VARTM Variability and Substantiation

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The Joint Advanced Materials and Structures Center of Excellence

FAA Sponsored Project Information

- Principal Investigators & Researchers
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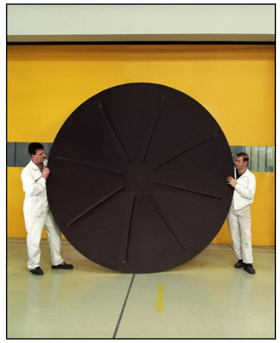
  - John W. Gillespie, Jr. (Co-PI) - "C" Josiah Hughes
  - Pit Schulze
- FAA Technical Monitor
  - Curtis Davies - David Westlund
- Industry Participation
  - Gore (Munich, Germany)
    - Provided membrane materials, access to instrumentation and technical input
  - Donaldson Membranes (Warminster, PA)
    - Provided membrane materials
  - Hexcel (Seguin, Texas)
    - Provided resin and fabric material and technical input
  - Cytec (Anaheim, CA)
    - Provided resin and fabric material and technical input
  - Premium AEROTEC formerly EADS (Augsburg, Germany)
    - Provided technical and financial input
  - Boeing (Philadelphia, PA)
    - Provided technical input

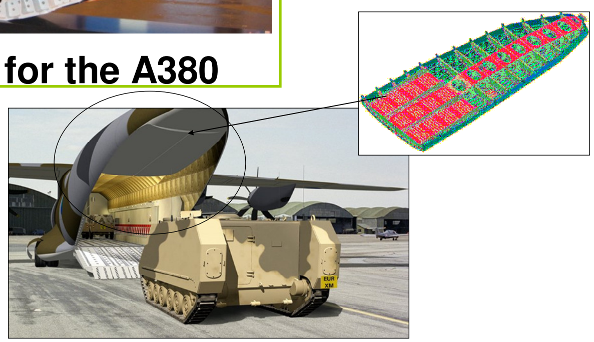
AEROSPACE VARTM'D COMPONENTS

Flap tracks for the A380

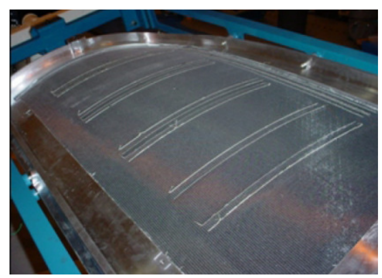


Pressure Dome

CH-47 Chinook Forward Pylon



A400M CFC Cargo Door



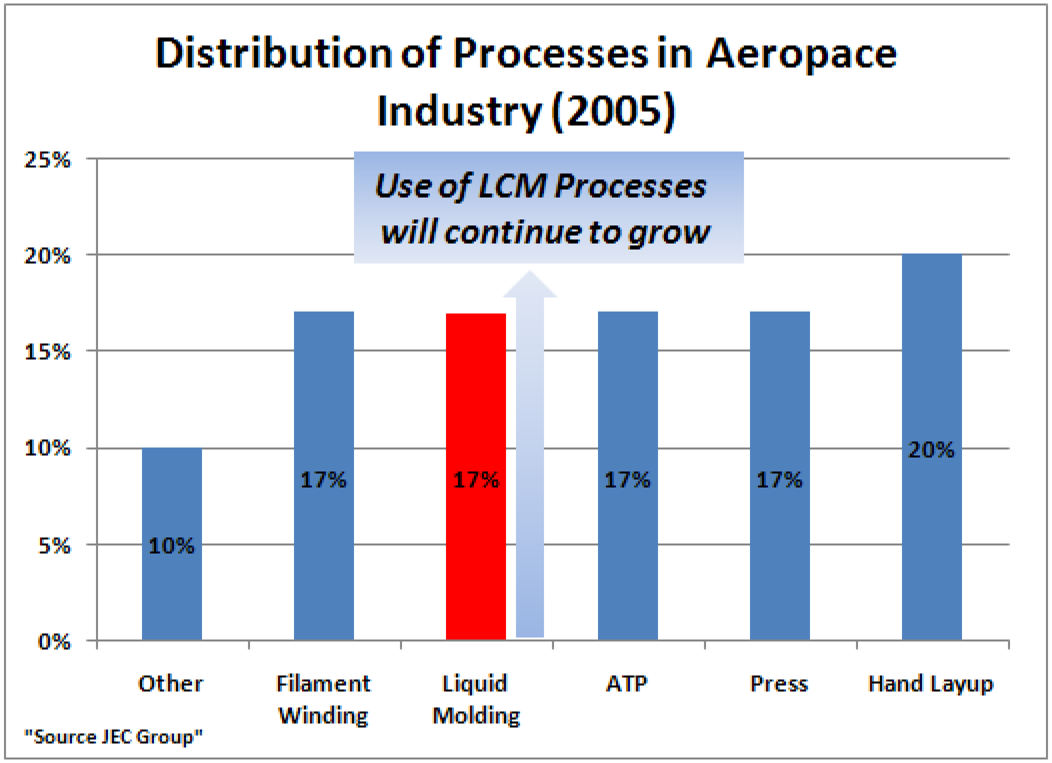
C-17 Main Landing Gear Door

Other BOEING Components

- LAIRCOM panels
- Leading edge 787
- Rear Bulkhead 787

MOTIVATION

- VARTM process:
  - Main advantages: low cost, high fiber volume fraction, large scale parts
  - Still some limitations
    - Limited fundamental understanding of process
    - High variability
      - From part to part
      - In the same part
  - Automation is still limited
  - Certification for new aerospace applications



APPROACH

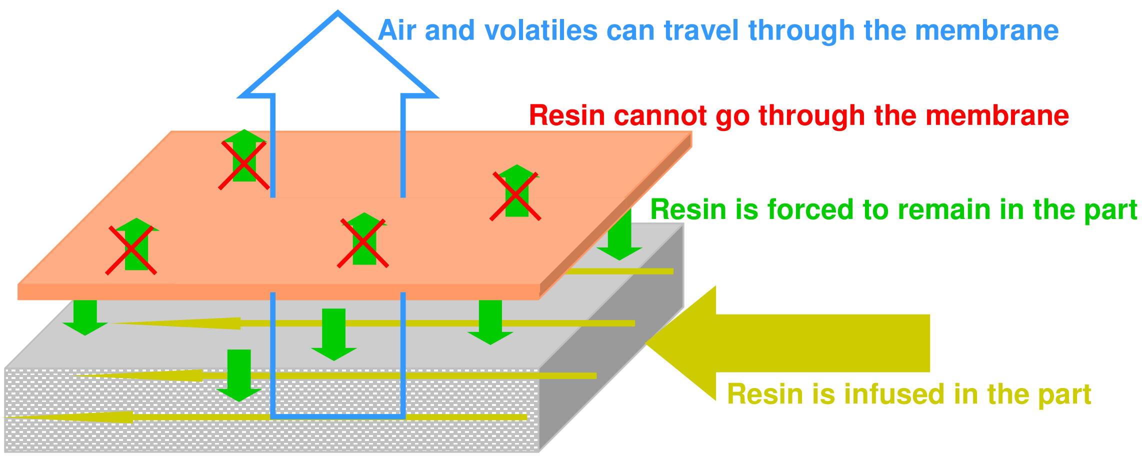
- Reduce variability in VARTM processing to provide viable alternative to prepreg-autoclave-processing
  - Develop VARTM cell with high degree of monitoring and control
  - Establish material/processing/property database
- Provide processing directions for high-quality manufacturing of aviation structures
  - Evaluate leading aerospace VARTM processes
  - Focus on membrane processing
    - Currently certified for 787 and A380 production
- Evaluate benefits and short-comings of VARTM variations

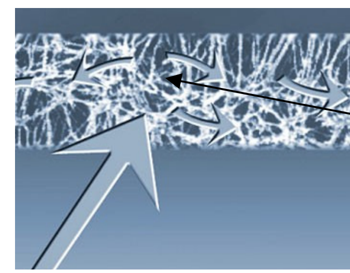
VARTM Process Variations

1. Seemans Resin Infusion Molding Process (SCRIMP)
   - Use of Distribution Media
   - Patent held by TPI Inc.
2. Vacuum-Assisted Processing (VAP)
   - Use of an additional membrane
   - Patents held by EADS
   - Reduces Void Content, Improves Process robustness
3. Controlled Atmospheric Resin Infusion Process (CAPRI)
   - Reduced pressure differential
   - Patent held by the Boeing Co.
   - Reduces thickness gradient, improves fiber volume fraction variation

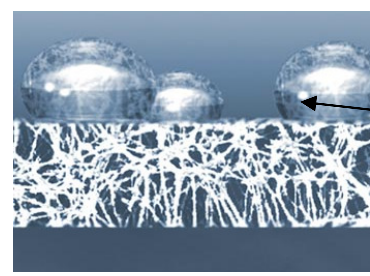
Improve Understanding of Membrane Behavior

- Desirable Characteristics for a membrane used in VARTM:
  - Gas permeable material
    - OR High air permeability through the thickness
  - Resin-proof material
    - OR Low liquid/resin permeability through the thickness
- Compatibility with resin
  - Compatible: The resin does not go through the membrane and is forced into the part
  - Incompatible: The resin penetrates the membrane



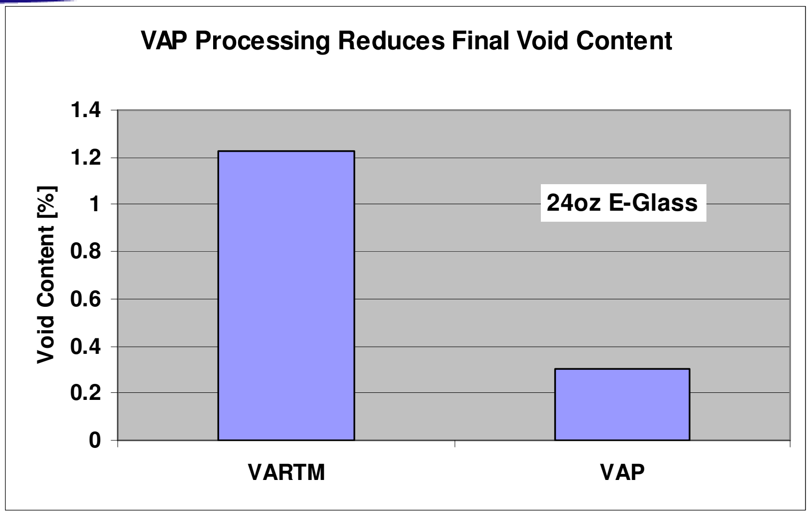


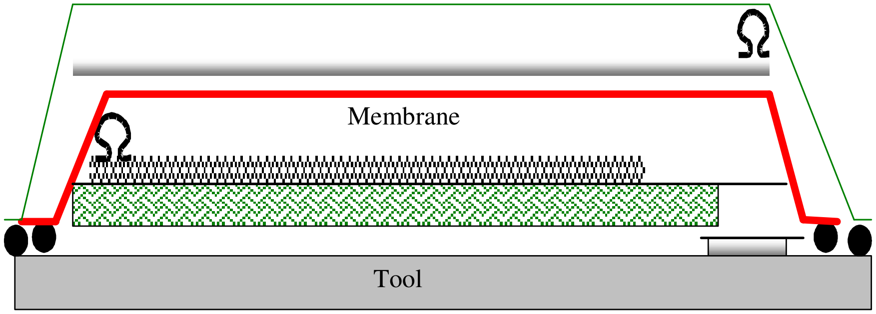
www.gore-tex.co.uk

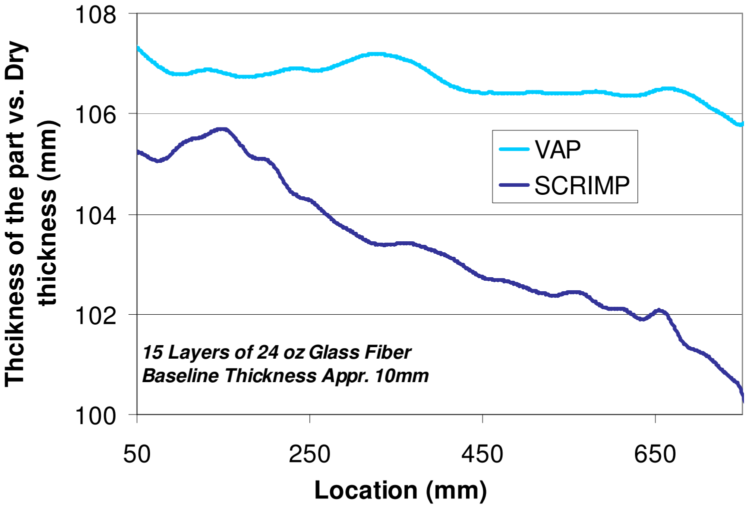


MEMBRANE-BASED VARTM PROCESSING (VAP)

- Utilize membrane cover to allow continues degassing and uniform vacuum pressure during VARTM processing
  - Reduces void content
  - Improves uniformity (fiber volume fraction, thickness)
  - Eliminates dry-spots

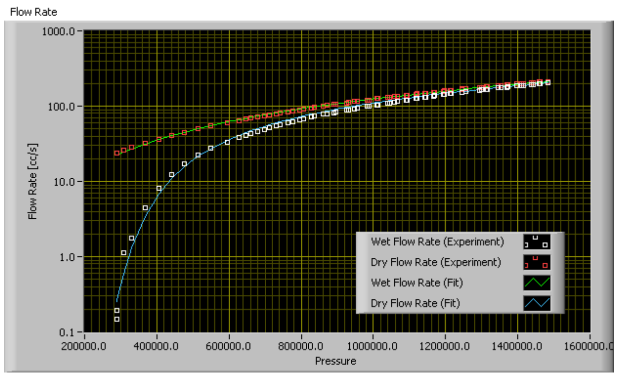




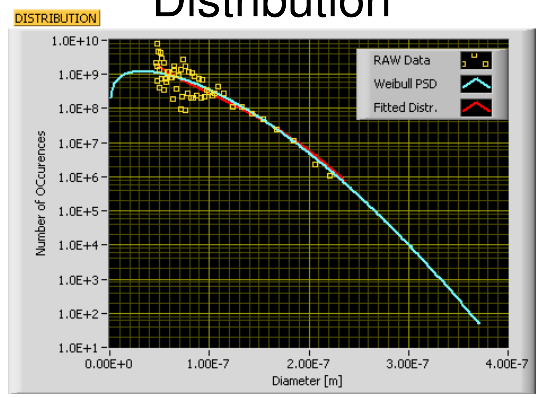


Statistical Analysis of Membrane

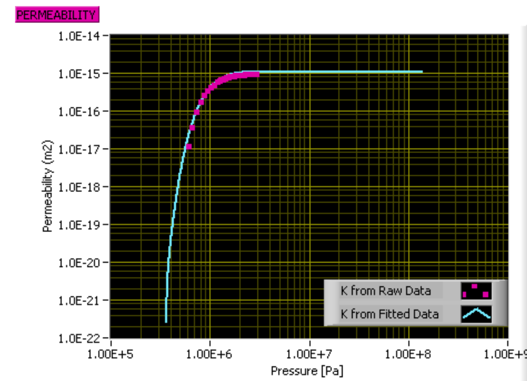
Fitted Porometer Data



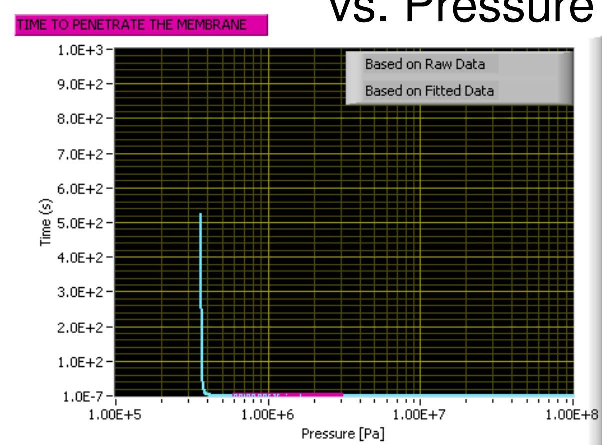
Improved Pore Size Distribution



Permeability vs Pressure



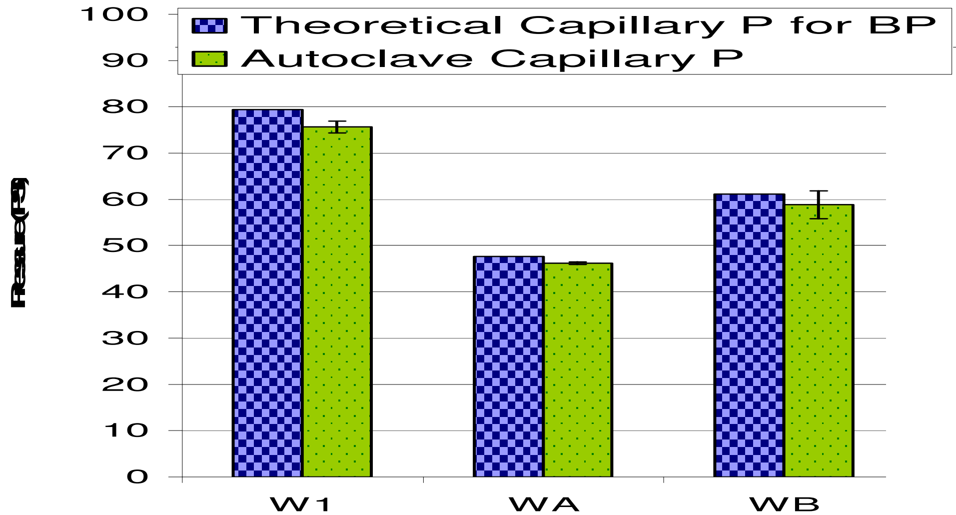
Penetration Time vs. Pressure

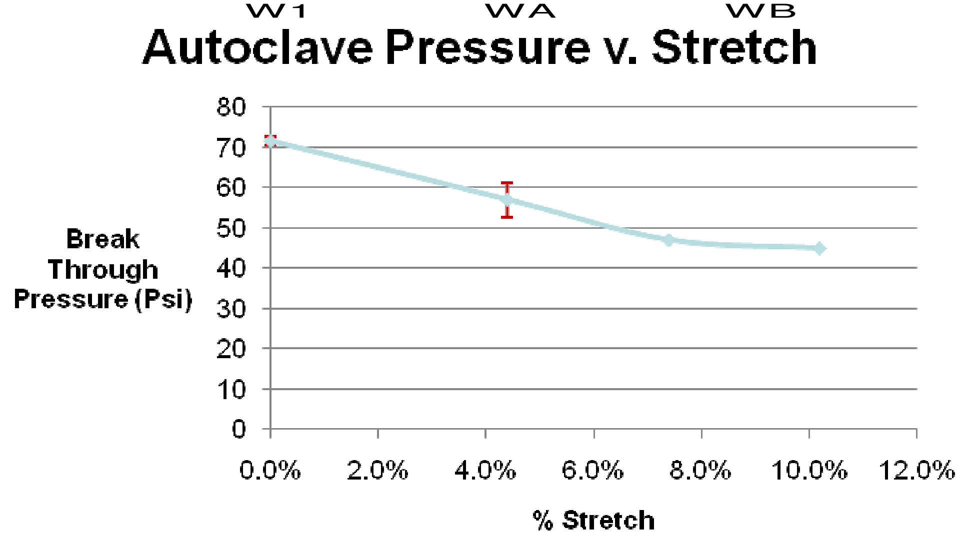


- Analysis and model implementation can be used to predict membrane performance for a wide variety of resin choices and process approaches (includes higher pressure application such as autoclave)
- Can be used to optimize membrane behavior
  - Increase contact angle, surface tension
  - Decrease "tail" of pore size distribution
- Effect of stretching can be incorporated in model (TBD)

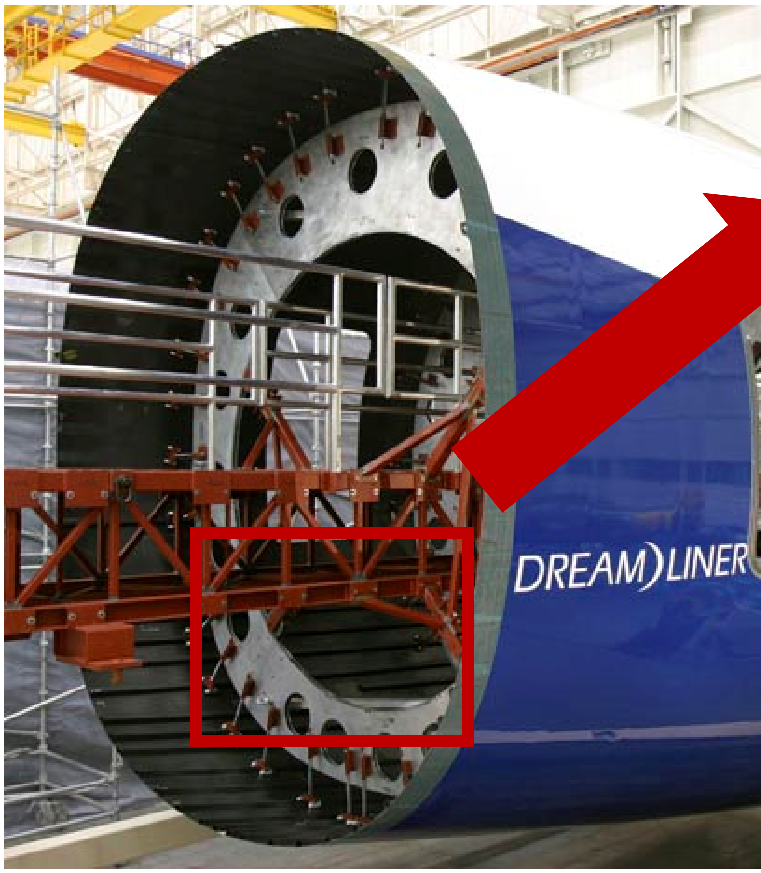
Autoclave Validation

- Some autoclave experiments have been performed to validate the capillary pressure at various % Strain values.
  - The stretched membranes were characterized using the porometer and contact angle experiments. The values generated from these experiments compared to the experimental capillary pressure determined from the autoclave.





Membrane Limitations



- Draping Limitations continue to be one of the major problems of the membrane
- Localized Stretching causes the membrane to tear and the resin travels through the membrane negating the advantages.

Membrane Stretching Evaluation

Industry experienced membrane failure for parts with complex draping requirements. To address this issue, basic characterization and a study of biaxial stretching of the membrane are performed.

Basic characterization of the membrane was conducted to obtain its Young's modulus, strain at break…

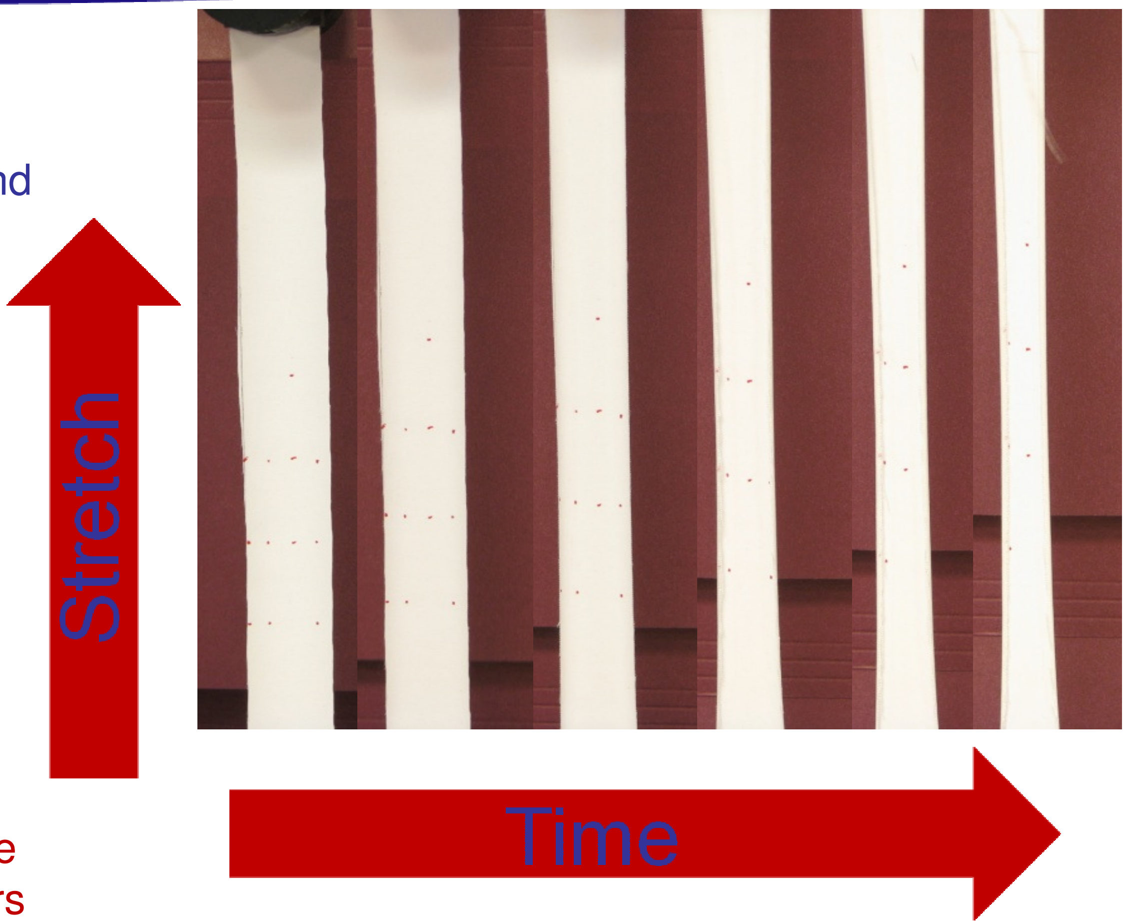
Because the membrane is made of PTFE, we suspected that its mechanical behavior was strain rate dependent, which was confirmed. Therefore, it appeared crucial to choose the right strain rate to conduct our study.

In order to address the behavior of the membrane and determine whether the membrane deforms mainly elastically or plastically, cycling was performed on the material.

Finally, to simulate more closely the deformation that the membrane can encounter while being used in VARTM, a biaxial stretching setup was created.

Stretch Behavior

- ♦The hybrid construction of the Composite Manufacturing Membrane (ePTFE Membrane and Fabric Support) has long been believed to be the cause of premature tearing of the ePTFE membrane.
  - ✧The ePTFE Membrane is transversely isotropic while the support is orthotropic (a plain weave fabric).
  - ✧A study of the Poisson Ratio of the Membrane and the support was undertook to analyze if the strain differences between the support and the membrane were sufficient to cause localized tears in the membrane and thus leaks.

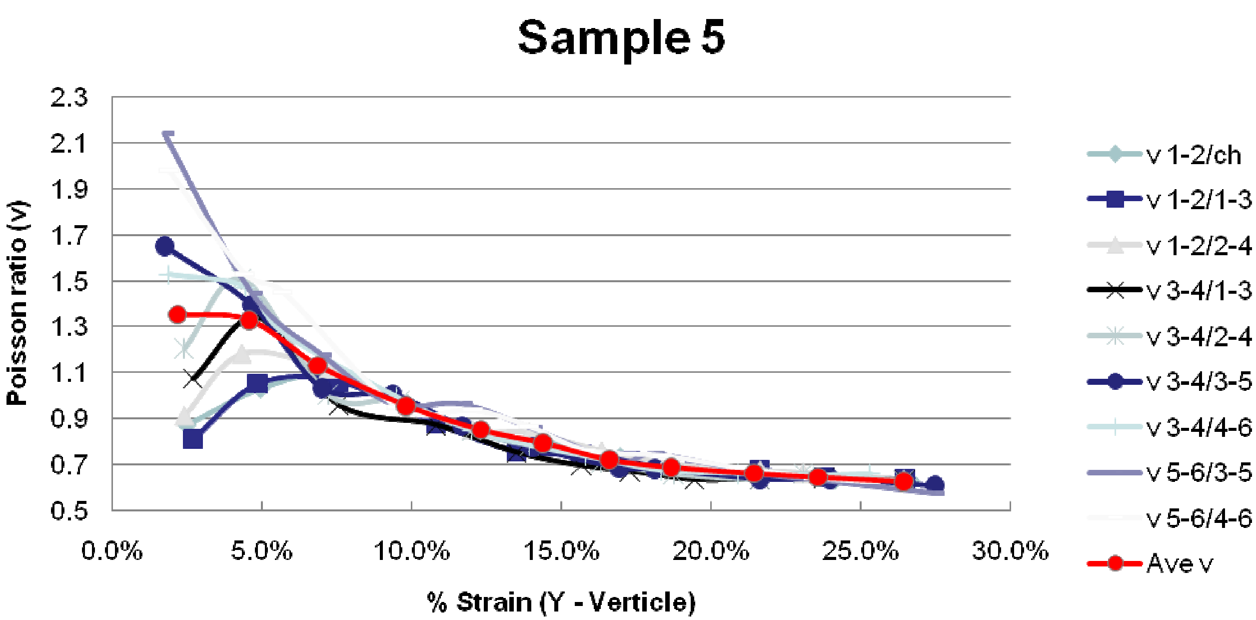


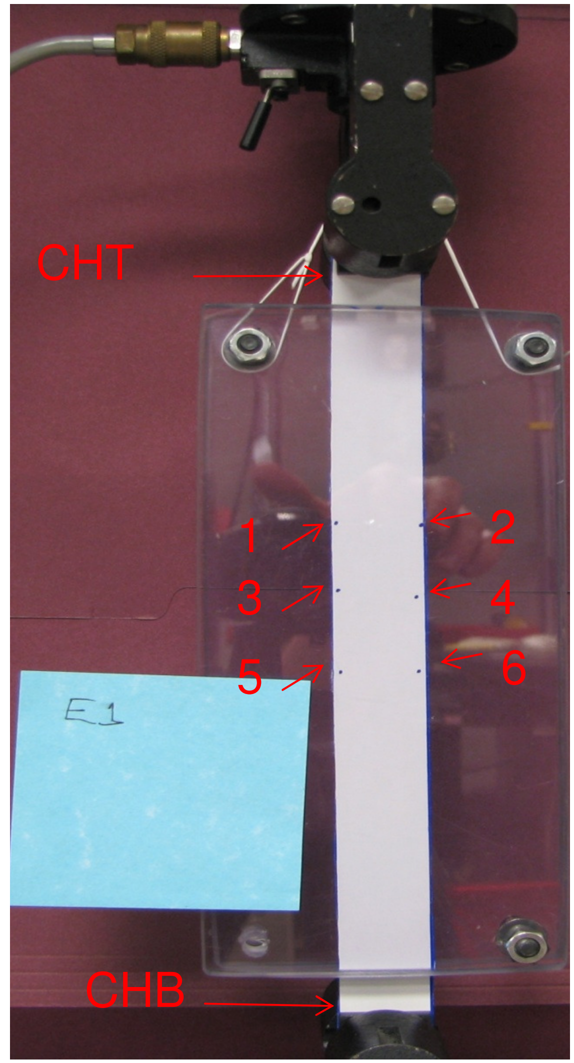
Poisson Ratio Mismatch

♦The membrane is far more elastic than the support. After comparing strains imposed on the membrane by the support, it was concluded that Poisson Ratio Mismatch is not responsible for tearing the membrane.

♦Localized strains between specific points and different locations across the gage length were used for redundant calculations.

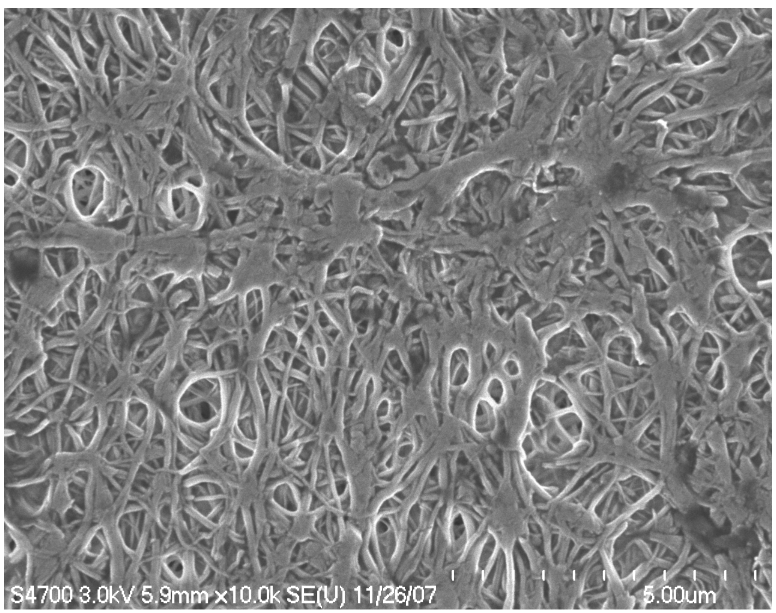
✧No significant deviations from the average were found.

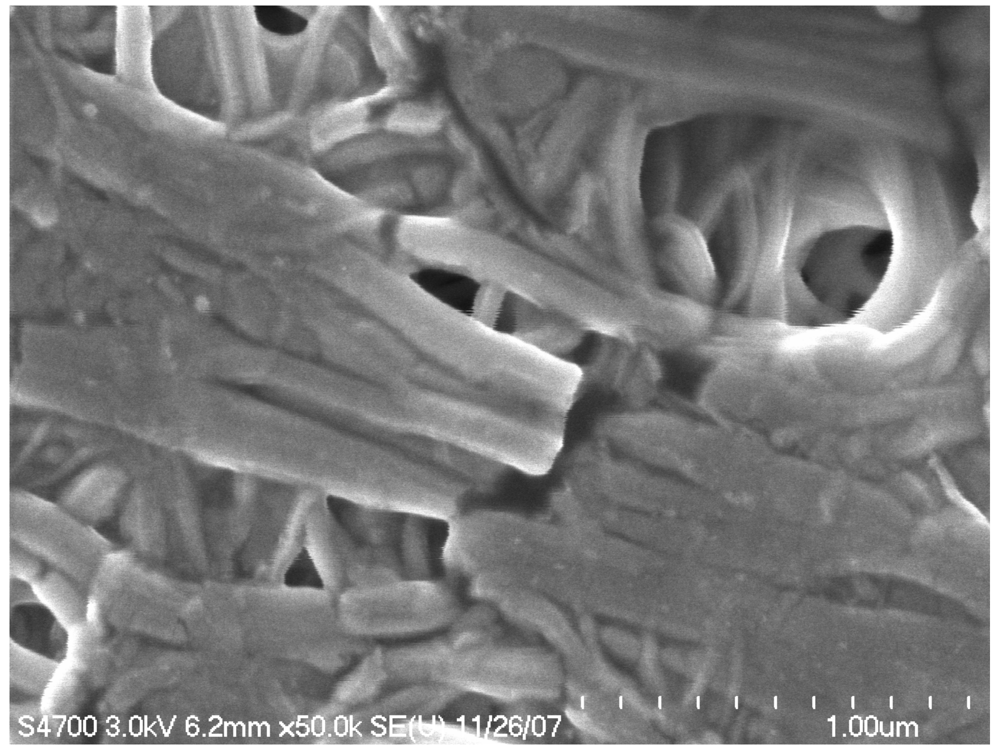




SEM Images
Stretch Damage

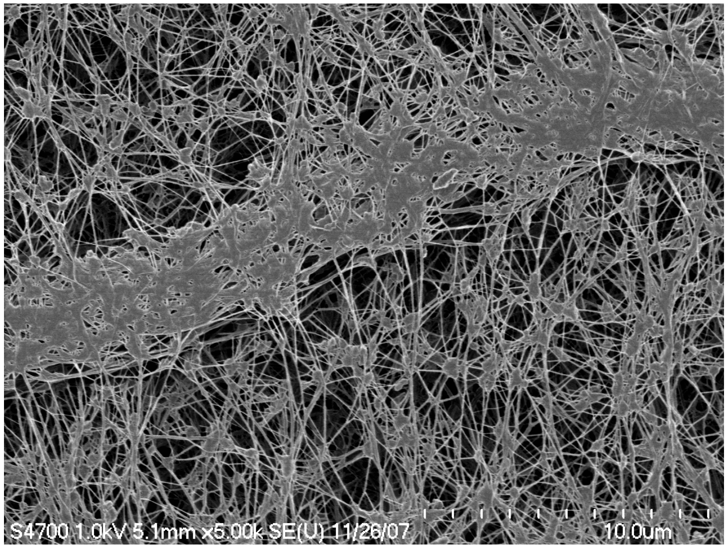
- SEM Images of stretched samples show visible affects of fibril tearing and
  - At 23% Unidirectional Strain, fibrils were dislocated from nodes and visible cracks and damager were present.
  - The membrane alone does not exhibit this behavior, so there must be some support limitations causing the damage.

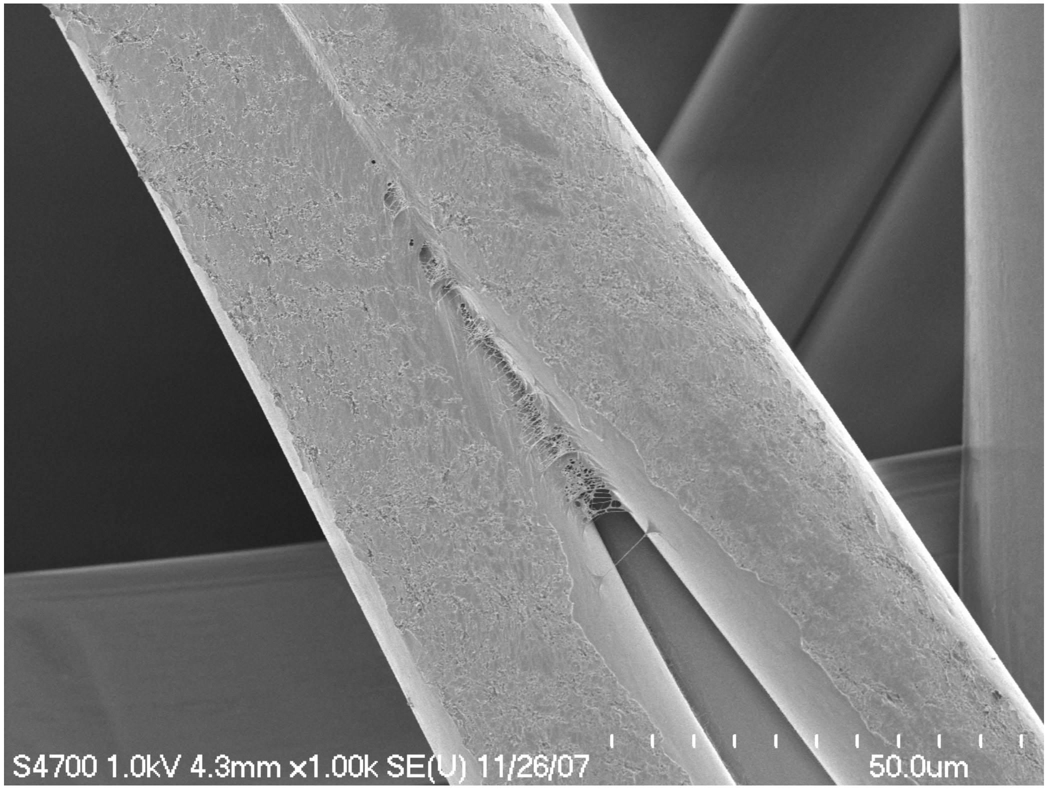




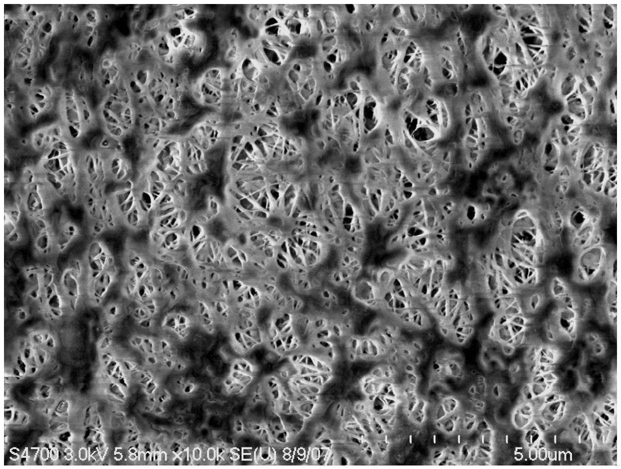
SEM
Adhesive Artifacts

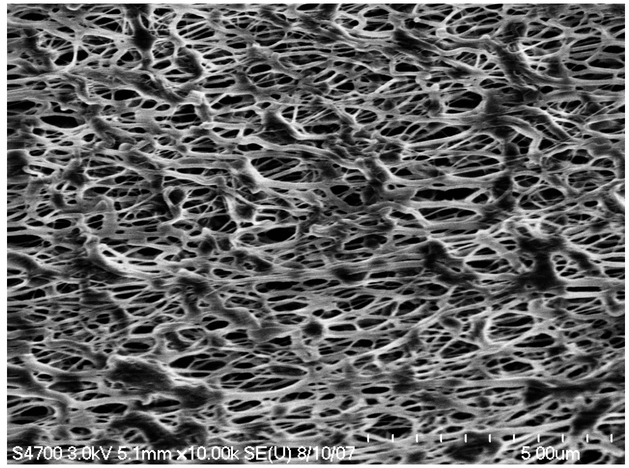
- SEM Images of stretched samples show adhesive residue on the support of the materials.
  - Residues of adhesive can be seen on the support structure of the membrane. These adhesive layers could be causing local strain concentrations and should be further researched as a potential failure mode.

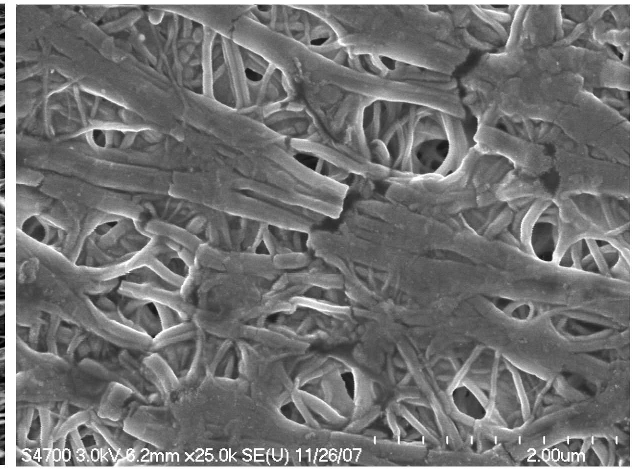




SEM INSIGHTS







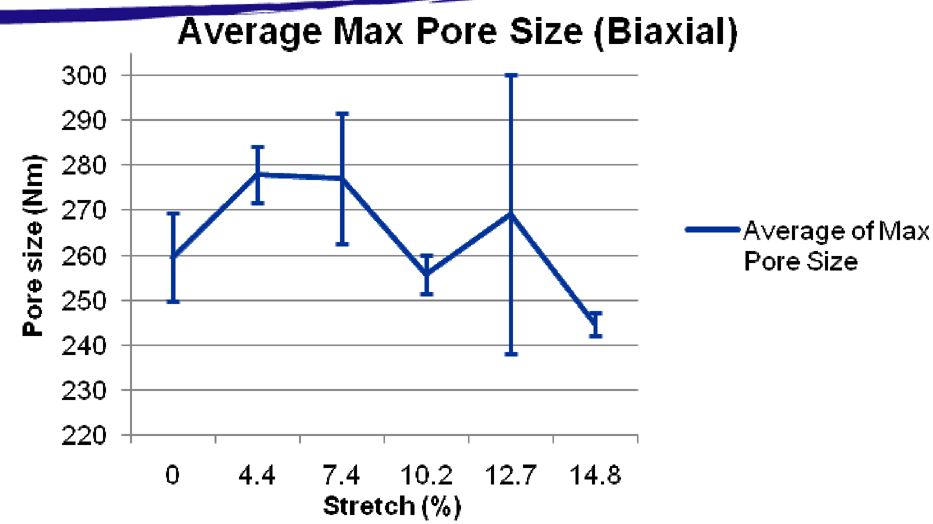
- SEM Images taken at measured strains show a change in the porosity and nanostructure. They do not show how they are changing.
- Many unique feature changes are observed as nodes turn into fibrils and fibrils elongate and rotate to change the shape of the pores.
  - The porometry data can be correlated to the measured geometry from the SEM images. The porometer gives values for a cylindrical pore; the membrane does not have cylindrical pores, analysis of the relationship of the porometer data to the SEM images could grant tremendous insight into the permeability of the stretched membranes.

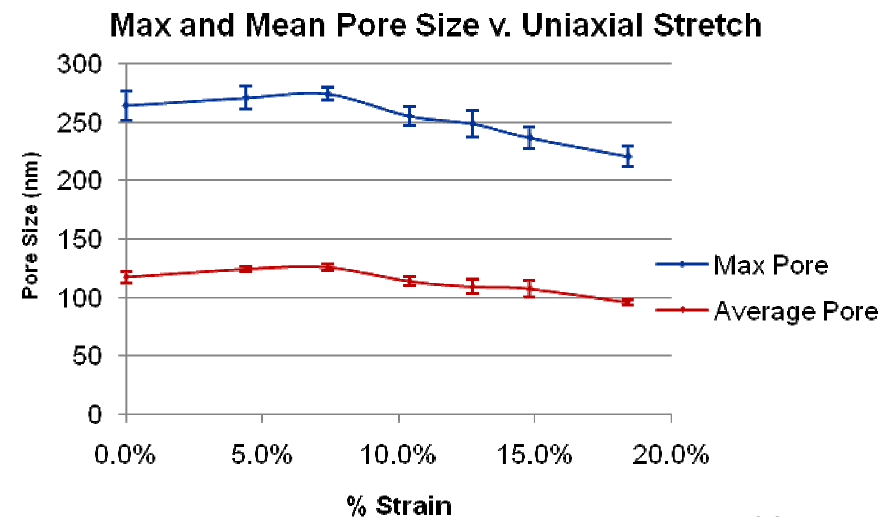
Membrane Analysis

- Membrane analysis has been limited to flat, unstretched samples.
- The Capillary Flow Porometer manufactured by Porous Materials, Inc. is excellent at providing the break through pressure, max pore size, mean pore size, and a general pore size distribution.
- The PMI Porometer is not capable of handling tools to test samples in a stretched state.

PMI Porometer v. Strain

- Membrane samples have been strained and then tested in the Porometer, but elastic recovery and variation in strain have created dubious results.
- A method to test the membrane in the stretched state is necessary.





Test Method

F 316 – 03

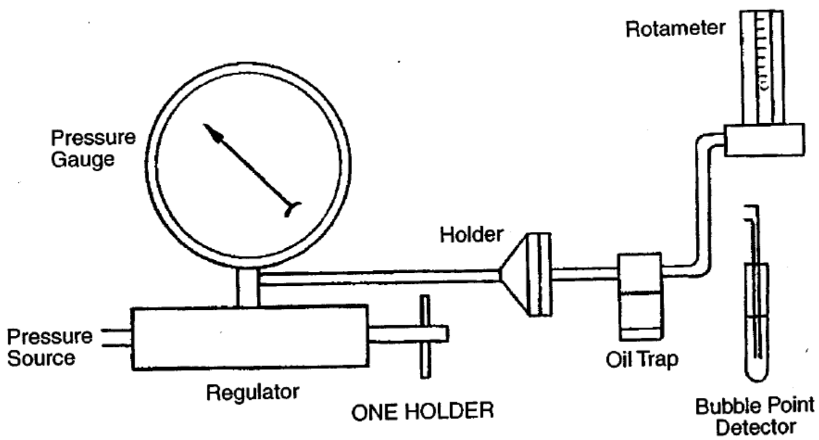


FIG. 6 Setup for One Holder

F 316 – 03

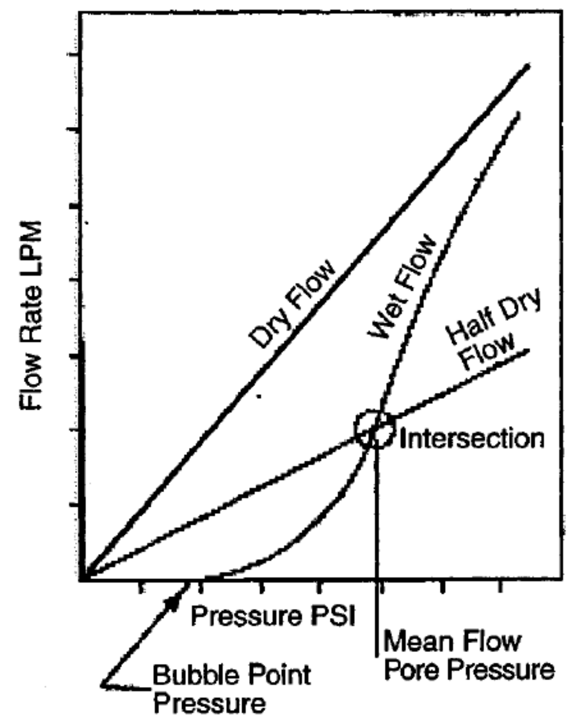
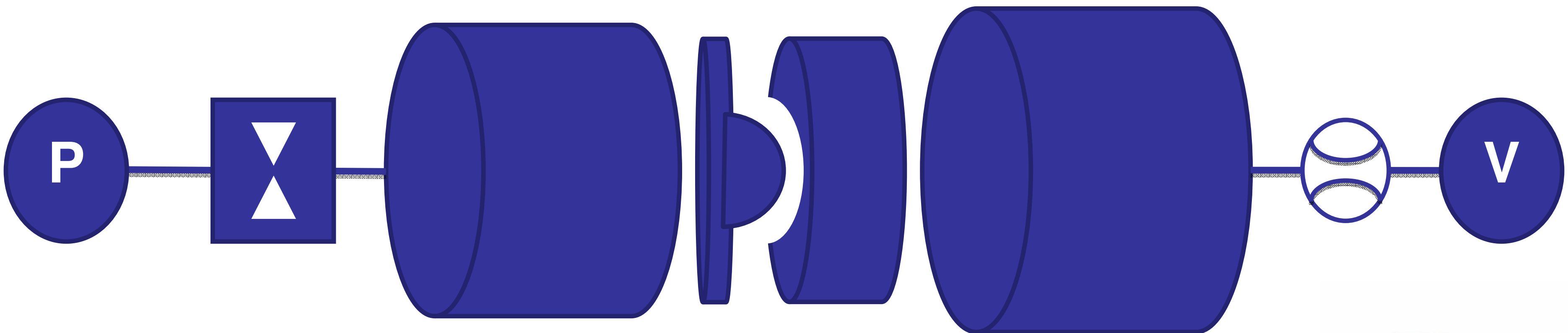
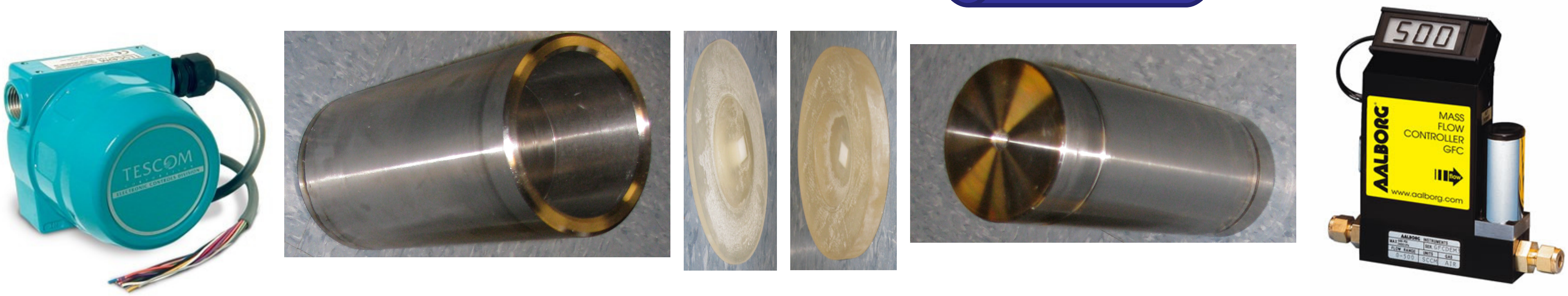


FIG. 8 Example of Mean Flow Pore Determination

- ASTM F 316-03 Standard Test Methods for Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Test

Test Fixture

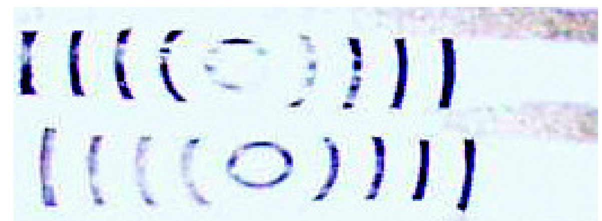




Piston and Cylinder : Plates for Stretching : Measure the input Pressure

Monitor the output flow : Calculate change in bubble point as a function of strain

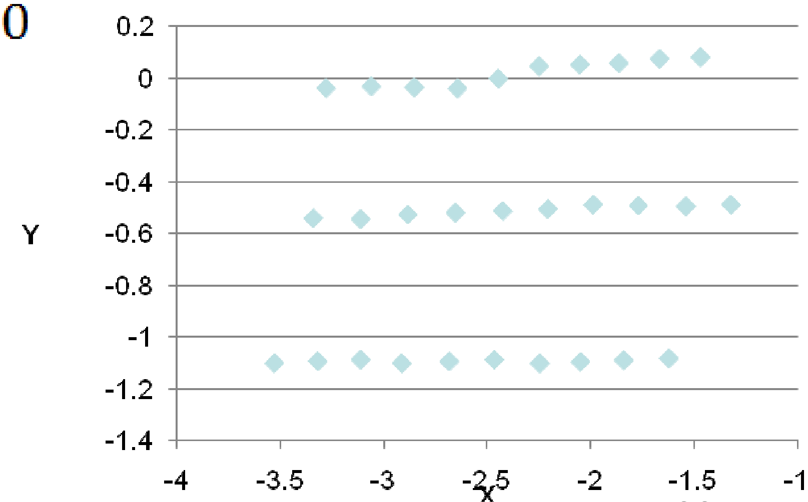
Validating Strain of Plates



- Membrane was stamped, stretched, relaxed, and measured to determine the homogeneity of stretch using the plates
- 3 Replicates were done in the 0° and 45° membrane
- The most interesting observation was the elastic recovery showed values between 8-10% compared to .2%

$$\%\ elastic\ recovery = \frac{l_{stretched} - l_{final}}{l_{stretched}}\ x\ 100$$

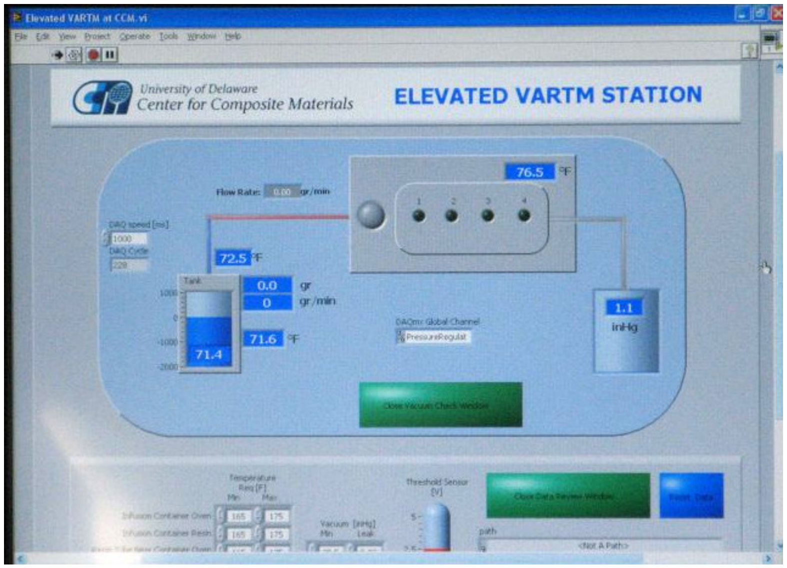
	Unstretched	Stretched 0°	Stretched 45°
Average	0.199796	0.210061	0.211584
Stdev	0.007134	0.011244	0.014005
Co Var	3.6%	5.4%	6.6%
% Strain		5.1%	5.6%



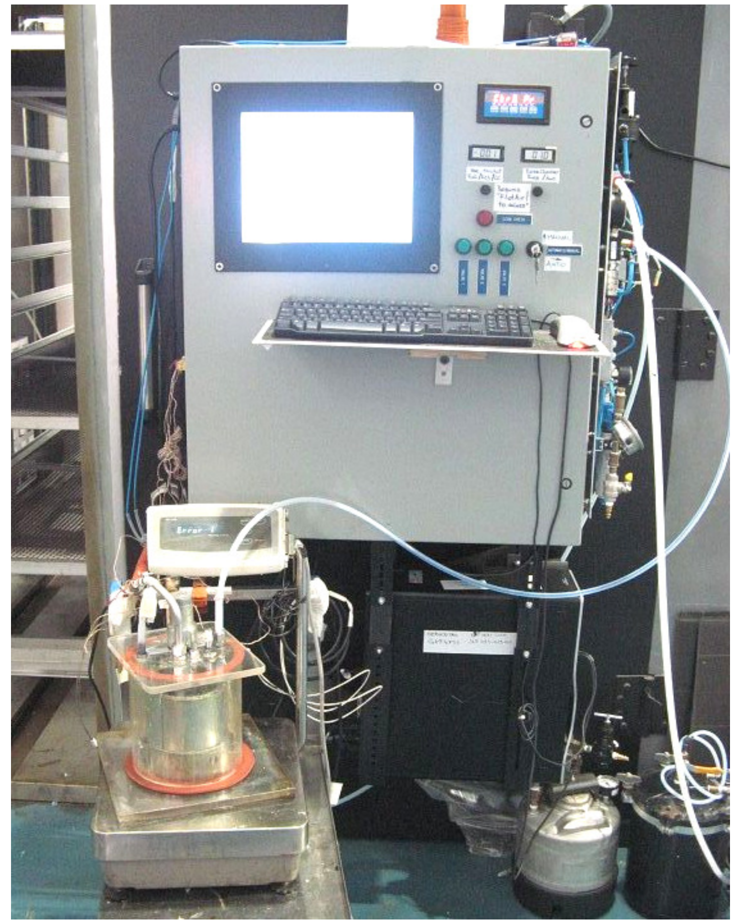
Expected Conclusions

- Better understanding of pore size distribution for stretched membrane
  - Provides real-world estimates of pressure capabilities
- Validation tool for real resin system replacing time-consuming autoclave experiments
- Validation tool for new membranes

Automated ET-VARTM Cell at UD-CCM

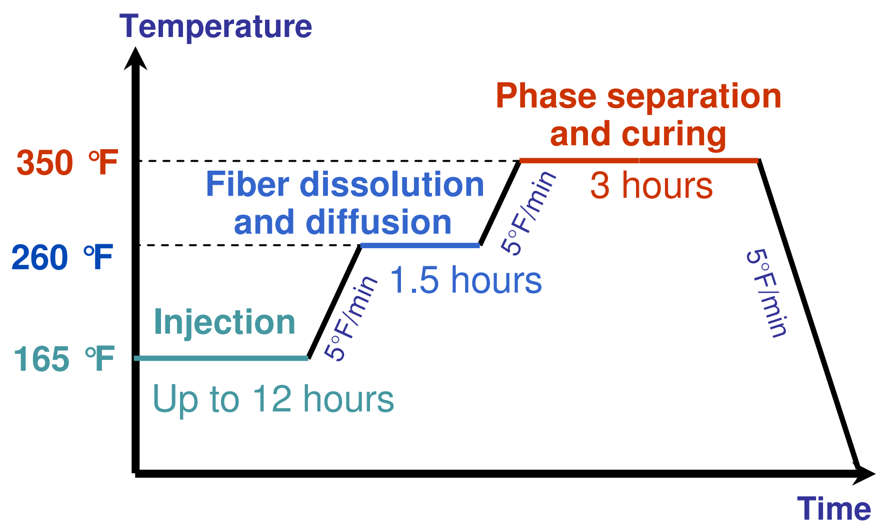


- **Control:**
  - **Pressure and Temperature**
  - **De-bulking, Degassing**
  - **Inlet Valve Opening**
- **Monitoring:**
  - **Infused Resin Weight**
  - **Flow Position**

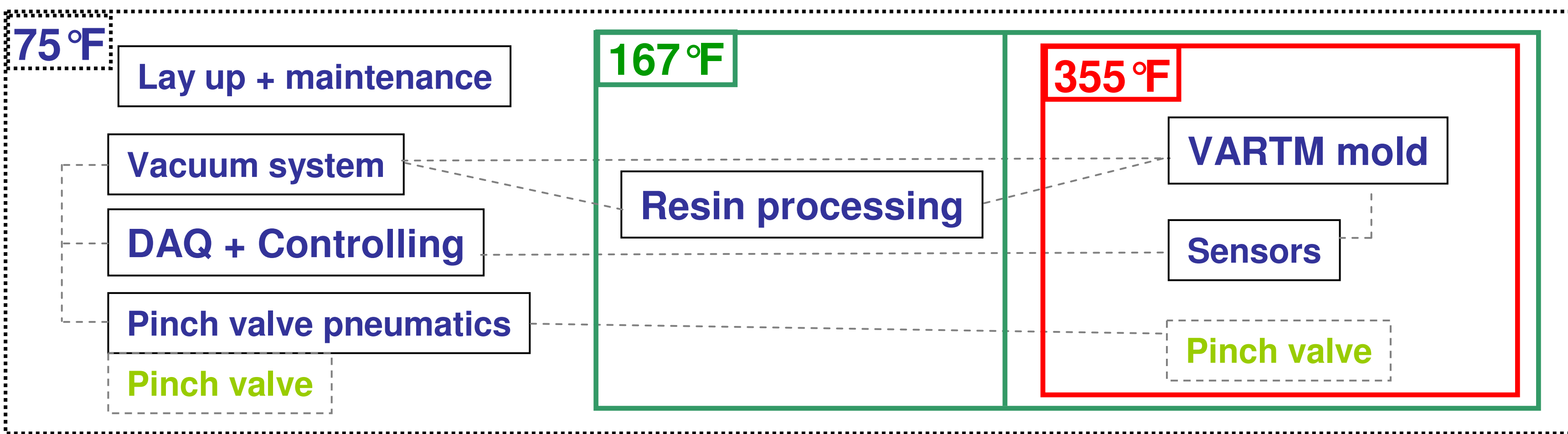


ET-VARTM with Cytec 977-20/PRIFORM™

- Processing of Cycom® 977-20 (Cytec)
  - Single component epoxy resin
  - Representing epoxy systems w/ heat initiated curing
  - Highly exothermic!

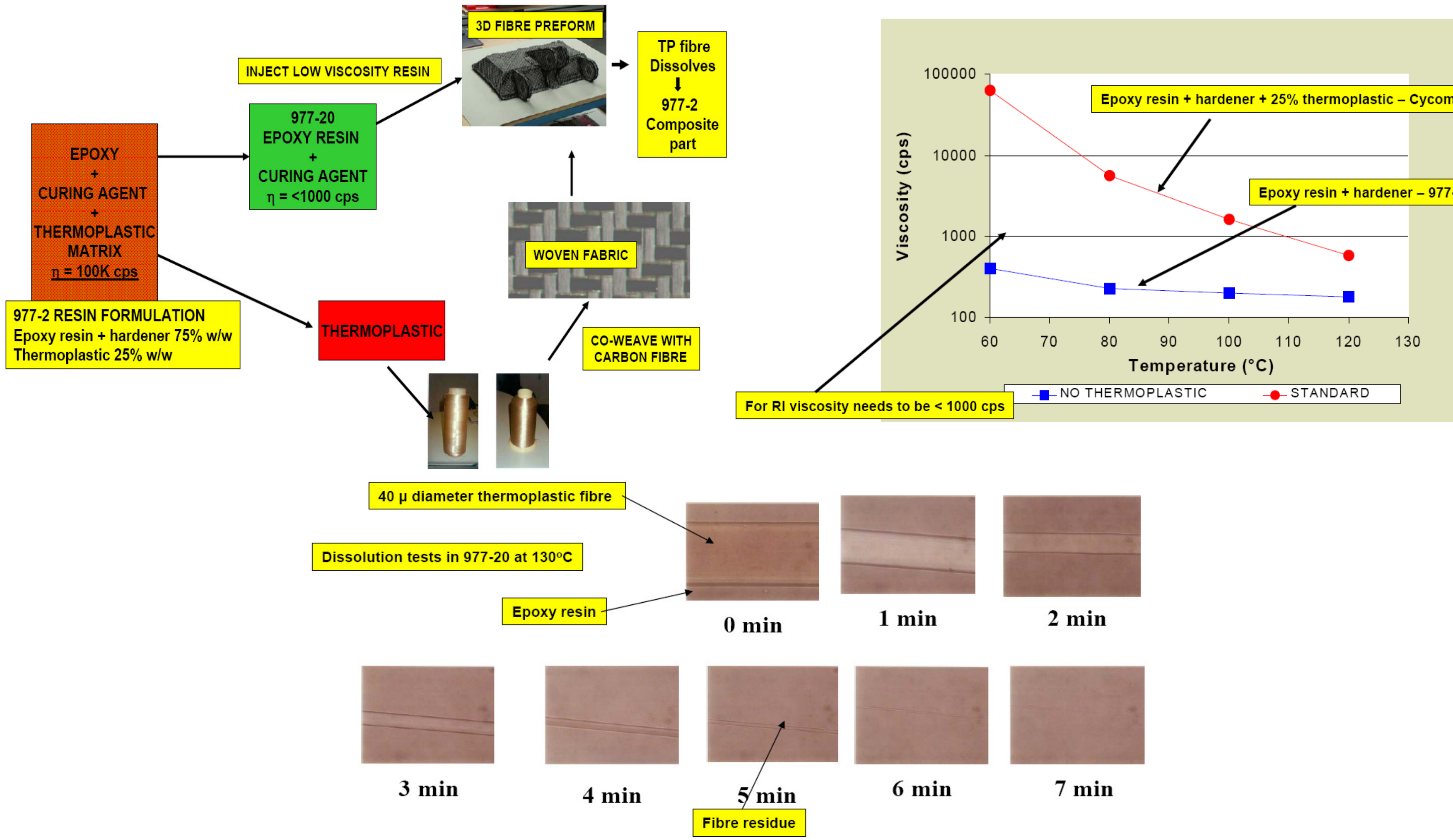


♦ **VARTM cell schematic**



Cytec 977-20/PRIFORM™

Source: T. McGrail, "Polymer Matrix Composites – OPPORTUNITIES and CHALLENGES", Cytec



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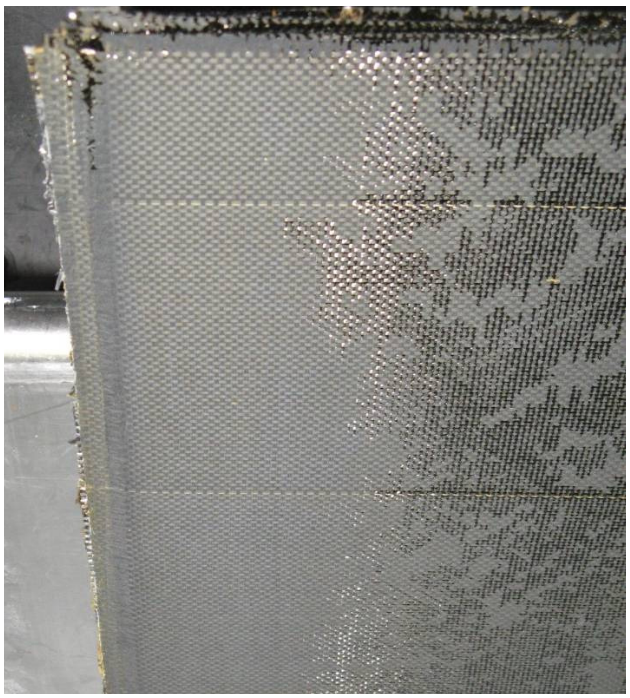
Void Formation Issues

Typical void formation in ET-VARTM:
• heavy macro-void formation visible
→ Indicator for lagging macro-flow



Modified ET-VARTM approach:
• increasing flow velocity by decreasing viscosity
→ significantly reduced macro-void formation

Property Database of Cycom 977-20

Cycom 977-20 with and without Priform

Some with RTM6

1. Unnotched Compression D3410
2. Open hole compression D-6484
3. Unnotched Tensile D-3039
4. Open hole Tensile D-5766
5. Drop weight Impact D 7136
6. Compression after Impact (CAI) D-7137
7. Short Beam Shear D-2344
8. Fiber Volume Fraction
9. Void Content
10. Tg

Mechanical Test Results

Quasi-isotropic 16-ply laminate (4)[(0/45)$_S$] - Values normalized to 50% F_{vf}

Test Method ASTM	977-2 Prepreg	977-20 RTM w/ PRIFORM	977-20 6k IM7 PW SGP196	977-20 w/ PRIFORM 6k IM7 5HS	RTM6 6k IM7 PW SGP196
Unnotched Compression D3410			64.0ksi ±4.7 ksi	72.9 ksi ±3.7 ksi	47.2 ksi ±2.7 ksi
Open Hole Compression **D-6484**					41.8 ksi 288 MPa
Unnotched Tensile D-3039			80.2 ksi ±5.9 ksi	72.5 ksi ±3.2 ksi	55.0 ksi ±5.5 ksi
Open Hole Tensile **D-5766**	43.6 ksi 300 MPa	43.9 ksi 302 MPa			56.7 ksi 390 MPa
Short Beam Strength **D-2344**	11.9 ksi 82 MPa	11.9 ksi 82 MPa	9.8 ksi ±0.5 ksi	11.0 ksi ±0.6 ksi	7.8 ksi ±0.4 ksi
Drop Weight Impact D-7136					
Compression After Impact D-7137					
Fiber Volume Fraction			51.1%	60.3%	45.5%
Void Content					
Tg					

A Look Forward

- Benefit to Aviation
  - Improved fundamental understanding of VARTM processing to understand benefits and disadvantages of various process variations
  - Reduce part-to-part variations / improve allowables
  - Automated VARTM will allow QA/QC of part production reducing costs and improve quality while maintaining traceability
  - Open-access database of structural properties
- Future needs
  - Work close with VARTM manufacturers to transition technology
  - Improve VARTM to achieve autoclave-level quality
  - Investigate more complex geometries / unitized structures