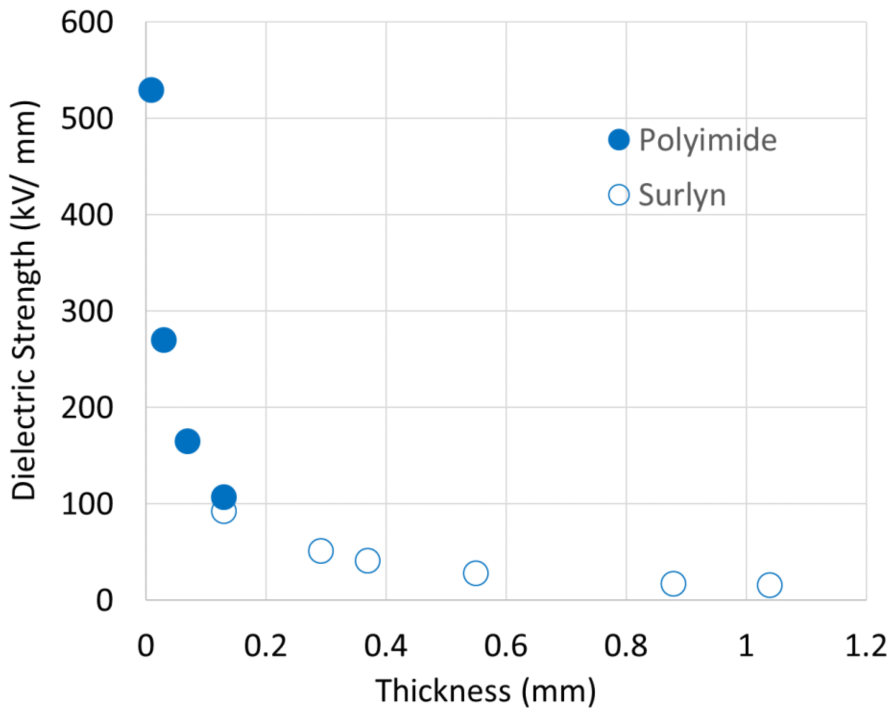
Eaton High Voltage Test Rig
Output voltage AC: V_{max} 60 kV
Test Environment: Air



Sample	Average Breakdown voltage (kV)	Average Dielectric Strength (kV/mm)
Polyimide (t=0.13 mm)	13.9	106.9
Surlyn (t=0.13 mm)	12.1	93.1

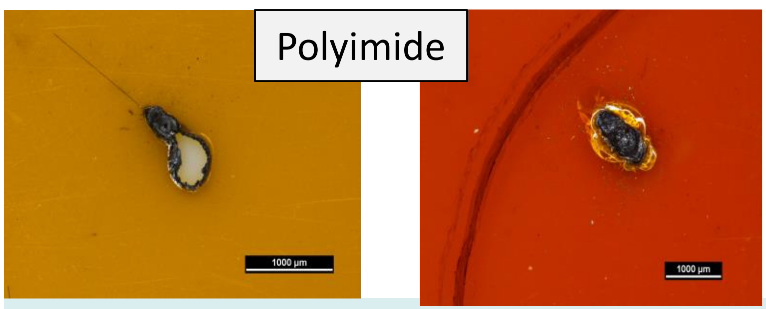
Effect of Thickness on Dielectric Breakdown (Air)



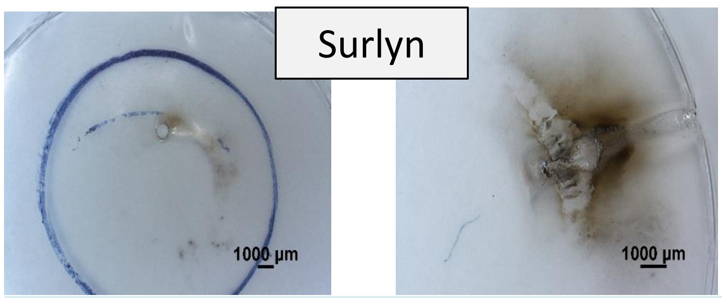


Breakdown voltage increases with increasing thickness.

Dielectric strength decreases with increasing thickness.



Punctures (decreasing thickness); charring (increasing thickness)



Puncture damage, but punctures were less noticeable in thicker samples.

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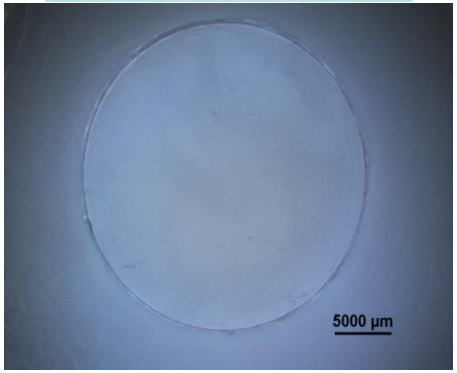
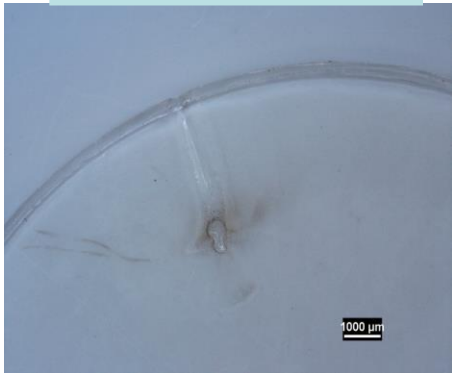
Evaluating Evidence of Healing after Dielectric Failure (Air)

Before Testing

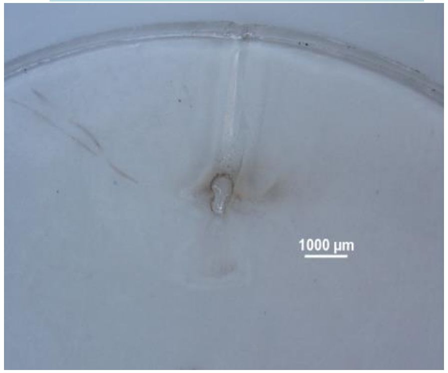


1 hour post-test

Day 3 post-test



Day 7 post-test

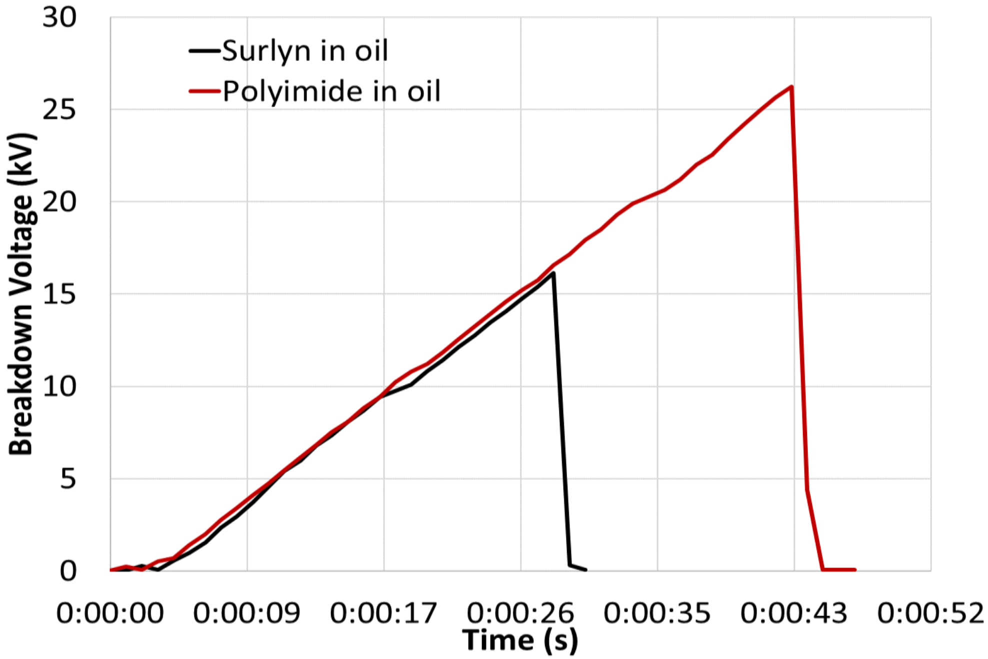


- Samples were dwelled at 70˚C for 7 days after testing.
- Surlyn did not show evidence of healing at most severe damage site
- Some discoloration cleared by day 7
- No healing can occur after thermal degradation
- Dielectric testing did not follow after dwelling at 70˚C for 7 days because damage was still noticeable

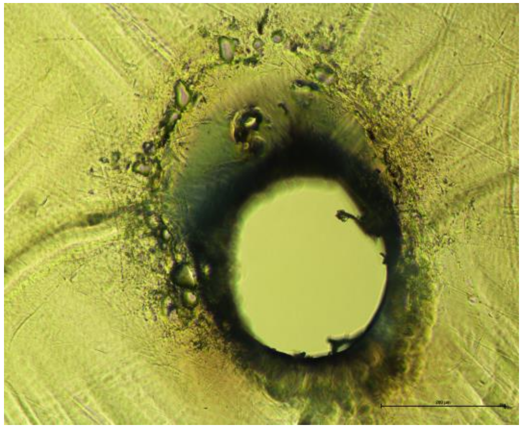
Dielectric Breakdown: Polyimide vs. Surlyn (Oil)

Testing environment: silicone oil

Sample	Breakdown voltage (kV)	Dielectric Strength (kV/mm)
Polyimide (t=0.13 mm)	26.9 ± 0.8	~206.9
Surlyn (t=0.13 mm)	16.8 ± 1.1	~129.0



Polyimide: Crack propagation; charring



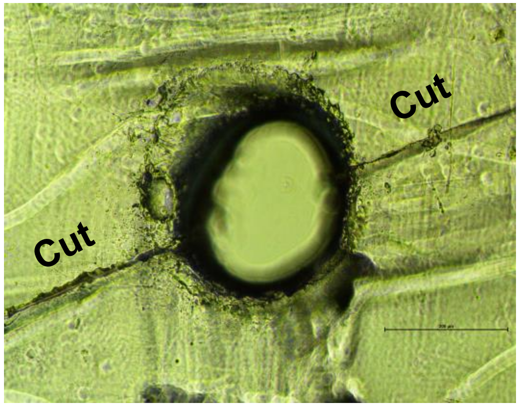
Surlyn: Punctures and bubbling

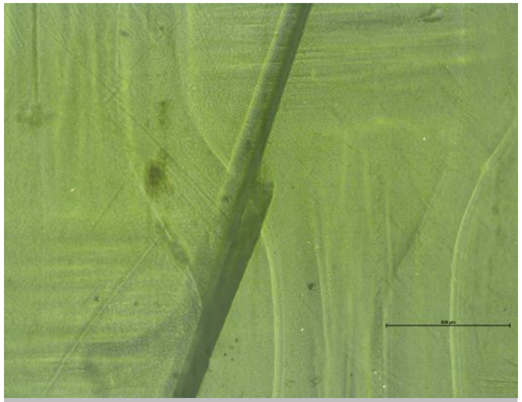
Polyimide: Propagating micro-cracks

Surlyn: Puncture

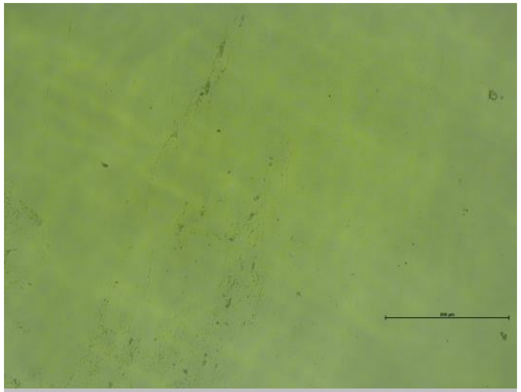
Evaluating Evidence of Healing after Mechanical Damage (Oil)

Surlyn was cut and then tested on dielectric rig. Most severe damage site fell along the incision line.

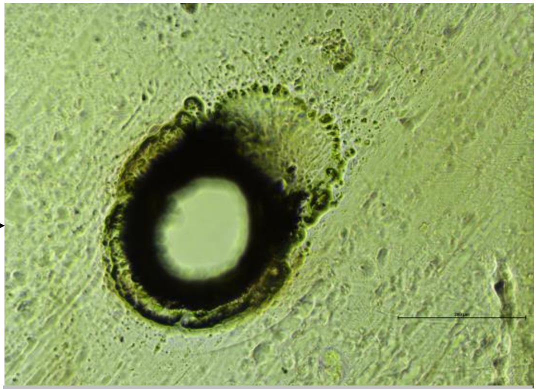




Surlyn with incision



Surlyn mended after applying heat. Scarring no longer visible.



Healed Surlyn after dielectric breakdown

	Surlyn	Surlyn (Cut)	Surlyn (Healed)
Breakdown Voltage (kV)	16.8 ±1.09	~9.7	~15.7

~93% recovery in dielectric strength after healing

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Conclusions

- Achieving close to full recovery in mechanical strength and dielectric properties is desirable and obtainable through intrinsic healing
- Polyimide films displayed severe charring at V_{max} in air. Surlyn showed some evidence of reversible damage at breakdown voltage.
- Damage induced by cuts and abrasions demonstrated healing. At least 90% recovery in dielectric strength and mechanical properties following healing.
- Damage caused by thermal degradation due to dielectric failure is irreversible.

Future Work:

- Define healing and test conditions following exposure to voltage
- Determine the effect of processing temperature on dielectric strength stability in physically cross-linked materials
- Evaluate dielectric strength recovery following multiple healing cycles

Acknowledgements

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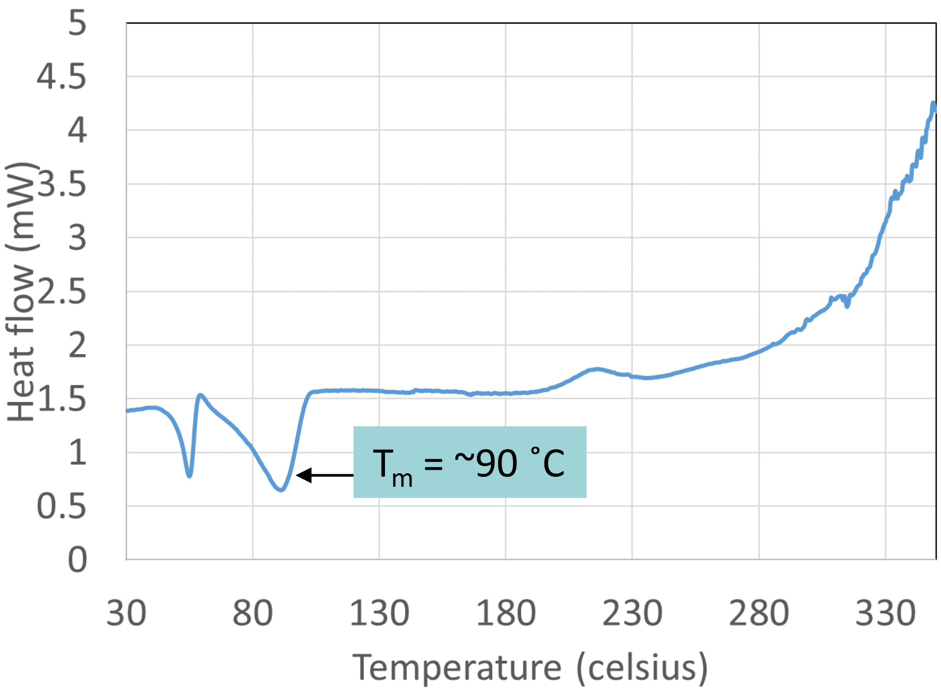
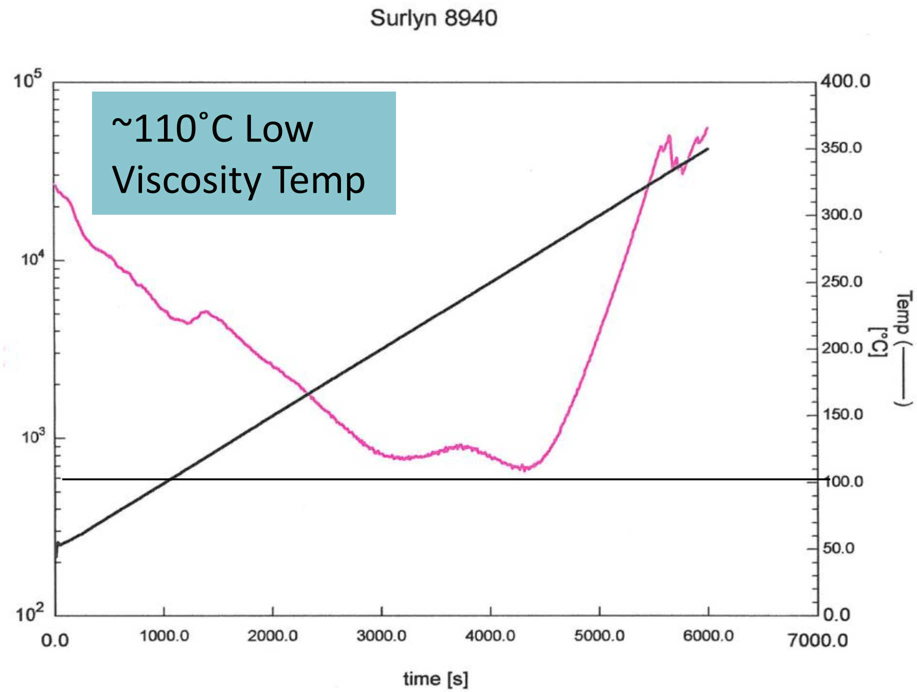
  - Jeremy Walker (NASA Graduate Student Intern Program)

QUESTIONS?

Film Processing





Surlyn films were processed by using a hot press at 115 ˚C for 1.5 hrs.