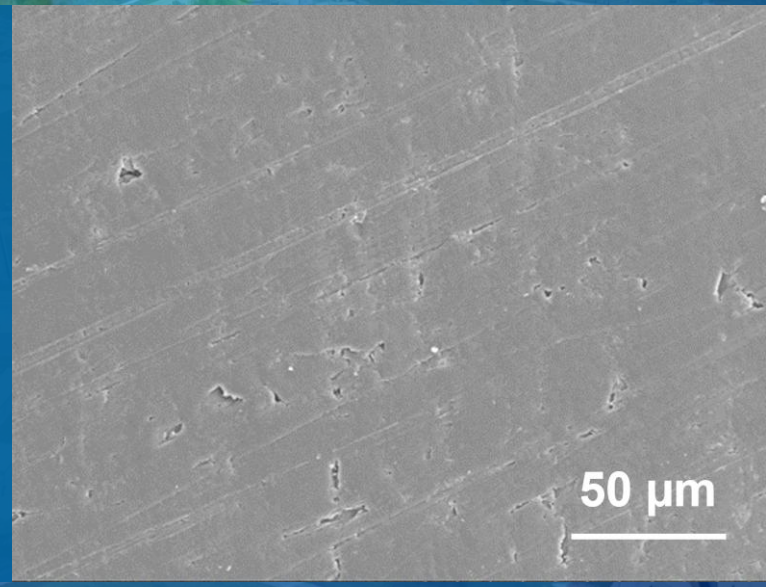
DOE OE TRAC PEER REVIEW 2026 Presentation ID#: 5.5

HIGH DIELECTRIC BREAKDOWN STRENGTH CERAMIC-POLYMER COMPOSITES



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Project Overview

- Project Description: To develop advanced ceramic-polymer dielectric materials with superior performance
  - High breakdown strength
  - Low dielectric loss tanδ
  - Long useful life
  - High temperature operation
- Period of Performance: **24 months** (11/10/2025 to 11/09/2027)
- Award Amount: **$750,000.00** (federal funding) + 320,000.00 (cost-share)
- Prime Awardee: Argonne National Laboratory
- Partners: S&C Electric Company
- Technology Area: 3 – Dielectric Materials

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Project Overview (Cont'd)

- Alignment/Supports strategic pathway: Developing advanced ceramic-polymer dielectric materials that improve the reliability, resilience, and modernization of next generation grid equipment. Knowledge learned from this project helps,

  1. **Stabilize** the grid by reducing the risk of insulation failure during high-voltage transients, elevated operating temperatures, and emergency overload conditions that can otherwise lead to outages and equipment damage.
  2. **Optimize** the grid to enhance performance by improving performance and operational efficiency.
  3. **Grow** the grid by advancing scalable, high-performance materials that support next-generation utility equipment.

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Problem Statement

Developing high-temperature operational, high dielectric breakdown strength, and low dielectric loss, ceramic-polymer composite dielectric materials to meet TRAC Lab Call objectives for Topic Area 3:

1. High dielectric strength >120 kV/cm
2. Low dielectric loss tanδ <0.05% at 60 Hz
3. Long useful life of 20-40 years
4. High operation temperature >130°C and 180°C in emergency

for harsh temperature applications beyond what cross-linked polyethylene (XLPE) can withstand.

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Multiphysics Modeling Framework for Predicting Dielectric Breakdown

Key assumptions and governing equations

- Quasi-static Maxwell equation

$$\nabla \cdot \boldsymbol{D} = 0$$
$$\boldsymbol{D} = \varepsilon(\omega, T)\boldsymbol{E}$$
$$\boldsymbol{E} = -\nabla\phi$$

- Everything defined in the complex domain

$$\boldsymbol{D} = \boldsymbol{D}' + j\boldsymbol{D}''$$
$$\varepsilon = \varepsilon' - j\varepsilon''$$
$$\phi = \phi' + j\phi''$$

- So, the Maxwell equation can be expressed as two coupled, real-valued partial differential equations

$$\nabla \cdot (\varepsilon'\nabla\phi') + \nabla \cdot (\varepsilon''\nabla\phi'') = 0$$
$$\nabla \cdot (\varepsilon'\nabla\phi'') - \nabla \cdot (\varepsilon''\nabla\phi') = 0$$

- Subject to kinematically uniform boundary conditions

$$\phi' = -\boldsymbol{E}_M\boldsymbol{x}$$
$$\phi'' = 0$$

- Homogenization for effective permittivity

$$\langle \boldsymbol{D} \rangle = \varepsilon \langle \boldsymbol{E} \rangle$$

- Notes:
  - We assume isotropic permittivity for each single phase, but the effective permittivity could be anisotropic depending on the microstructure.
  - Imaginary permittivity (i.e., dielectric loss) can be derived through probing real component of the electric potential.
  - The homogenization is performed by sweeping the ranges of interest for ω and T.

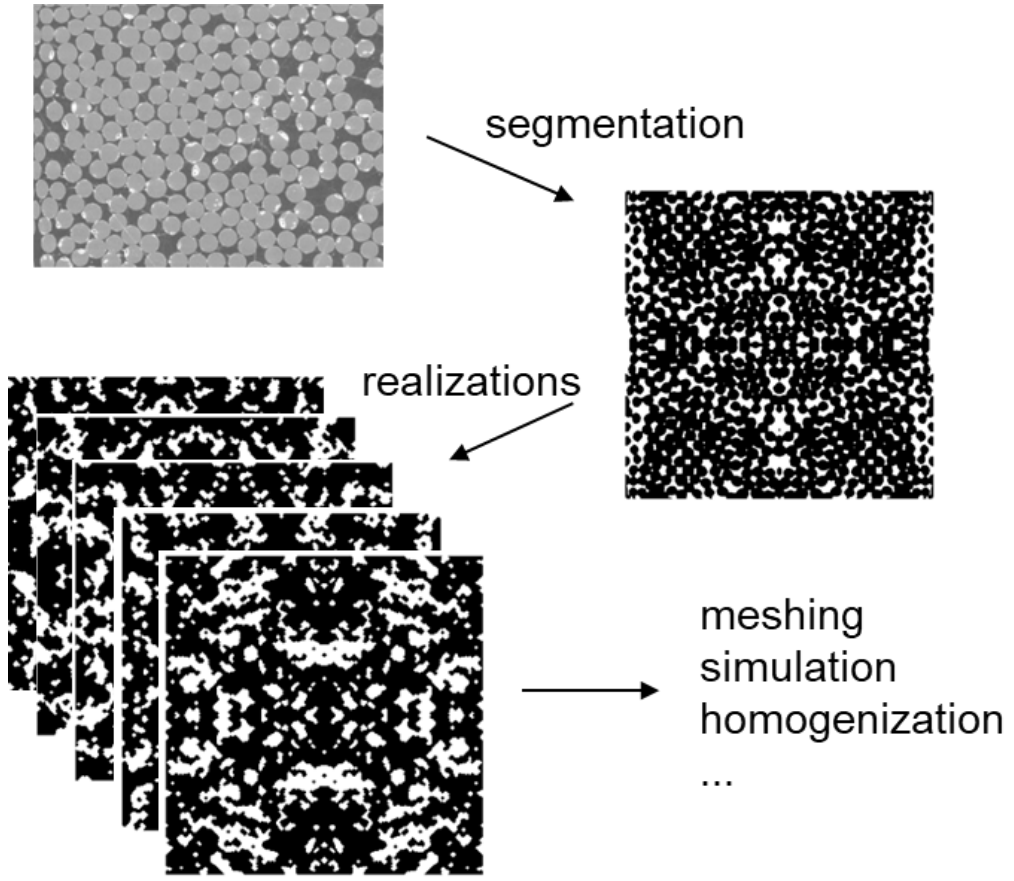
MOOSE: *Multiphysics Object-Oriented Simulation Environment*

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Multiphysics Modeling Framework for Predicting Dielectric Breakdown (Cont'd)

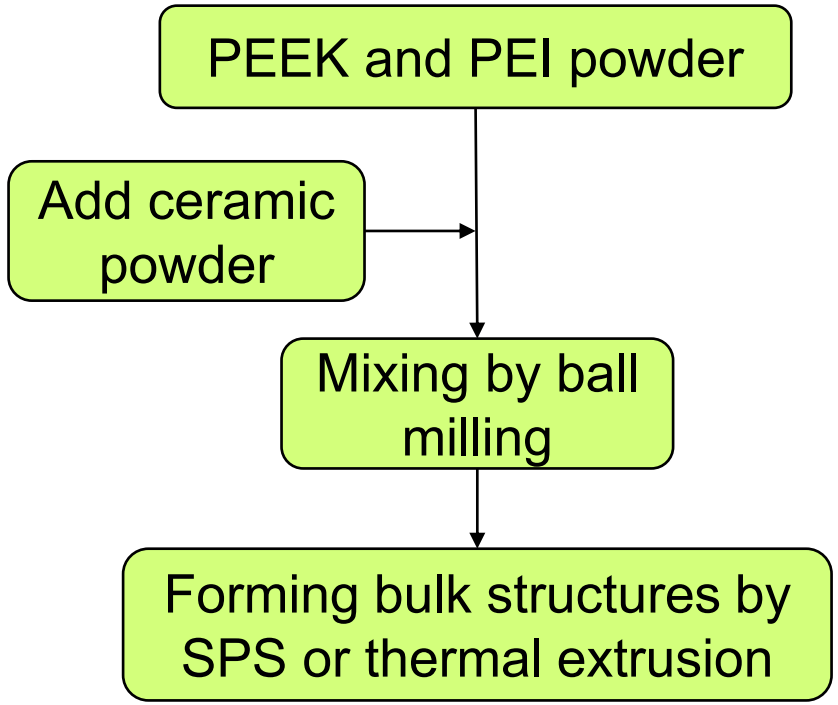
Sampling statistical features of the RVE

- Looking for an upper bound for $\bar{\epsilon}$, we cannot focus on one single snapshot of the microstructure and call it good.
- RVE (representative volume element) is identified through meshing simulation homogenization
- Key steps:
  - Get micro-images from scanning electron microscopy (SEM)
  - Estimate the empirical covariance of the composite
  - Use the estimated covariance to realize hundreds of representative microstructures until we reach statistical convergence



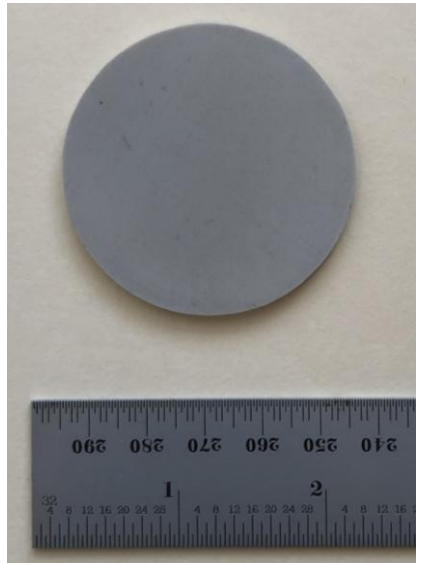
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Experimental Synthesis of High Temperature Dielectric Composite Materials





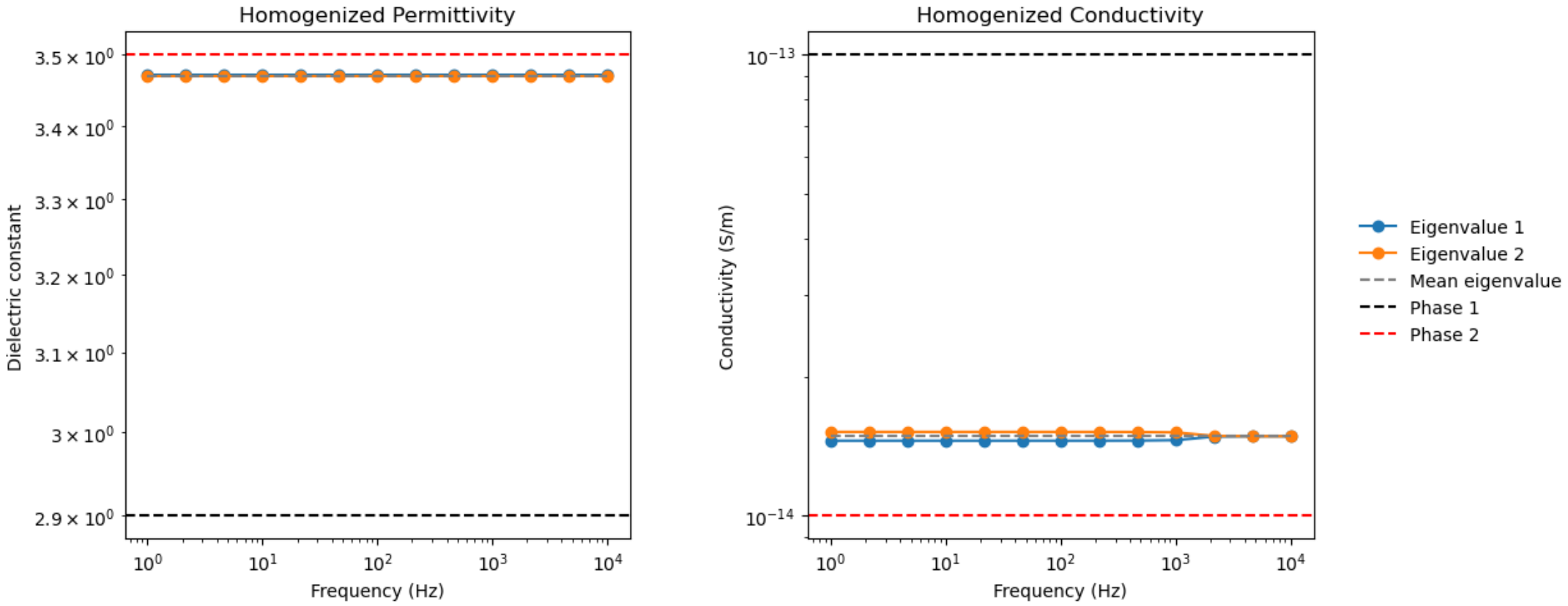




- ✓ High temperature polyether ether ketone (PEEK) and polyetherimide (PEI) mixed
- ✓ Powder mixture was blended at room temperature by ball milling process
- ✓ Premixed dry powder was processed for making dense bulk parts by spark plasma sintering (SPS) process under vacuum

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Results: Dielectric Property Computation

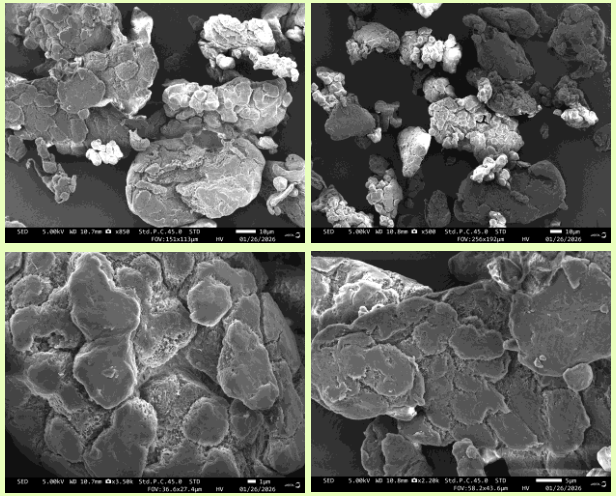


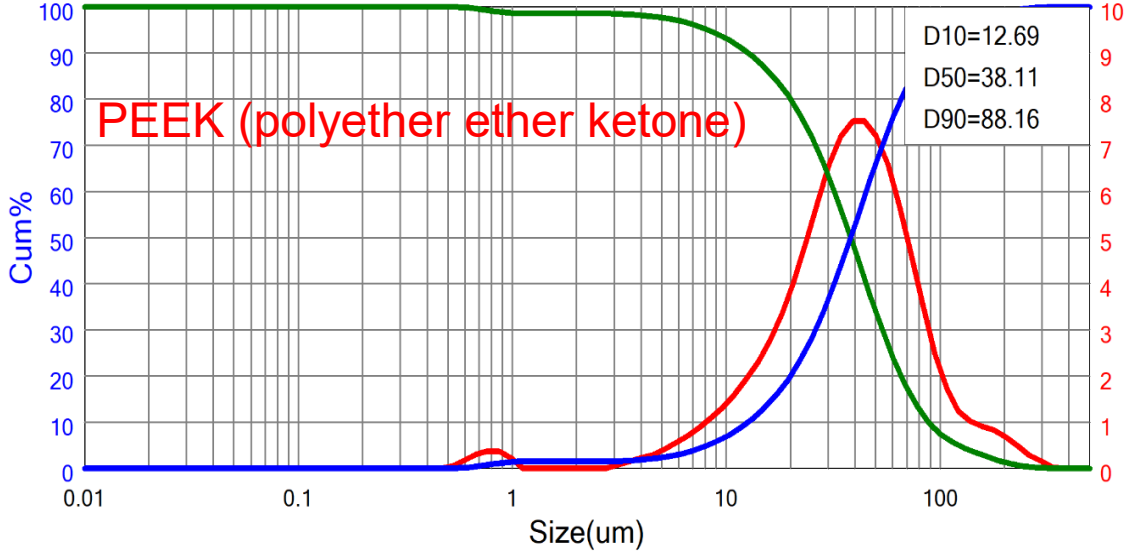
Simulated permittivity and conductivity of dielectric material investigated.

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Characterization of as Received Powders

PEEK powder SEM Images

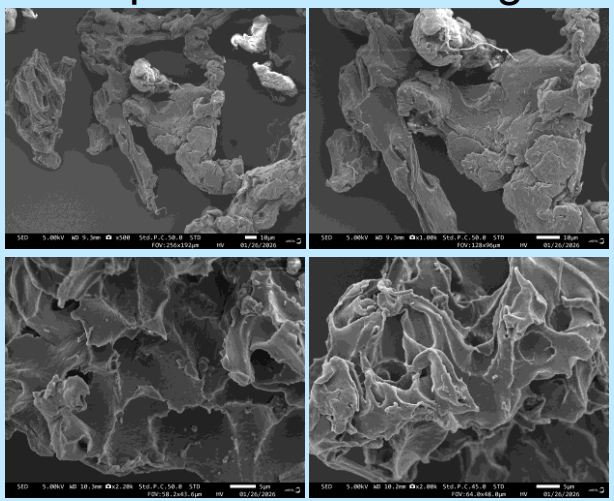


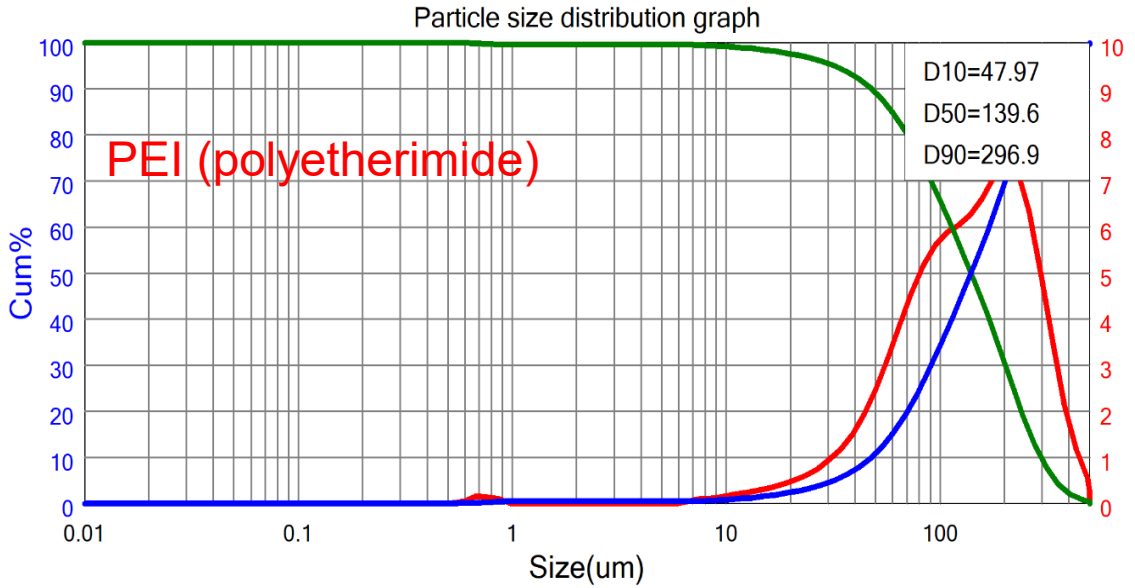


Table

Diam um	Percent
0.000 - 2.000	1.47
2.000 - 5.000	0.84
5.000 - 10.00	4.51
10.00 - 20.00	13.20
20.00 - 45.00	39.83
45.00 - 75.00	25.54
75.00 - 100.0	7.14
100.0 - 200.0	6.11
200.0 - 300.0	1.28
300.0 - 400.0	0.08

PEI powder SEM Images





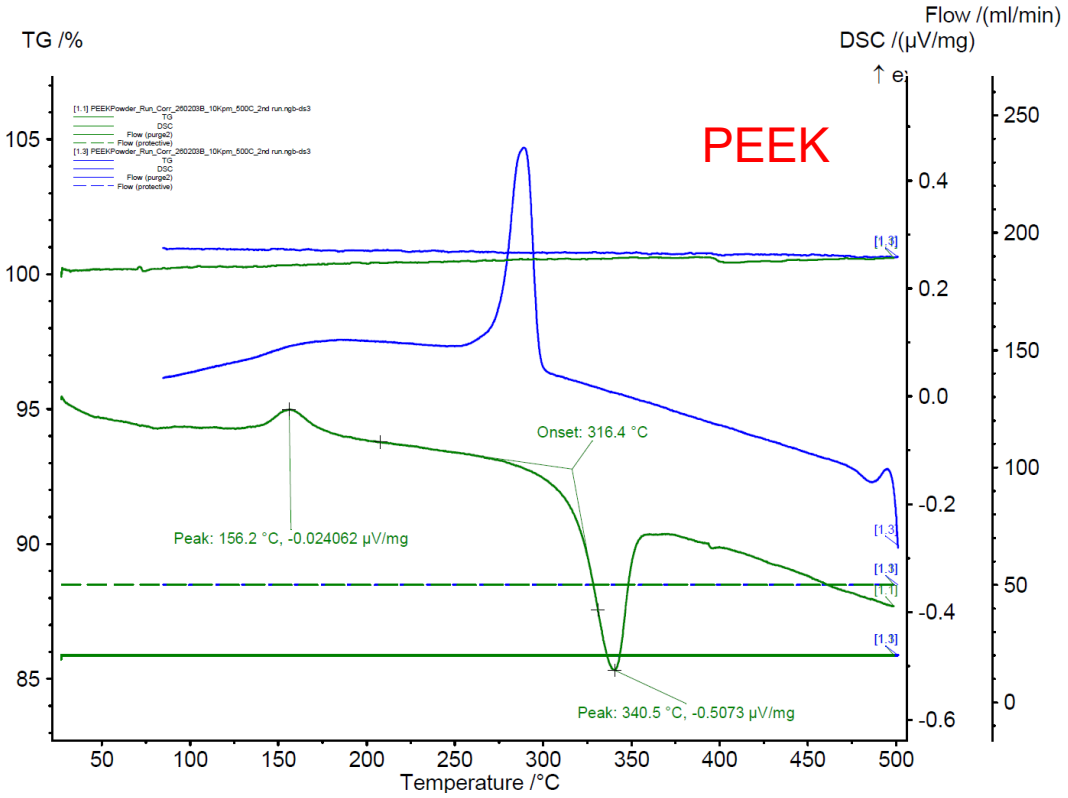
Table

Diam um	Percent
0.000 - 20.00	2.40
20.00 - 45.00	6.52
45.00 - 75.00	13.25
75.00 - 100.0	12.03
100.0 - 200.0	35.16
200.0 - 300.0	21.04
300.0 - 400.0	7.37
400.0 - 500.0	1.81
500.0 - 600.0	0.38
600.0 - 700.0	0.04

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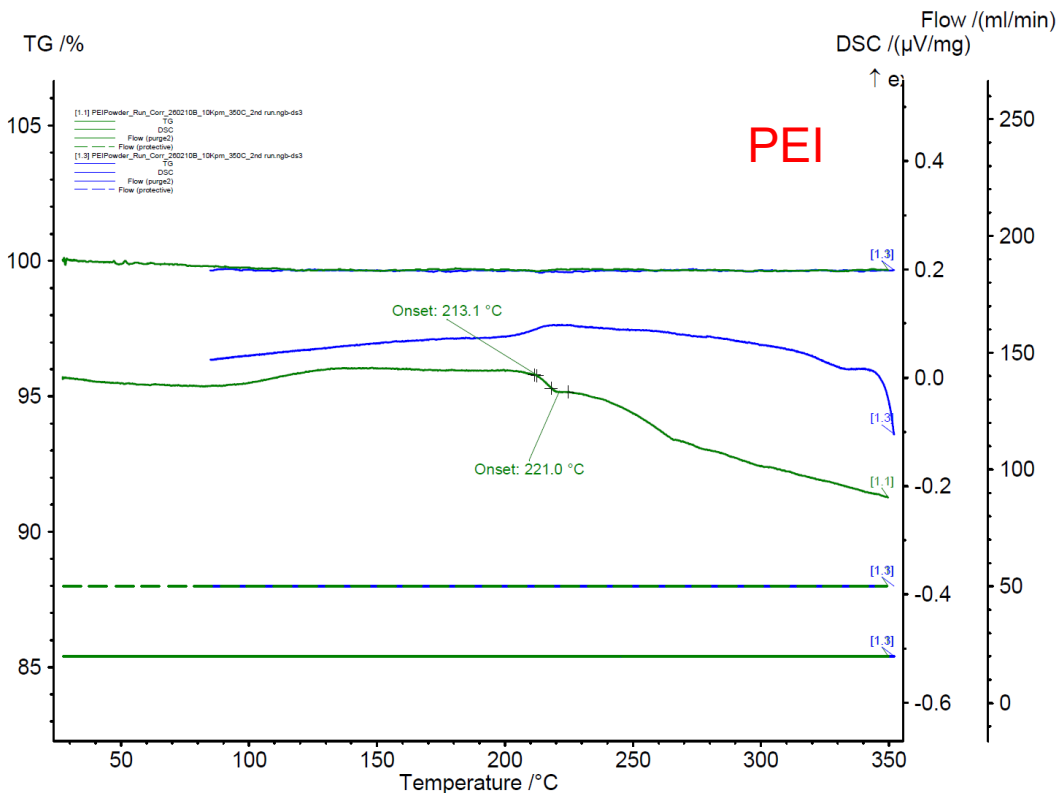
Characterization of as Received Powders (Cont'd)

TGA/DSC analysis of PEEK powder



PEEK: polyether ether ketone

TGA/DSC analysis of PEI powder

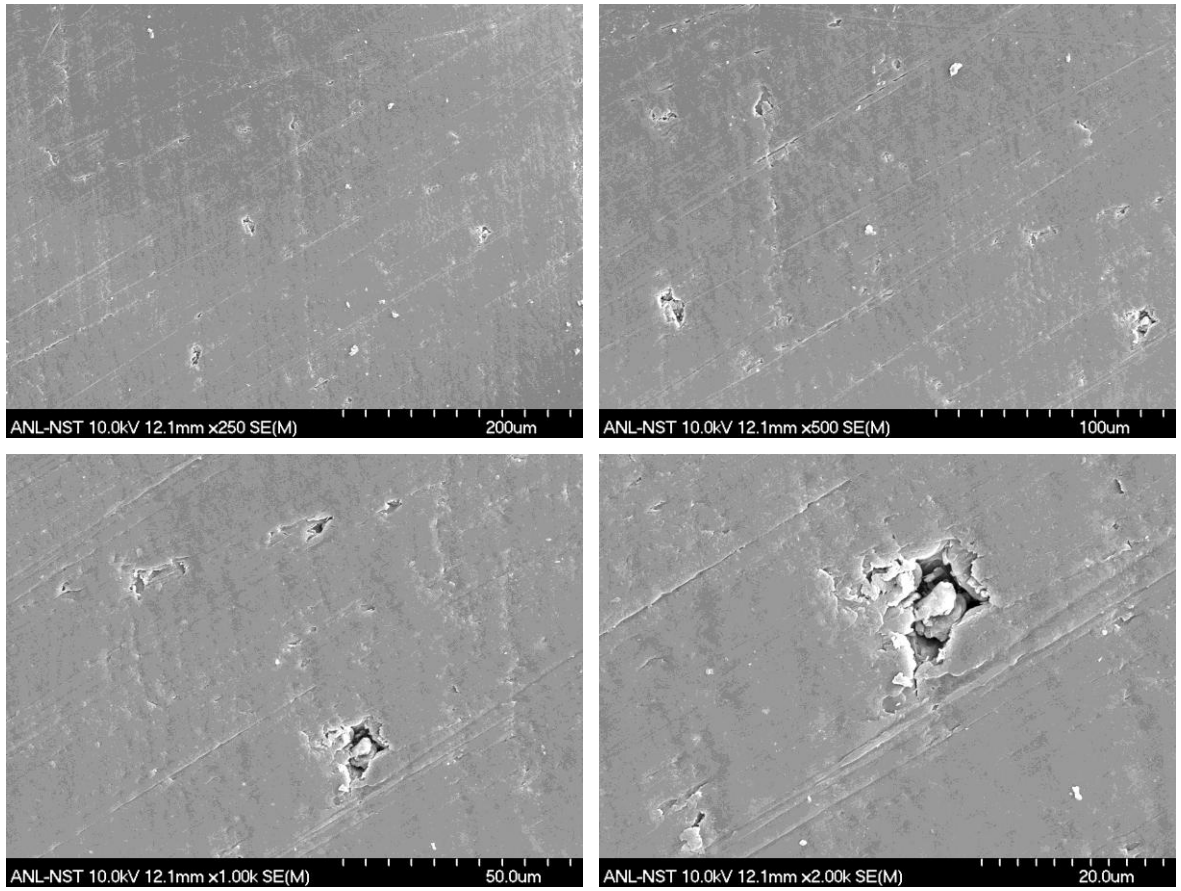


PEI: polyetherimide

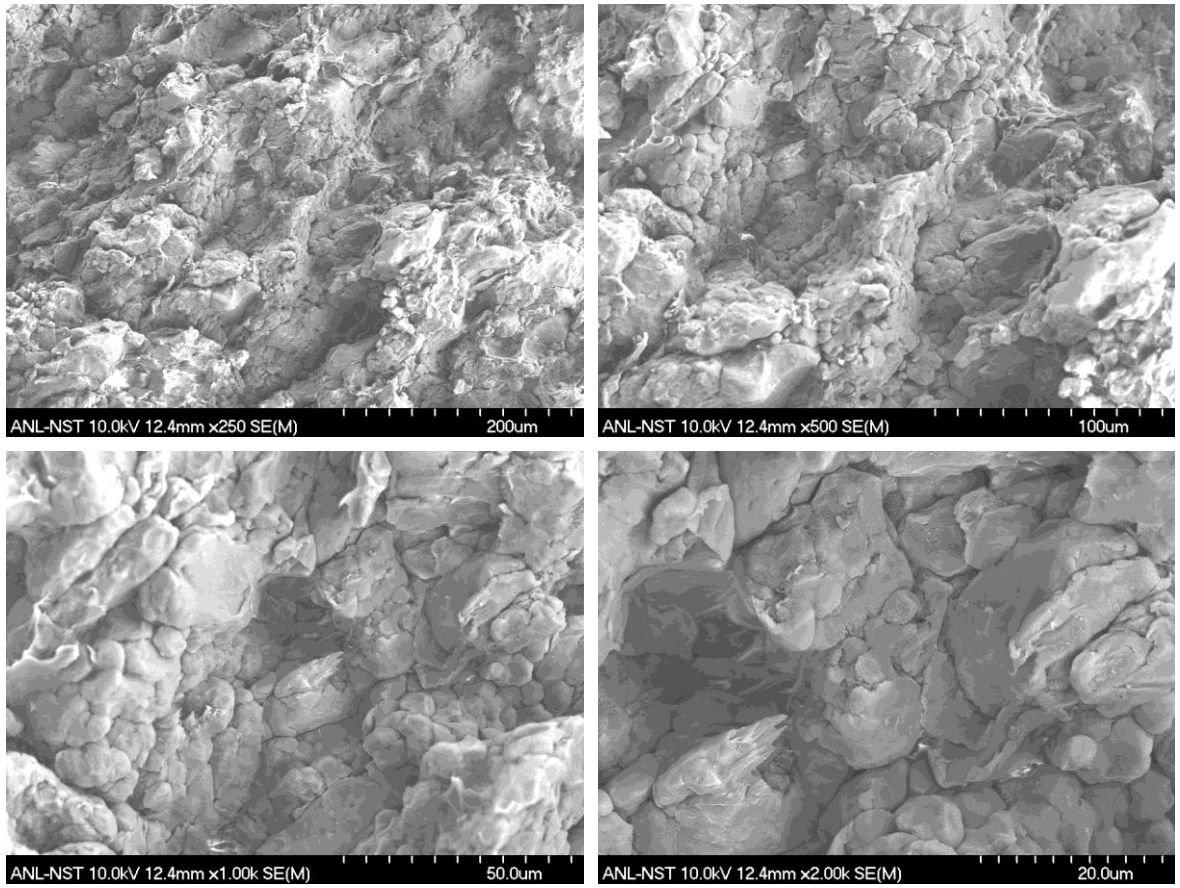
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SEM Microstructure of PEEK + 15wt% PEI by SPS

Polished surface SEM microstructure



Fracture surface SEM microstructure



Bulk specimen of PEEK + 15%PEI made by SPS process with bulk density >99%

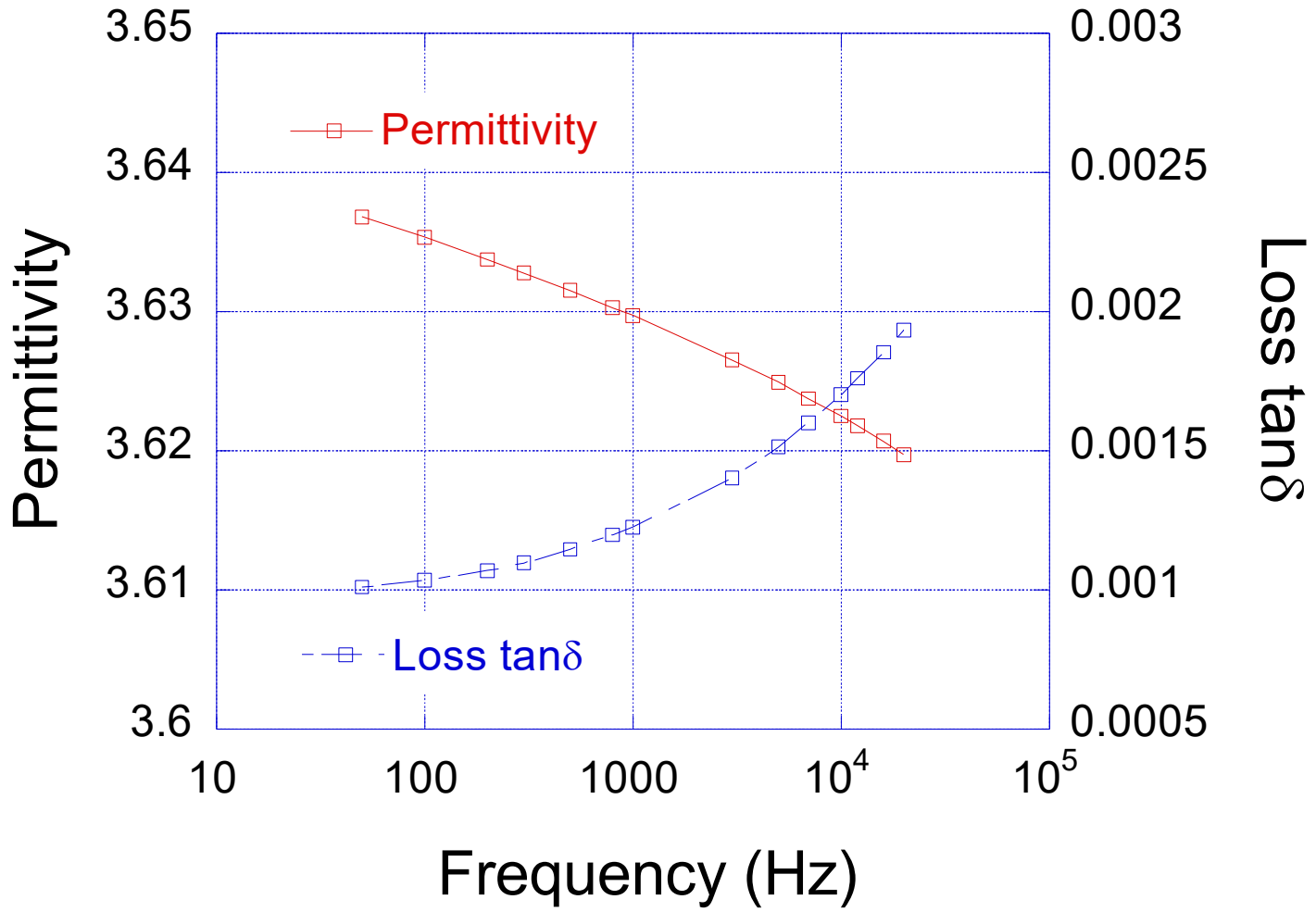
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Bulk Samples Made by SPS Process

Sample	Composition	Processing Condition	Theoretical Density (g/cm^3)	Experimental Density (g/cm^3)	Relative Density (%)
829-16-02	Pure PEEK Powder	Spark Plasma sintering, 270 °C, 10 MPa, 5 min	1.320	1.307	99.02
829-19-02	PEEK+5wt%PEI		1.317	1.313	99.69
829-22-01	PEEK+10wt%PEI		1.314	1.307	99.46
829-23-01	PEEK+15wt%PEI		1.312	1.300	99.08
829-23-02	PEEK+20wt%PEI		1.309	1.294	98.85

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Dielectric Performance at Room Temperature



- ✓ Demonstrated fabrication of bulk PEEK/PEI high temperature dielectric bulk structures by powder metallurgy and SPS processing
- ✓ Achieved high bulk density (>99%) and superior dielectric performance (low dielectric loss <0.002)

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Conclusion and Impact

- AI framework using LLM confirmed that properly processed PEEK + PEI can realistically satisfy all targeted properties:
  - Both base polymers have intrinsically low dielectric loss at 50/60 Hz.
  - Breakdown strength is in the correct regime without requiring high filler loading.
  - Thermal stability is inherent - Tg and decomposition comfortably exceed 130°C.
- PEEK and PEI powders acquired and powder mixture prepared with and without fine ceramics powder
- Bulk polymer composites fabricated by Spark Plasma Sintering (SPS) processing
- Proper incorporation of fine ceramics powder (filler) into polymer composite materials can further improve dielectric performance

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Future Direction/Next Step

- Optimization of processing conditions for making PEEK + PEI composite materials by SPS with ceramic powder infusion
- Investigate mixing of PEEK and PEI polymer composites by micro compounding and thermal extrusion
- Advanced characterization of bulk composite materials fabricated by Spark Plasma Sintering (SPS) processing
  - SEM microstructure analysis
  - Dielectric property testing
  - Thermal stability measurements
  - Dielectric breakdown strength testing
  - HALT (Highly Accelerated Life Test) analysis for lifetime prediction
- Power system components fabrication and evaluation

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