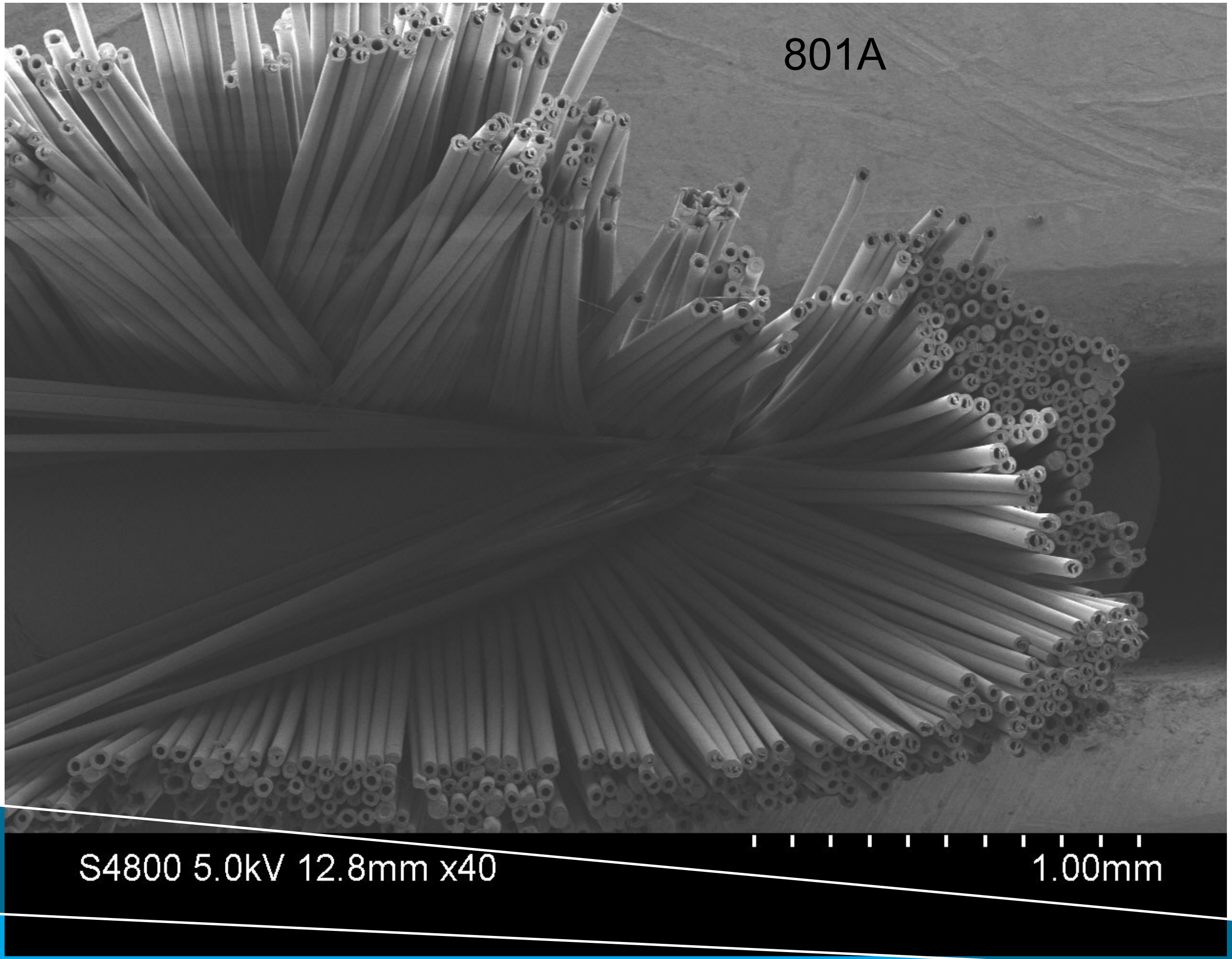
Low-Cost, High-Strength Hollow Carbon Fiber



Dr. Matthew C. Weisenberger

Associate Director, University of Kentucky Center for Applied Energy Research

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Dr. Matthew Weisenberger

- **Associate Director**, UK CAER since 2015
  - **Group Lead**: Carbon Material Research Group
- **Adjunct Assistant Professor** in MSE
  - Full member of the graduate faculty
- **Fiber Research**:
  - **Carbon fiber** processing, structure, and performance, including solution-spun PAN based carbon fiber, melt spun (mesophase) pitch-based carbon fiber
    - Electrically conductive polymer fiber spinning, characterization and applications: PEDOT:PSS fiber, n-PBDF fiber

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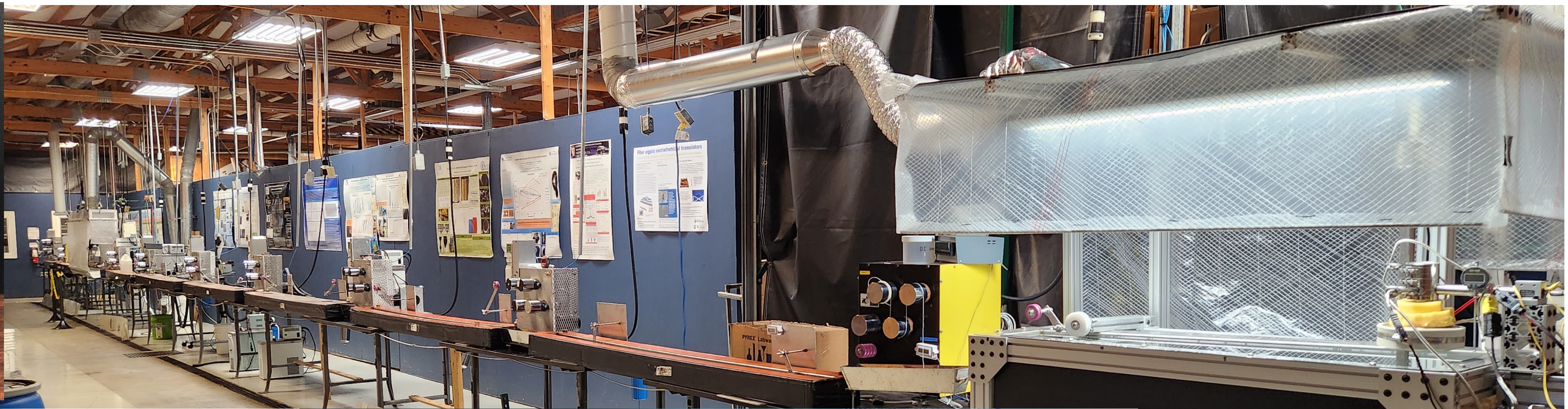
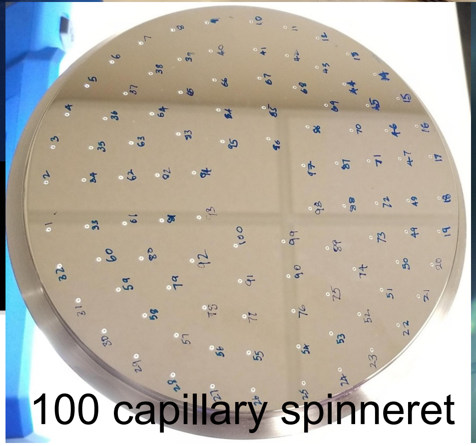
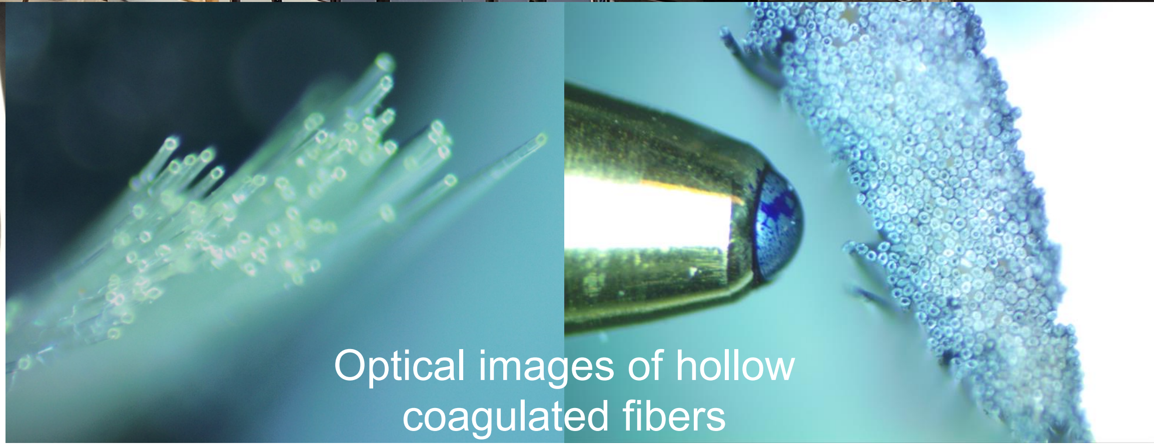
Solution Spinning Line at UK CAER





100 capillary spinneret



Optical images of hollow coagulated fibers

Why Hollow?

<u>Eliminate disordered fiber core</u>, leading to:

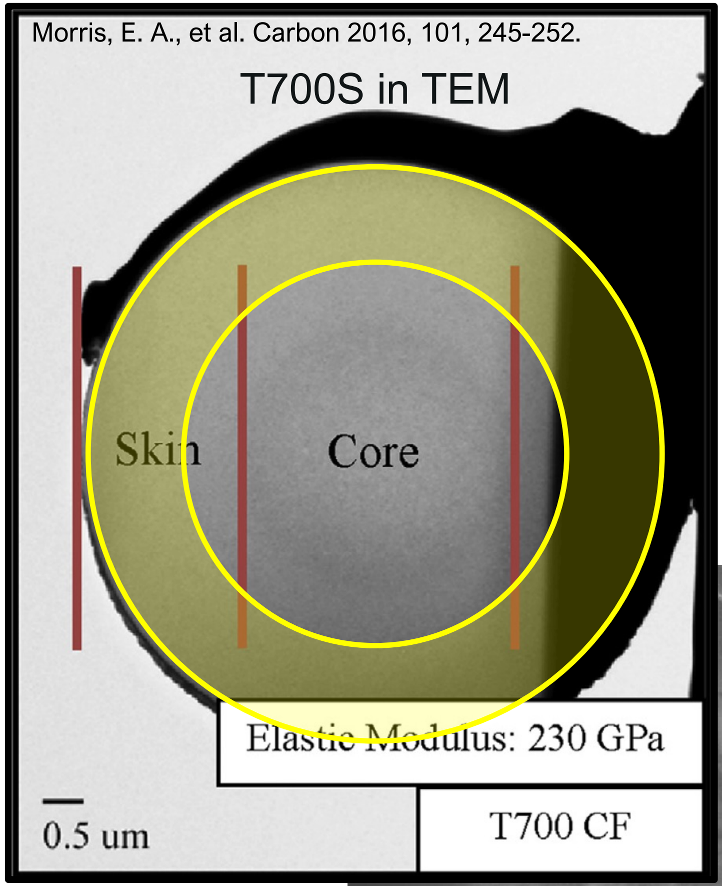
1. **Maximizing specific properties (use less kg of CF)**
   - ✓ Higher gravimetric capacity (kWh/kg)
   - ✓ Less kg of HCF need for same composite
   - ✓ Effectively lowers cost
     - Lower tank cost: ($/kWh)
2. **Faster oxidation**
   - ✓ Lower cost ($/kg CF)

<u>Key Challenges</u>

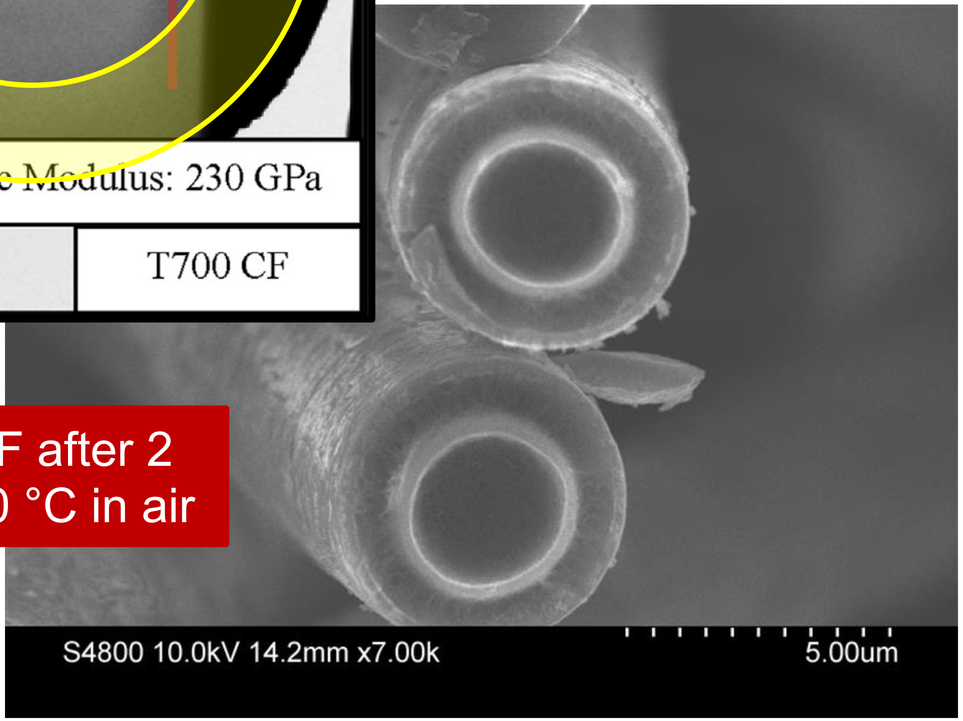
Achieve target OD/ID of hollow precursor

14/9.3 µm (OD/ID)

Conserve T700S tensile properties



Overlay (yellow) of target HCF dimensions:
7 µm OD
4.65 µm ID



T700S CF after 2 hrs. at 600 °C in air

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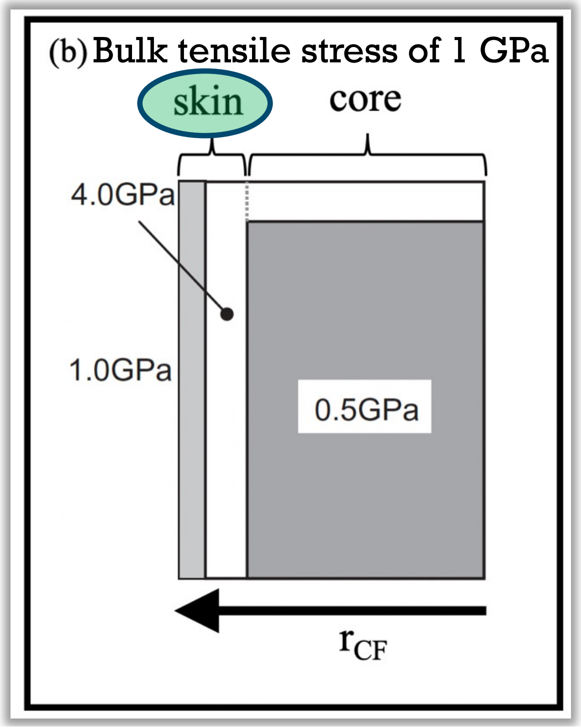
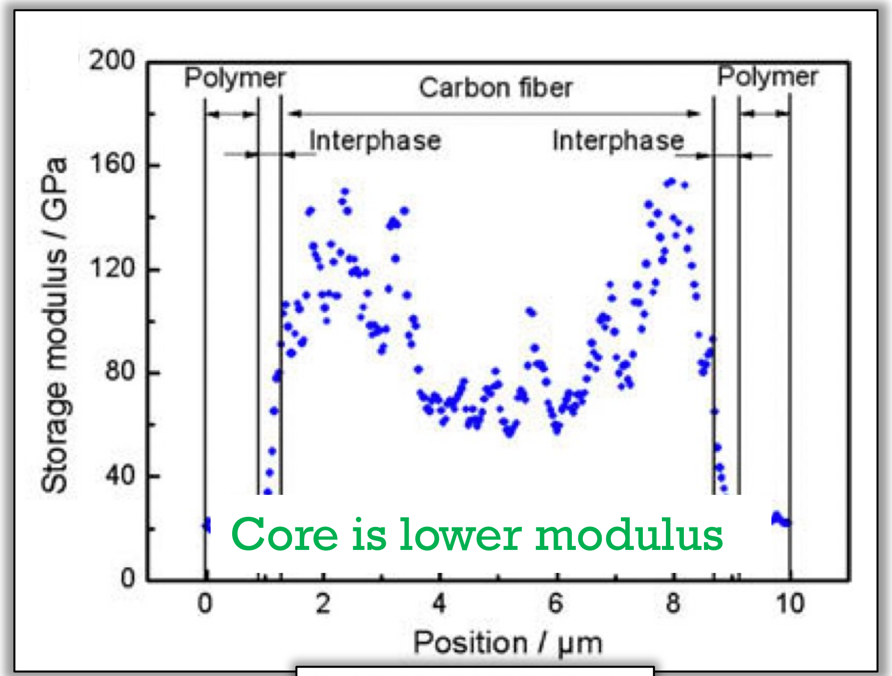
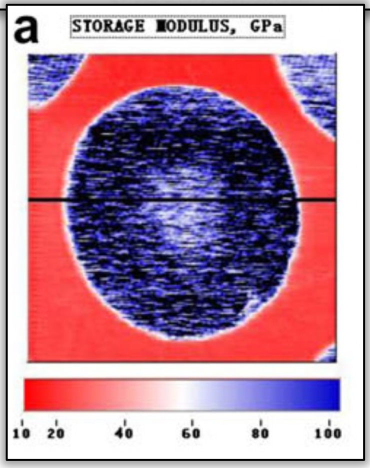
Prospect for Higher Specific Properties



Kobayashi, T., et al. (2013). Carbon 53, 29-37

Spatial stress distribution indicates
skin carries highest stress
Therefore, defects in the skin are more likely to reduce fiber strength





Gu, Y., et al. (2010). *Carbon* **48**, 3229-3235

THE GOAL

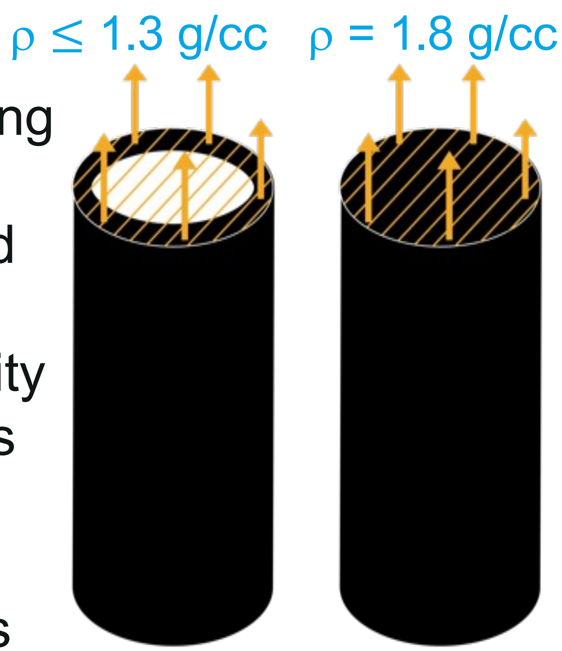
T700 tensile properties CONSERVED

GOAL

Load carrying capacity conserved

Fiber density decreases

Specific properties increase



$\sigma_{hollow} = \sigma_{solid}$

HCF specific tensile properties to equal those of T1100

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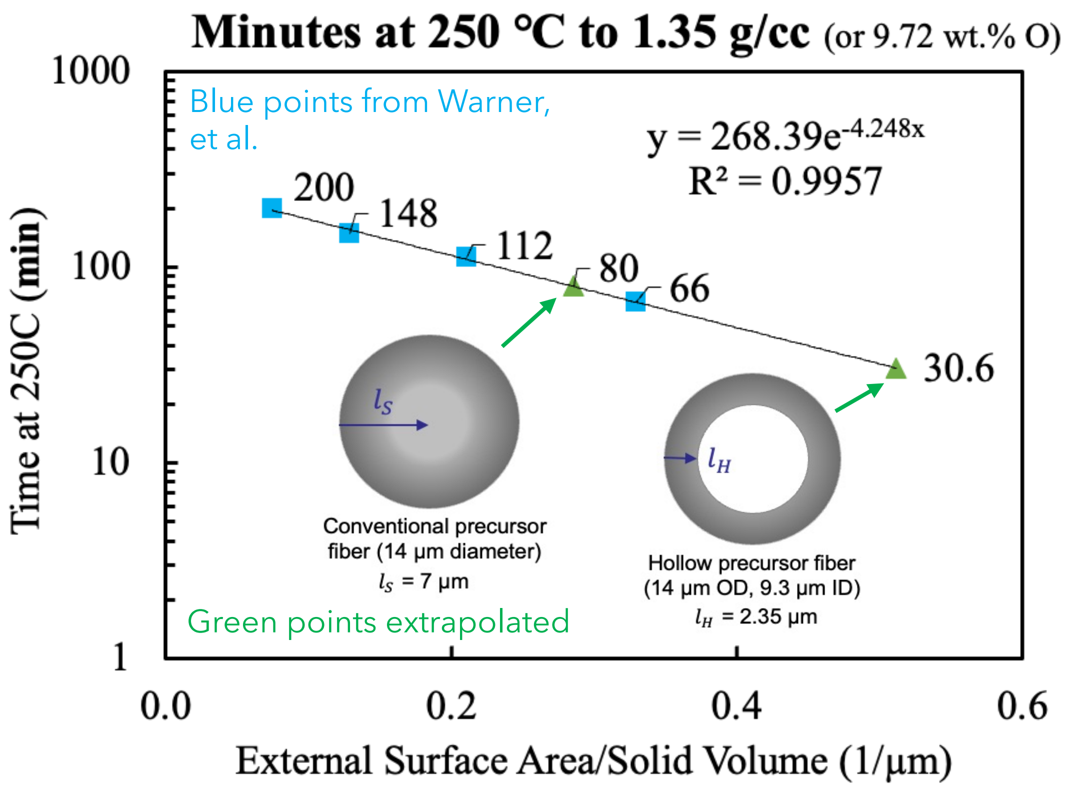
Prospect for Faster Oxidation

Faster oxidation

- Reduced oxygen diffusion distance
- Lower CF processing cost
- Hypothesized to arrive at target ox density in < ½ the time



OVERALL PREDICTED COST AND PERFORMANCE ADVANTAGES

T700 tensile performance
T1100 specific properties

-12% $/kg CF

-29% $/kWh ($H_2$ stored)

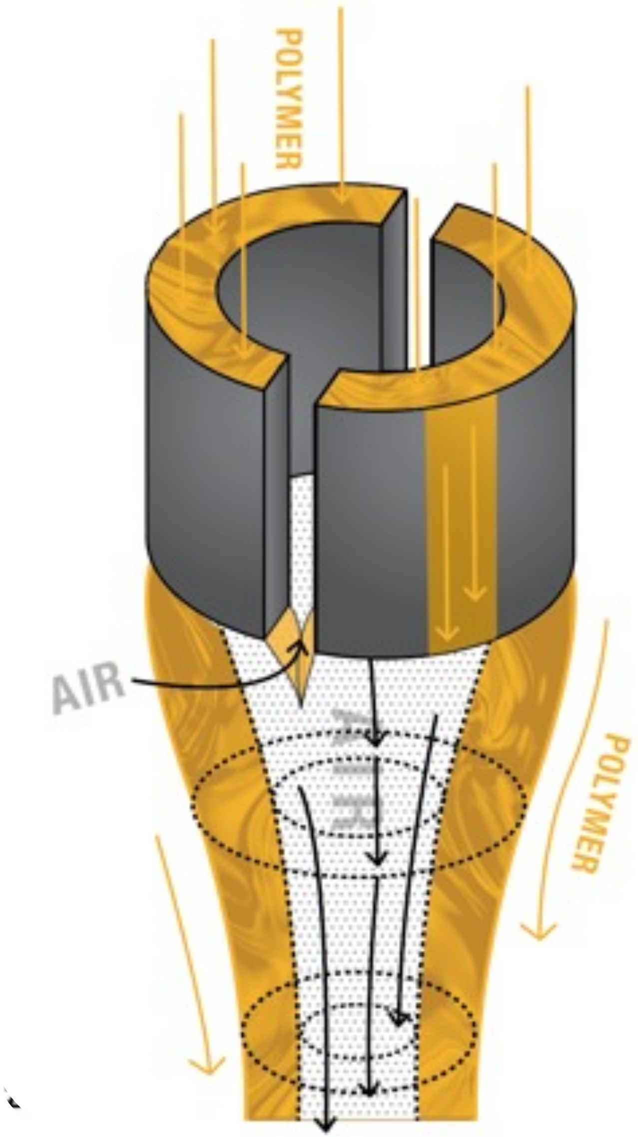
+30% kWh/kg (H_2 stored)

Strategic Analysis, Inc.

Warner, S. B., et al. *J. Mater. Sci.* **1979,** 14, (3), 556-564

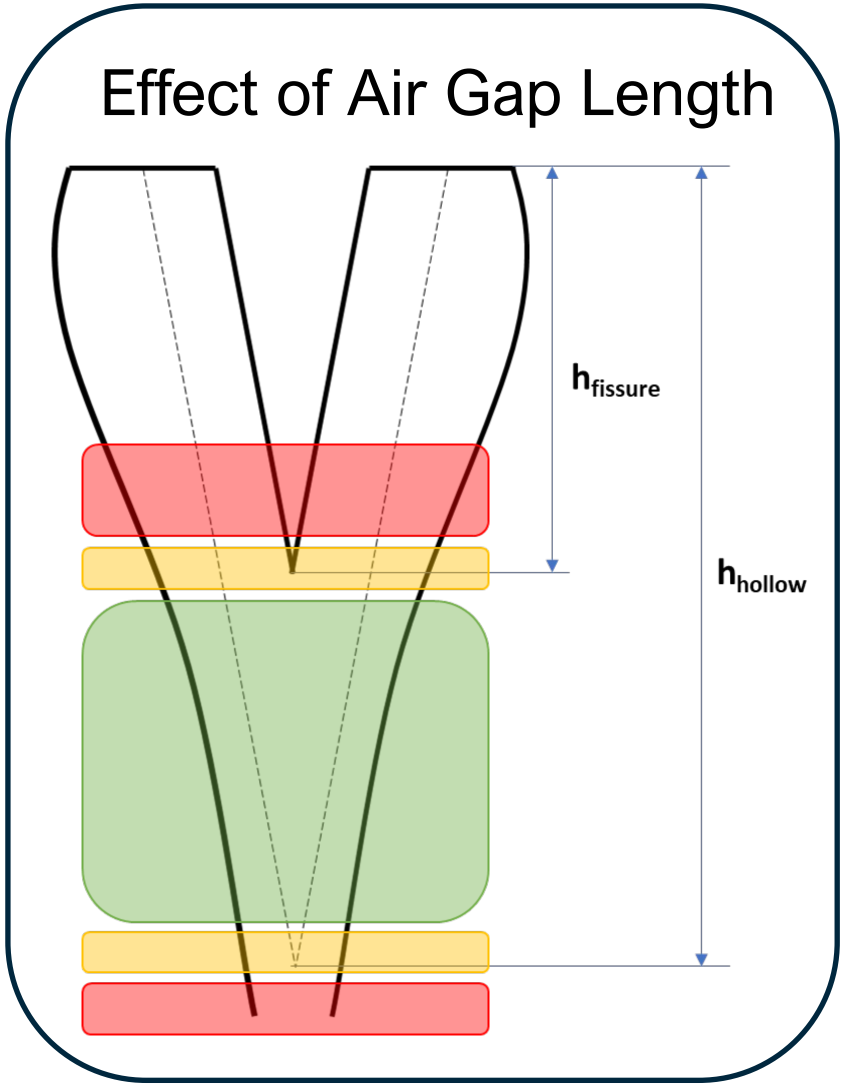
Hollow Precursor Solution Spinning

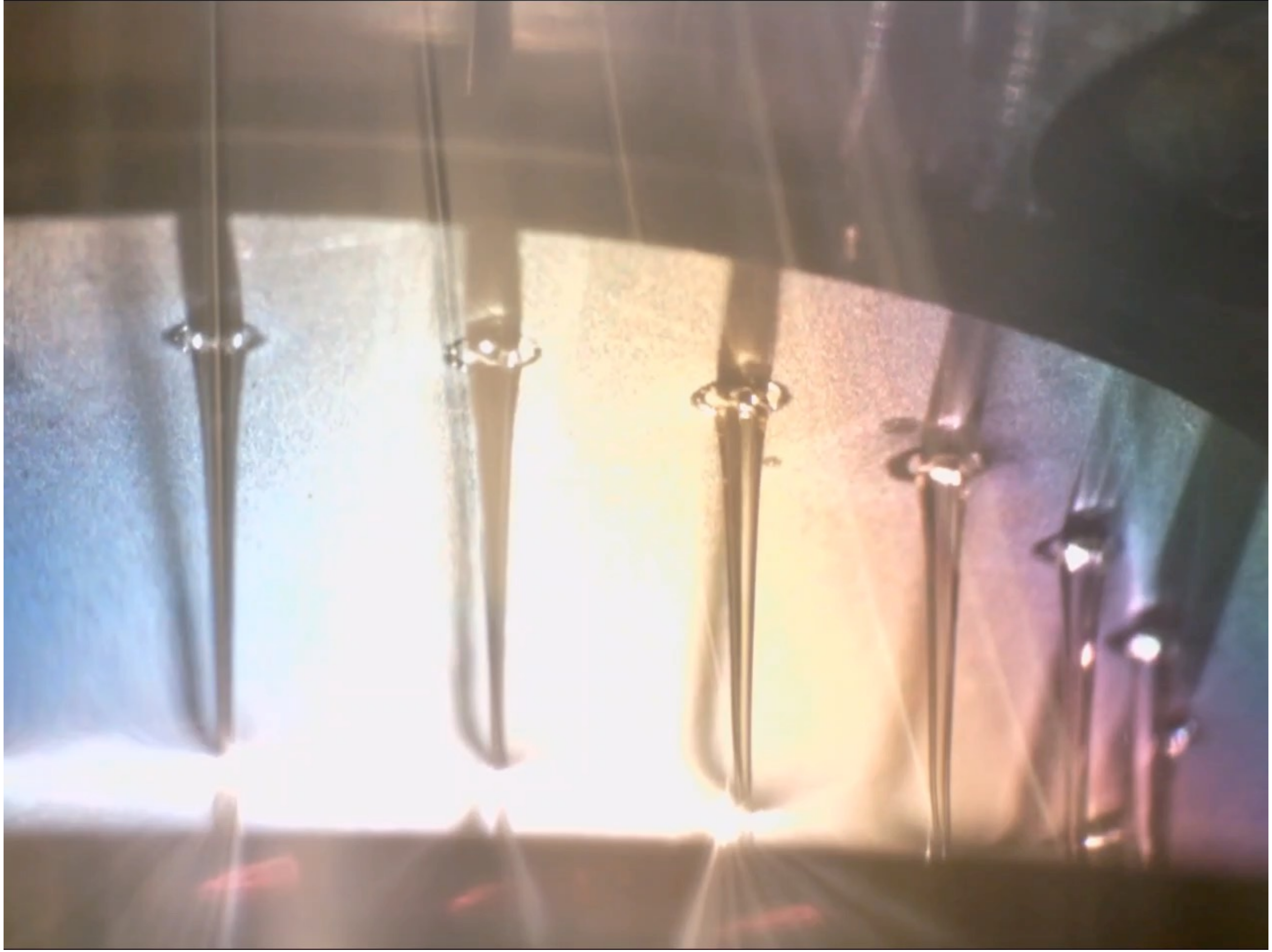
Spinning Multifilament Hollow Fiber



2C spinneret capillary

- Lumen supported by air entering through the heal points between the 2Cs
- 2Cs "heal" in the air gap to form a hollow filament





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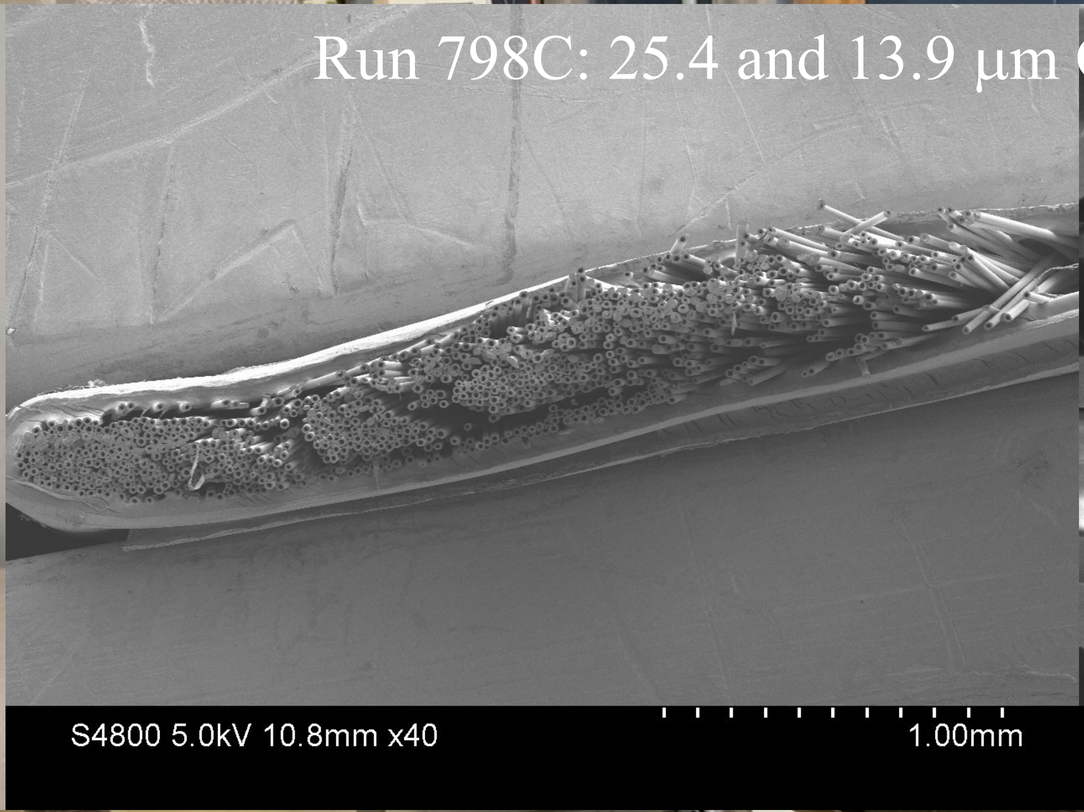
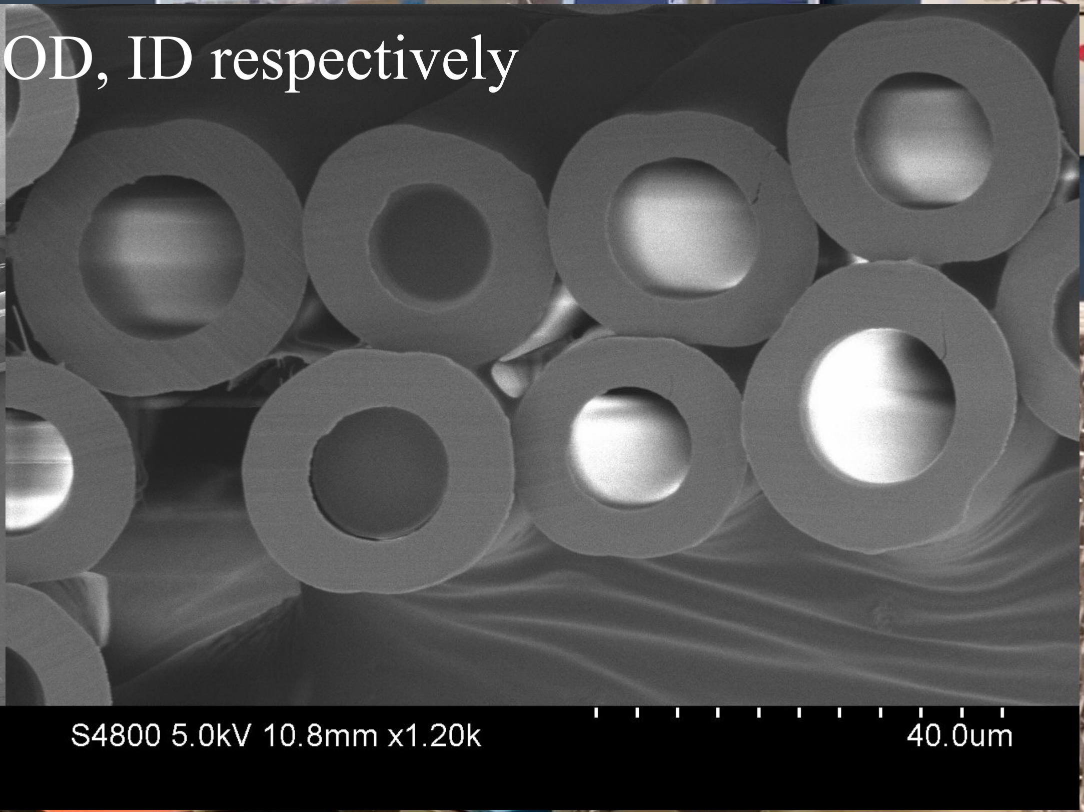
The Effects of Lignin Addition on the Properties of PAN Based Carbon Fiber
Fiber organic electrochemical transistors

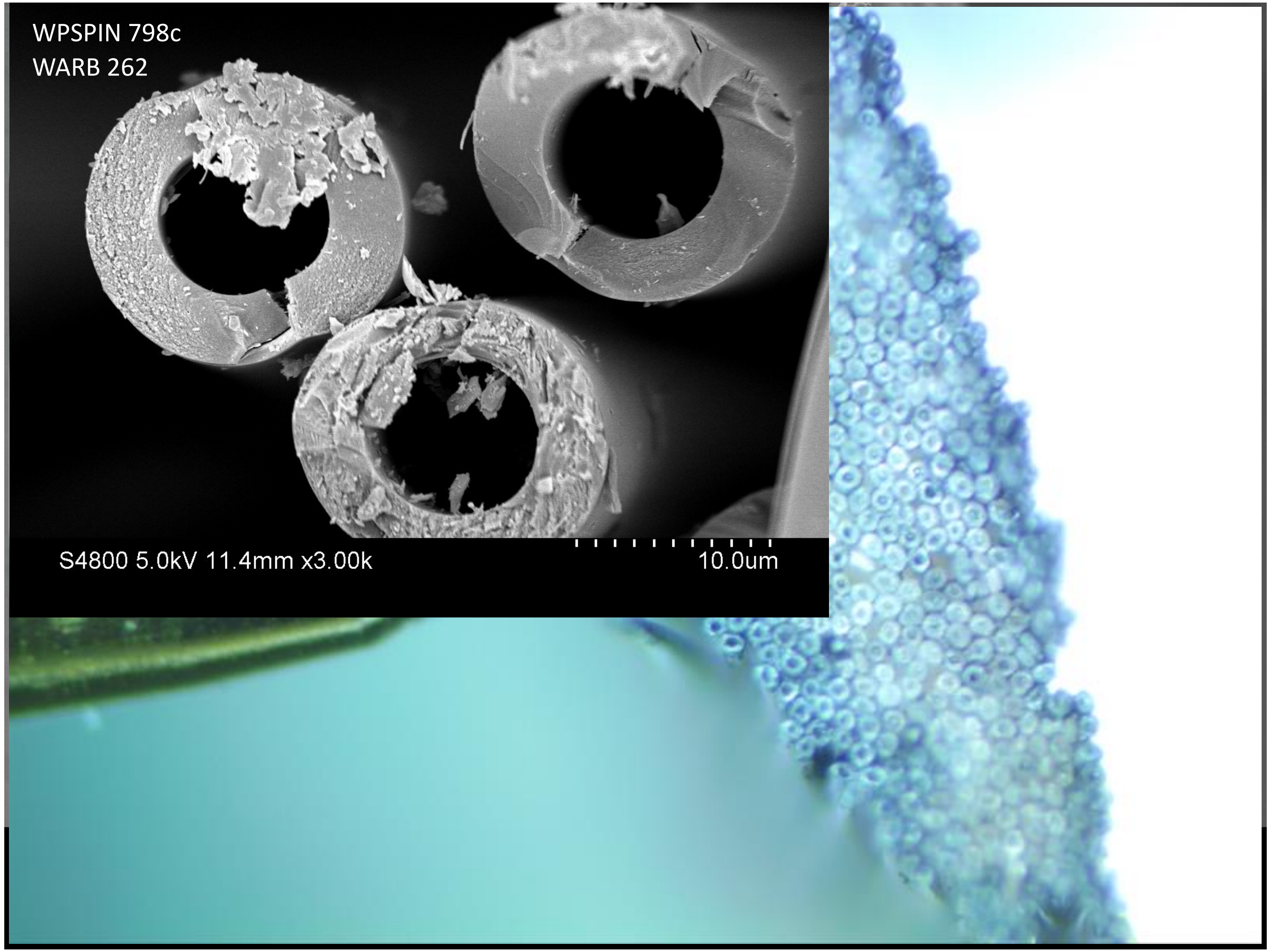
Run 798C: 25.4 and 13.9 µm OD, ID respectively



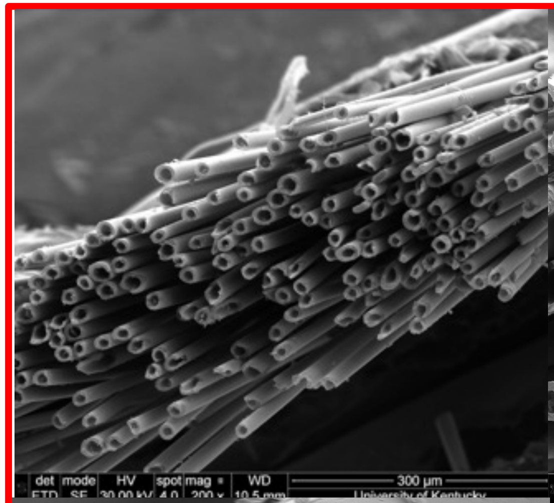


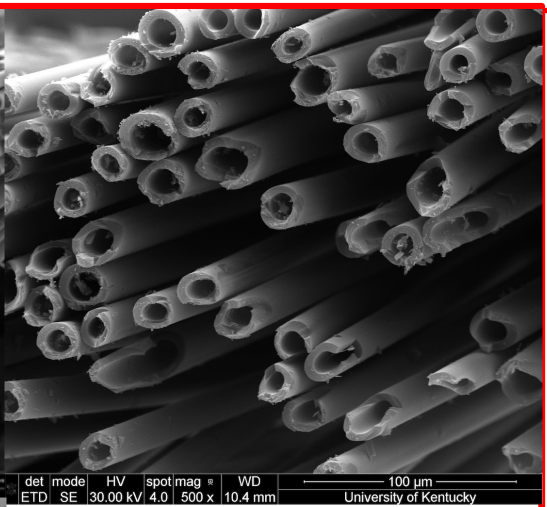
Hollow Fiber Carbonization

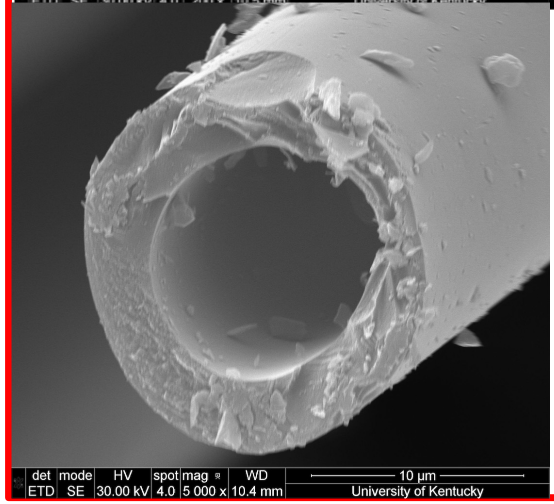
Hollow Carbon Fiber Perspective



Hollow Carbon Fiber Tensile Properties







HCF 290

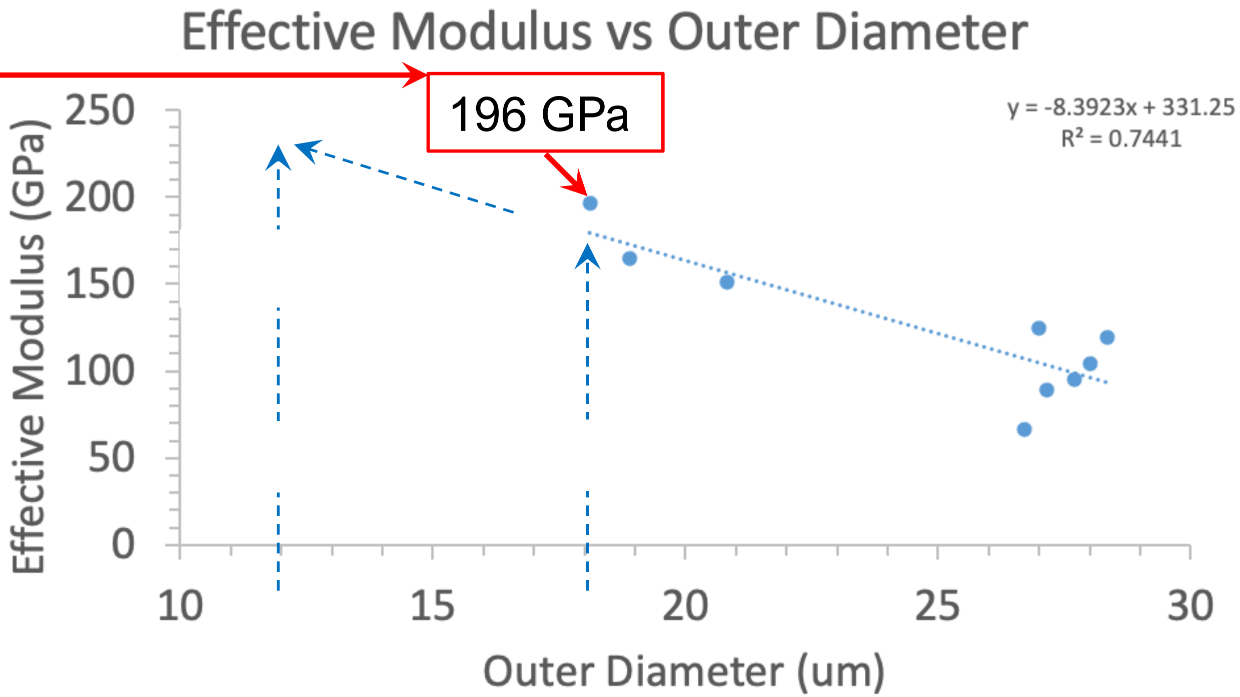
18.1/10.2 µm OD/ID

31% Open Area

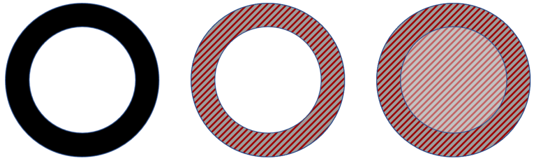
Effective Modulus: 196 GPa (28.4 Msi)

Effective Density: 1.23 g/cc

Effective Strength: 1236 MPa (179 ksi)



- **Current HCF exceeds specific modulus of T700**
- Trend demonstrates effective modulus increases with decreasing OD
- We hypothesize strength will improve with decreasing OD



Hollow Fiber A_{true} $A_{effective}$

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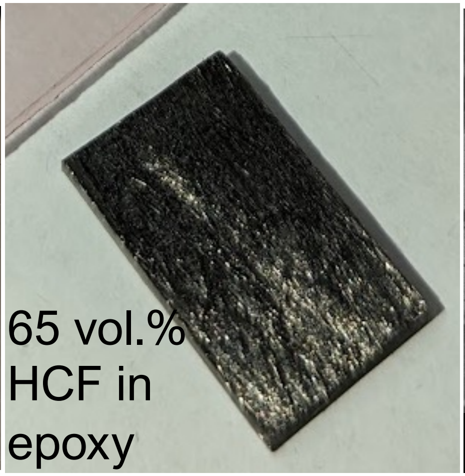
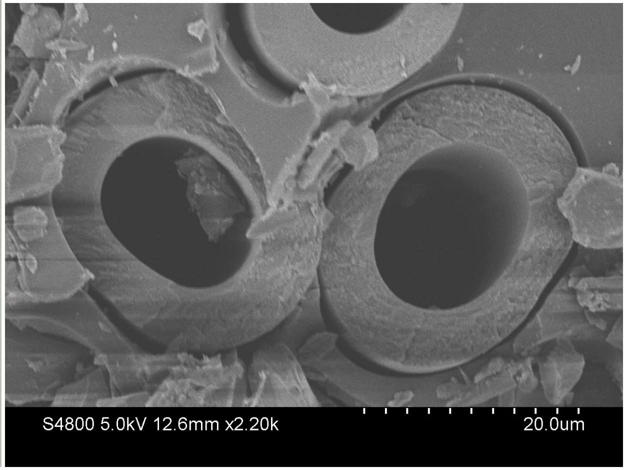
Hollow Carbon Fiber Composite





Composite Specimen '(fiber type)	Vol. fraction fiber (%)	Density (g/cm^3)
T700S - epoxy	64	1.58
HCF – epoxy	65	1.24

~ 22% reduction in composite density

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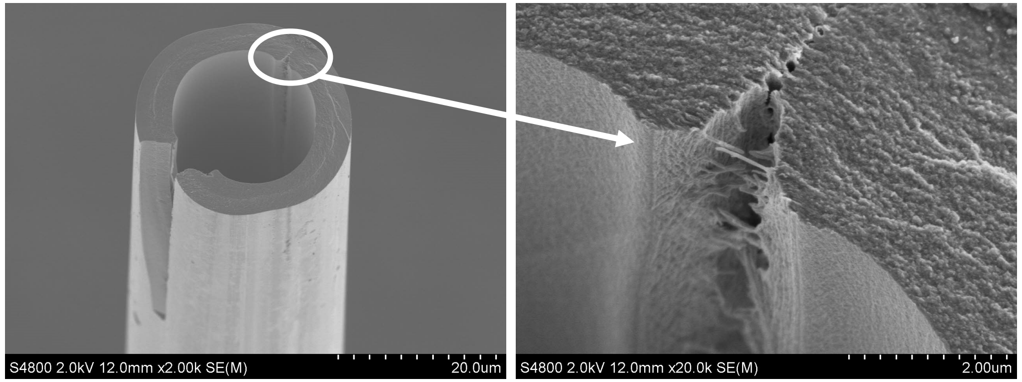
Challenges



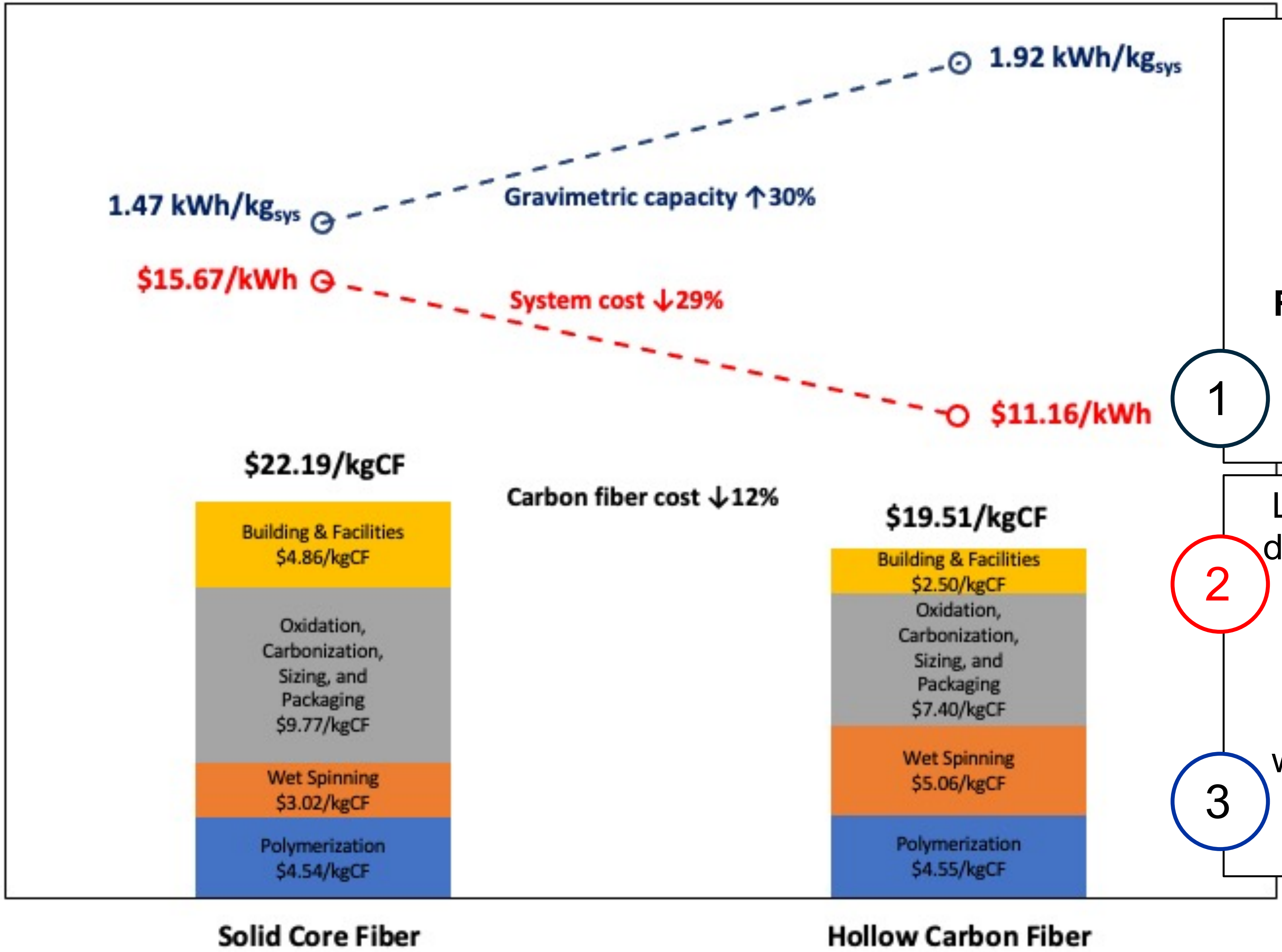
1. **Structural issues exist in the HF as a result of non-fully merged sections during spinning**
    - ➢ Spinneret design and control of spinning parameters is key

2. **The ability to oxidize in 50% of the time for a HF compared to a solid fiber needs to be proven**
    - ➢ To accurately evaluate this, hollow and solid fibers of the same outer diameter, with small ODs (from 20 down to 14 μm), will be spun (a non-trivial task) under similar conditions and then oxidized. Ox fiber densities will be compared.

3. **Improvements in HCF tensile properties needed to achieve T700S properties**
    - ➢ HCF tensile properties will continue to improve with reduced fiber dimensions (less volume in which defects can exist)
    - ➢ Reduce HF precursor diameter through reduced spinneret capillary dimensions, and improvement in fiber drawing methods – all leading to reduced HCF dimensions

Hollow Carbon Fiber Cost Analysis:

Strategic Analysis Inc.



More precursor lines needed to maintain daily mass throughput:
~ 60 % increase in spinning cost

2x faster oxidation line speed & constant web linear density:
Facility output increases almost 2x

1 **NET COST REDUCTION ($/kg CF): ~ 12%**

2 Less HCF needed due to lower linear density but conserved tensile strength
~ 29 % decrease in H_2 storage system cost

3 Low density HCF composite system while maintaining the same stored H_2
~ 30 % increase in gravimetric capacity

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Conclusions

- Hollow PAN precursor fiber spinning established
  - Currently at ~ 25 μm OD and 13.5 μm ID
  - Targeting 14 μm OD and 9.3 μm ID
- Hollow carbon fiber tow processing established
  - Currently at 18.1 μm OD and 10.2 μm ID
  - Effective modulus and of 196 GPa, effective strength of 1.3 GPa
    - Improvement in tensile properties expected at smaller OD fiber
  - Targeting 7 μm OD and 4.6 μm ID
- Cost reductions have been modelled for target HCF

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