VARTM Variability and Substantiation

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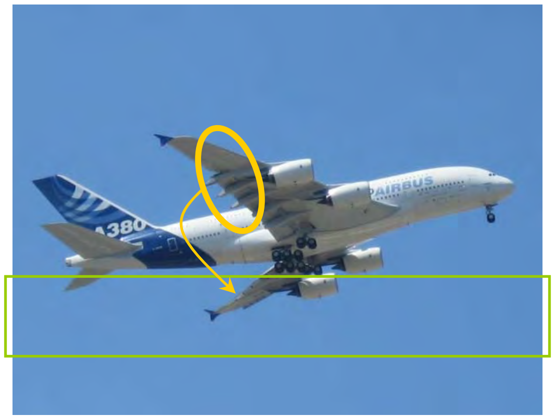
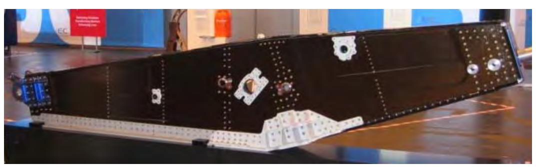
FAA Sponsored Project Information

- Principal Investigators & Researchers
  - Dirk Heider (PI)
  - John W. Gillespie, Jr. (Co-PI)
  - Solange Amouroux
  - "C" Josiah Hughes
- FAA Technical Monitor
  - Curtis Davies
- 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
  - EADS (Augsburg, Germany)
    - Provided technical and financial input
  - Boeing (Philadelphia, PA)
    - Provided technical input

AEROSPACE VARTM'D COMPONENTS

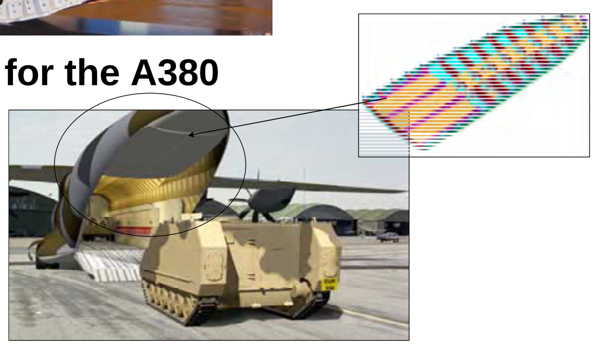




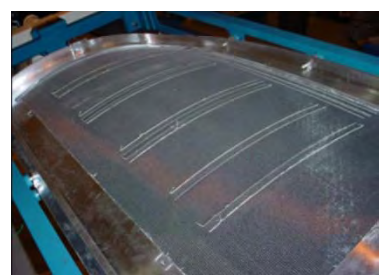
Flap tracks for the A380

Pressure Dome

CH-47 Chinook Forward Pylon



A400M CFC Cargo Door



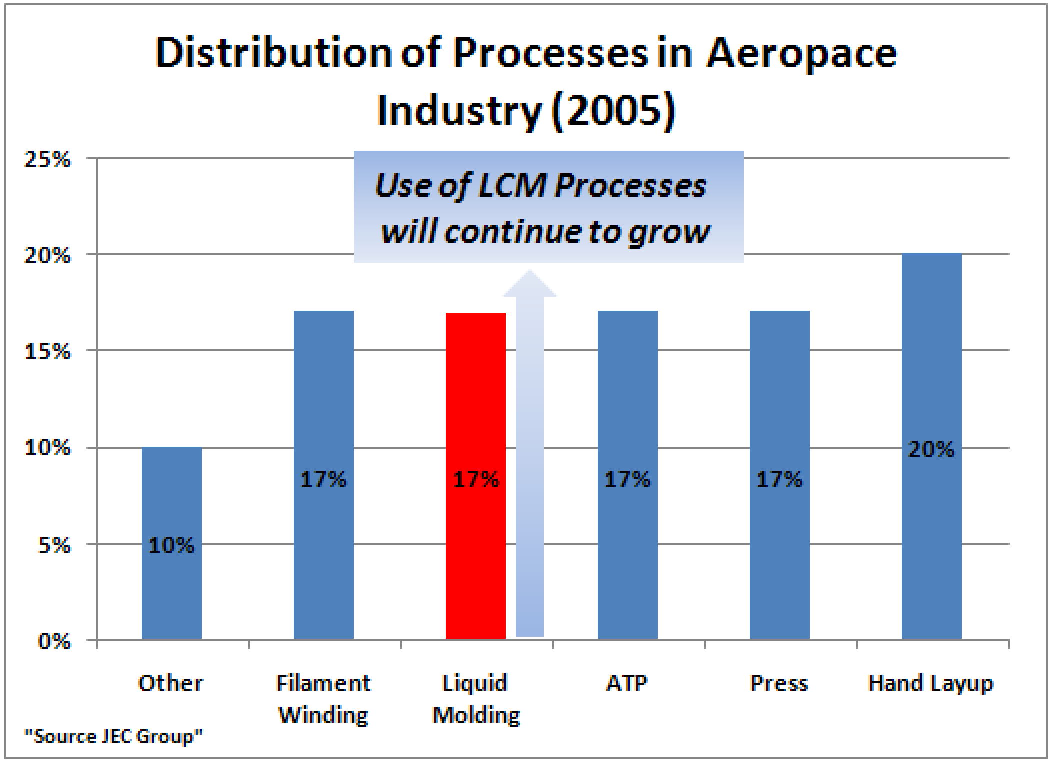
C-17 Main Landing Gear Door

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



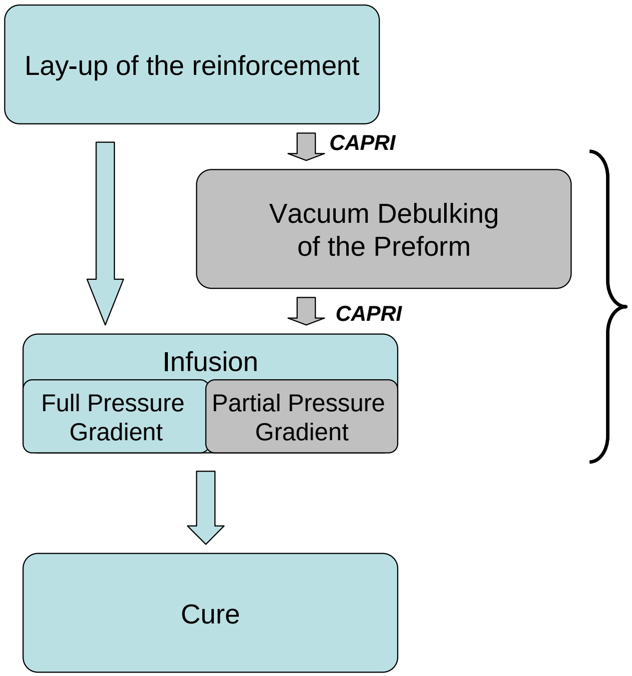
APPROACH

- Establish the fundamental understanding of the various VARTM processes
  - Flow model is fully developed for SCRIMP, VAP, and CAPRI process
  - Compaction behavior has been evaluated for all processes
    - Dry compaction during debulking
    - Relationship between compaction, permeability and pressure changes has been established
  - Effect of resin bleeding
    - Model has been implemented
  - Effect of dual-scale flow behavior has to be further studied to better understand micro-void formation
- Optimize membrane material (VAP)
  - Understand membrane mechanisms
  - Recommend material improvements (increased pressure, improved drapability)
- Establish an elevated temperature VARTM work cell for toughened epoxies
- Develop a material database for aerospace resins

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

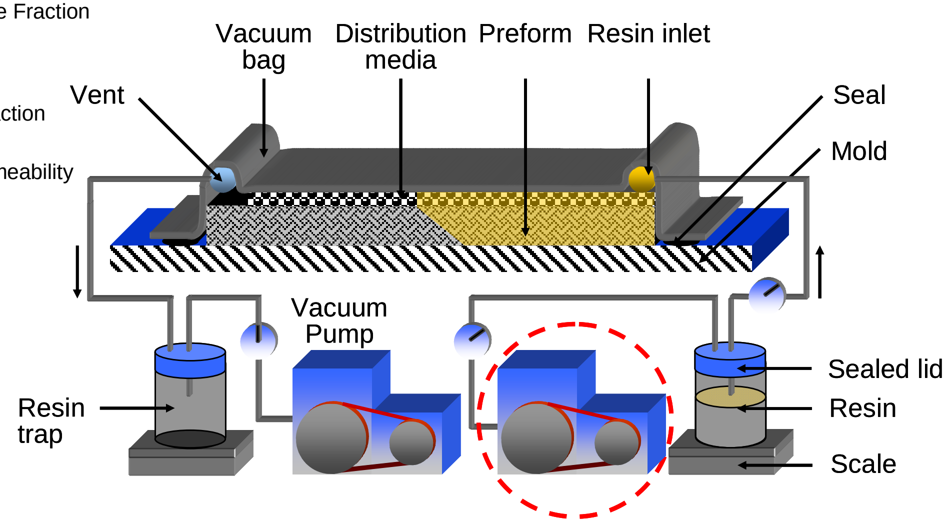
Process Variations: The CAPRI Process



- Controlled Atmospheric Pressure Resin Infusion
- Adds vacuum debulking and reduce pressure differential to setup

Advantages
- Increased Fiber Volume Fraction
- Reduced Gradients
  - Pressure
  - Thickness
  - Fiber Volume Fraction

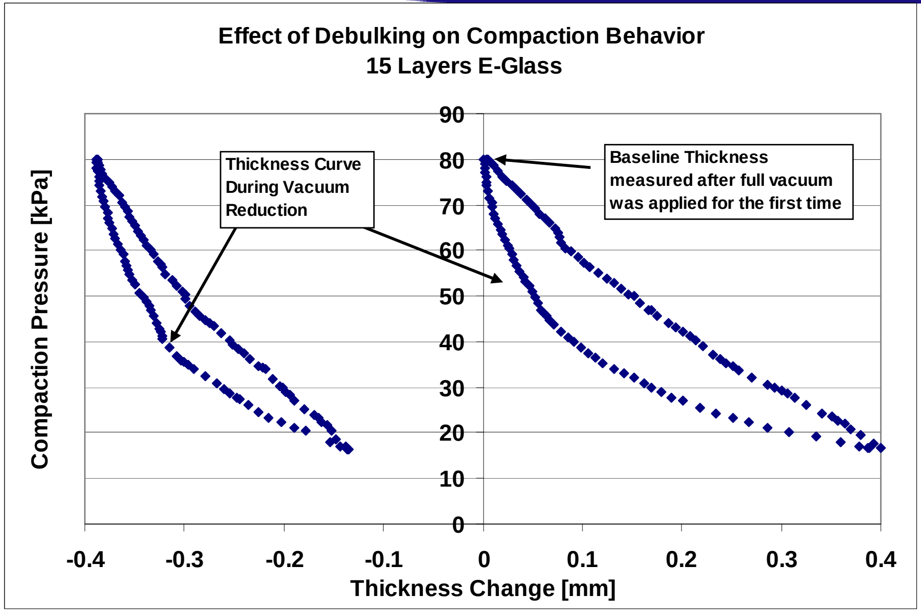
Disadvantages
- Decrease in fabric permeability
- Increase in flow times
- Increase in lead length

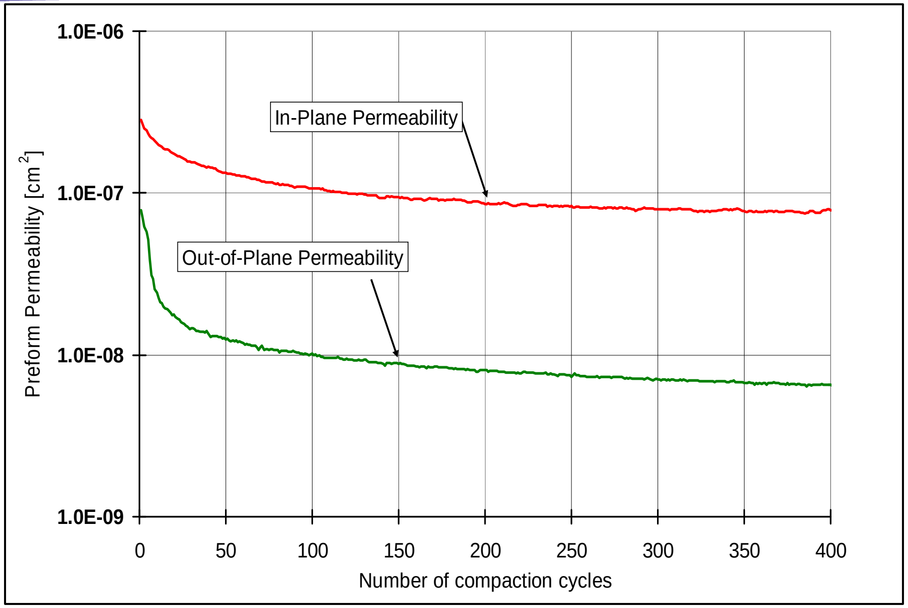


CAPRI Patent held by Boeing

Woods, J., Modin, A. E., Hawkins, R. D., Hanks, D. J., “Controlled Atmospheric Pressure Infusion Process”, International Patent WO 03/101708 A1.

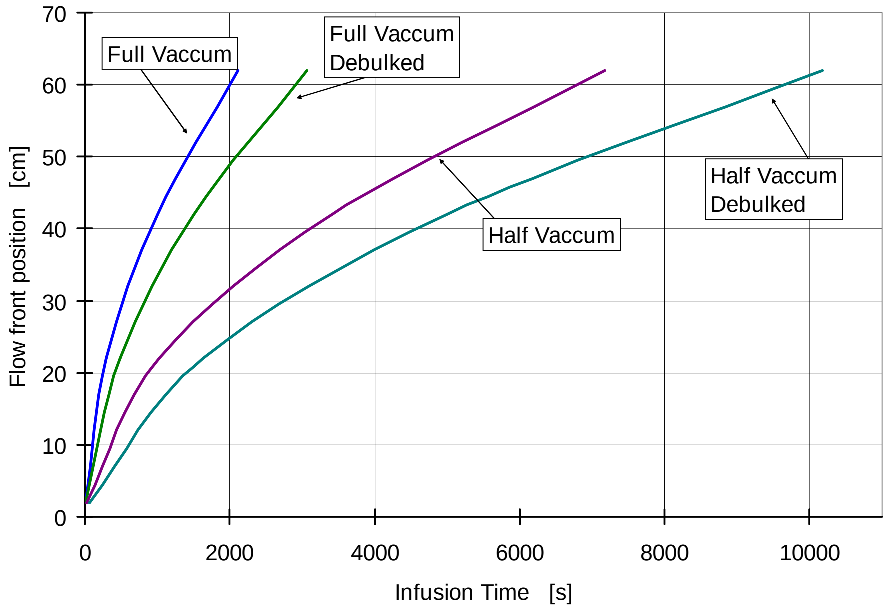
Effect of Debulking on Thickness and Permeability

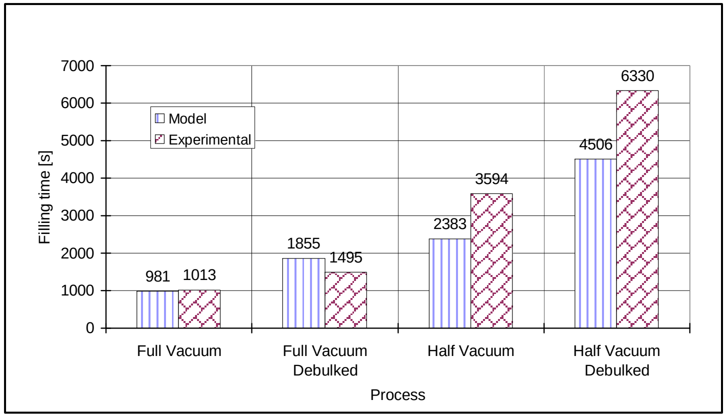


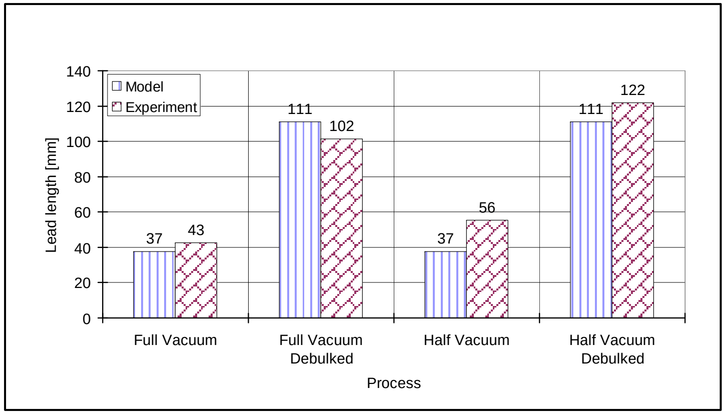


- The thickness and spring-back behavior is greatly reduced during debulking
  - Reduces thickness gradient
    - Initial Thickness: 9.14 mm Debulked Thickness: 8.76 mm
  - Increases Fiber Volume Content (F_v):
    - Initial F_v = 54% Debulked F_v = 58%
  - Decreases permeability
    - In Plane 5x reduction, Out-of-Plane 10x reduction in Permeability

CAPRI Flow Behavior

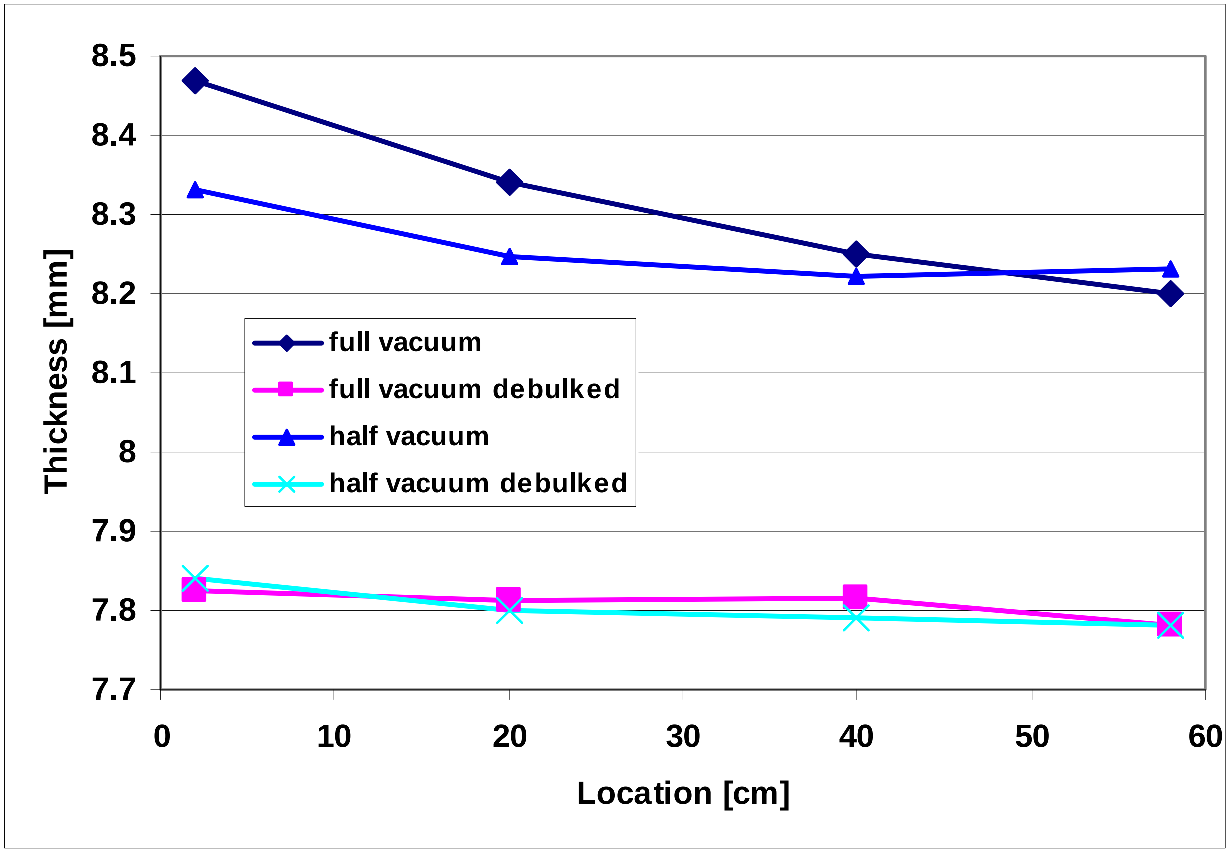






- Flow behavior changes due to reduced pressure gradient and decreased permeability
- 1-D analytical flow model has been developed and can predict lead length and fill time

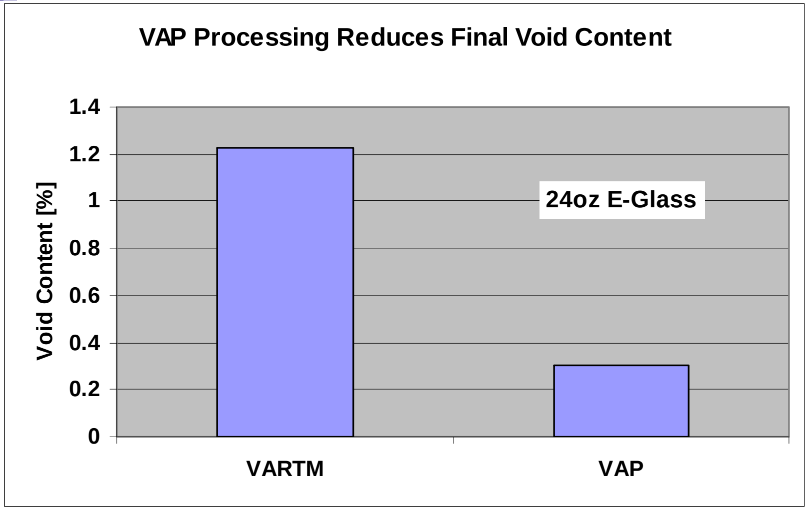
Thickness Behavior Comparison between CAPRI and SCRIMP

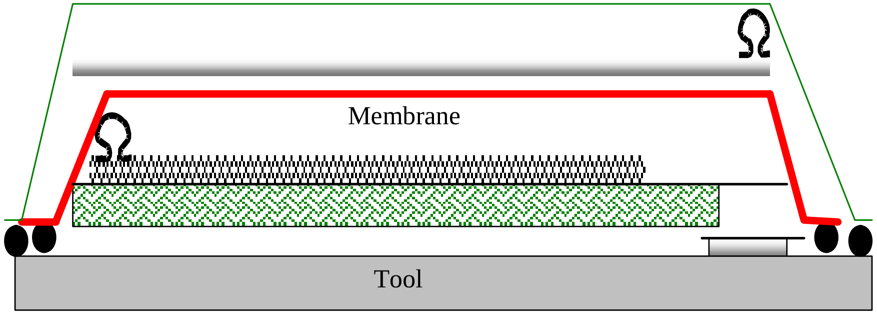


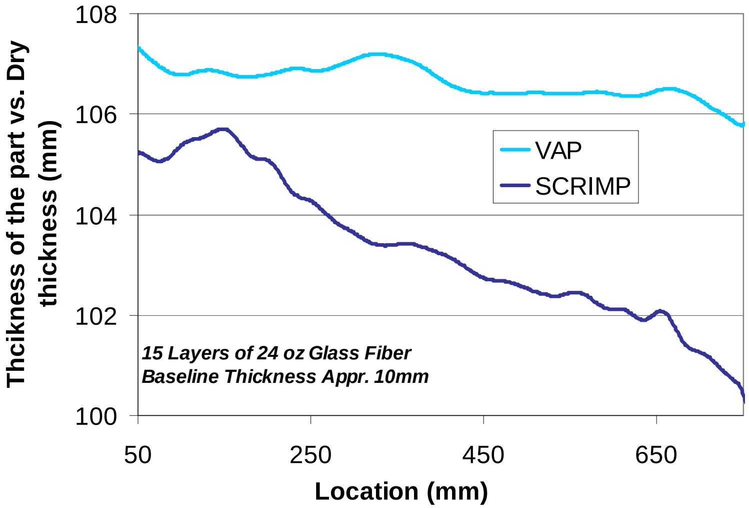
- Debulking can greatly increase final fiber volume fraction
- The thickness gradient is reduced when the CAPRI pressure is applied (insignificant for the debulked case)

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

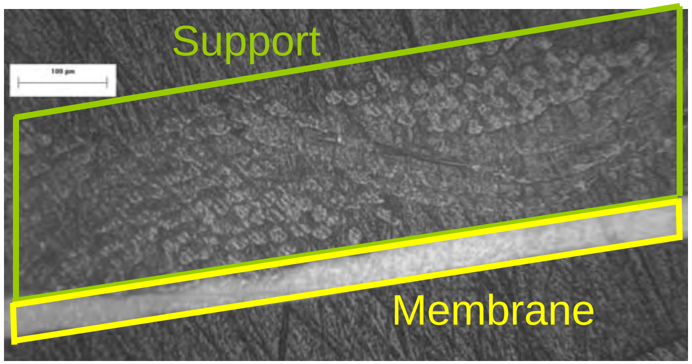


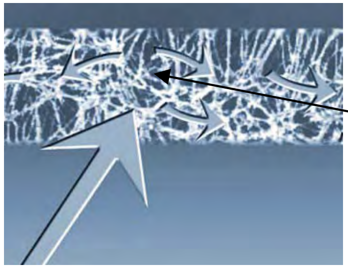




MAIN REQUIREMENTS OF THE MEMBRANE

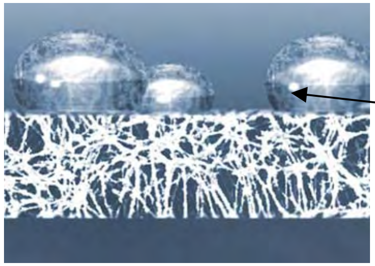
- Desirable Characteristics for a membrane used in VARTM:
  - Gas permeable material
    - OR High air permeability through the thickness
  - Resin-proof material
    - OR Low liquid/resin permeability through the thickness
- Compatibility with resin
  - Compatible: The resin does not go through the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



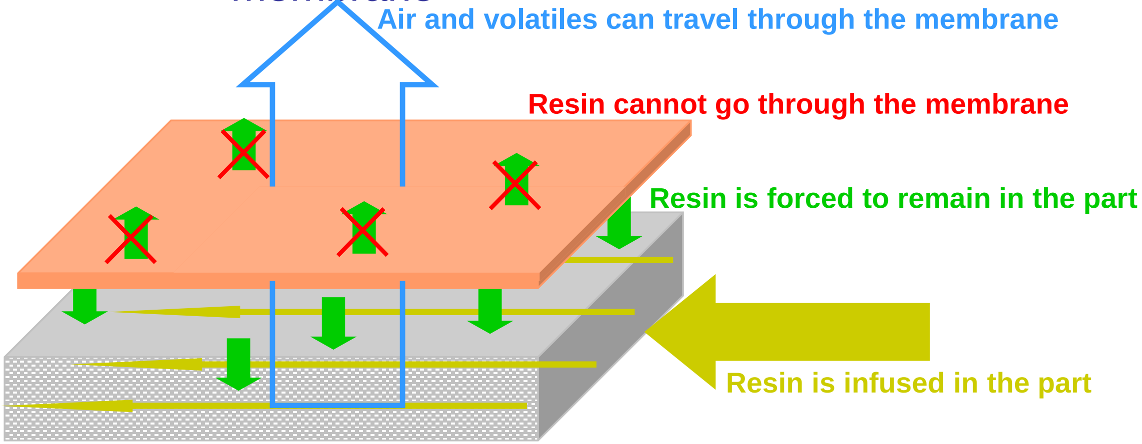


High air permeability

www.gore-tex.co.uk



Low liquid permeability



Membrane Model Development

- **Goal**
  - Predicts the permeability of the membrane as a function of pressure
    - Zero permeability for pressures below the capillary pressure of the largest pore in the membrane
  - Predict the impregnation time of the membrane by the resin to make sure that: $t_{impregnation} \geq t_{gel}$

Laplace Equation

$$P_c = -\frac{2\gamma\cos\theta}{r}$$

$$P_1^* = P_1 + \boxed{P_c}$$

$$\Delta P^* = P_0 - \left[\boxed{P_1^*} + P_g\right]$$

Kozeny-Carman

$$K = \frac{\varepsilon^3}{k\tau^2 S^{*2}}$$

Darcy's law

$$\dot{\xi} = \frac{\boxed{K}}{\eta}\frac{\boxed{\Delta P^*}}{\xi}$$

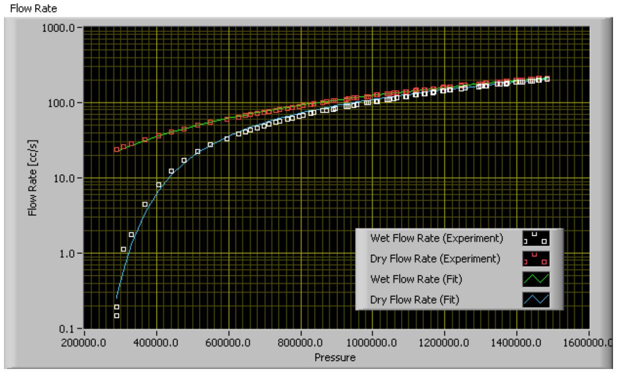
$$\int \dot{\xi}\, dt \Rightarrow \xi = f(t)\, or\ t = f(\xi)$$

vt for ξ=h

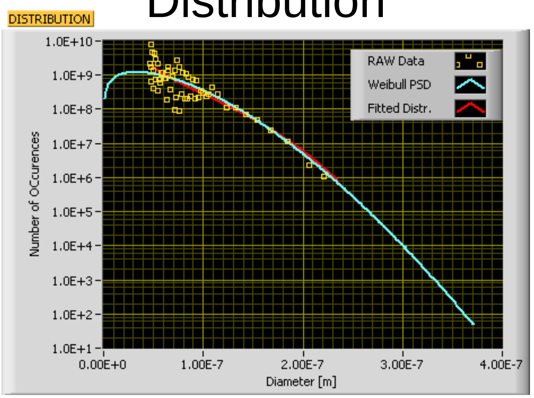
$$t = \frac{h^2}{\frac{2}{5}\frac{\varepsilon^3}{\eta S^{*2}}\left[\Delta P + \frac{2\gamma\cos\theta}{r} - P_g\right]}$$

Statistical Analysis of Membrane

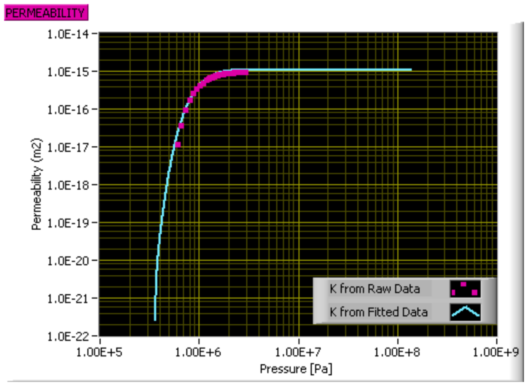
Fitted Porometer Data



Improved Pore Size Distribution

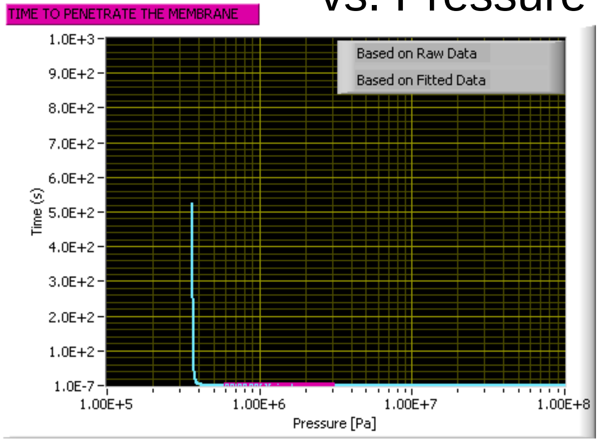


Permeability vs Pressure



- 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)

Penetration Time vs. Pressure



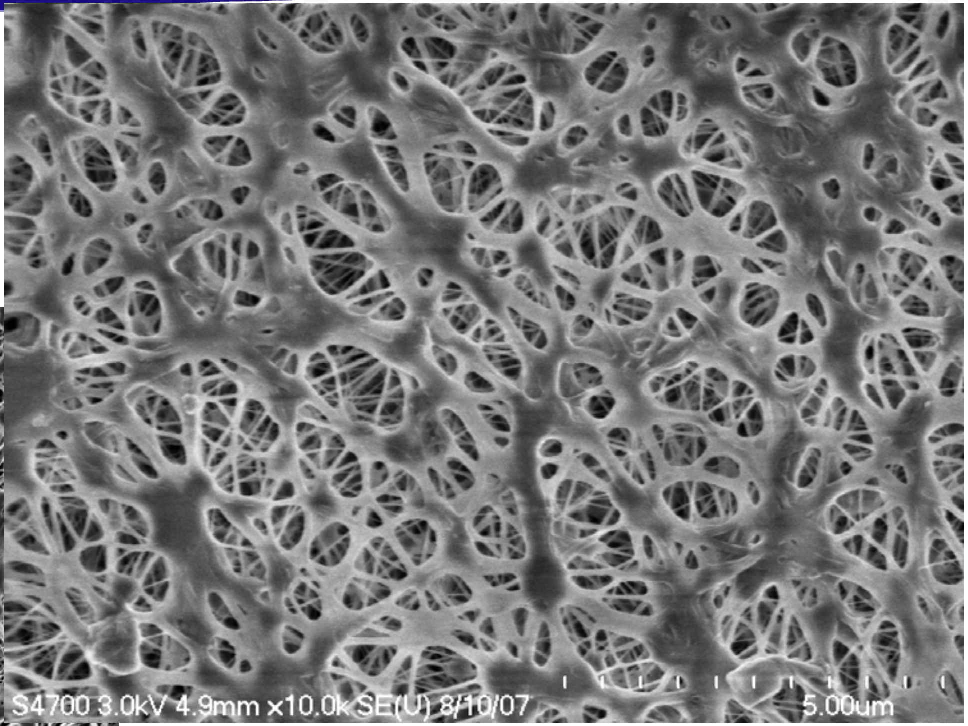
On-Going Work
Draping Investigations

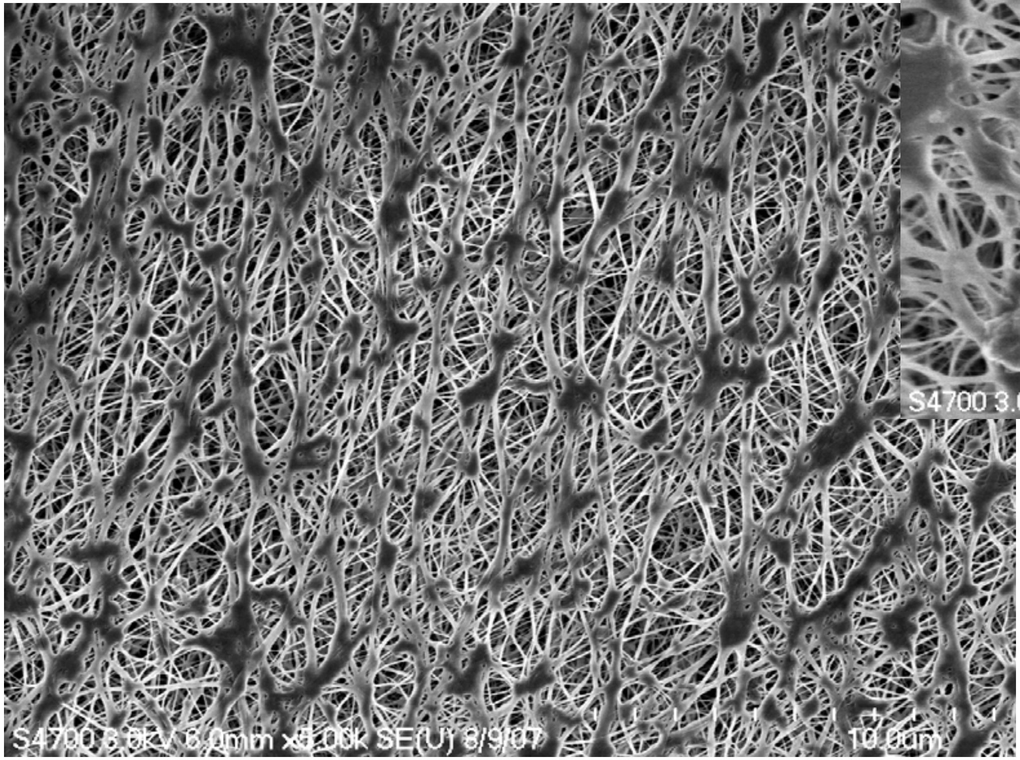
Industry experienced membrane failure for parts with complex draping requirements. To address this issue, basic characterization and a study of biaxial stretching of the membrane are performed.

- 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.

SEM Microstructure

- ♦SEM Images of unstretched membrane.
  - ✧Node - fibril structure accounts for small pores and high permeability.

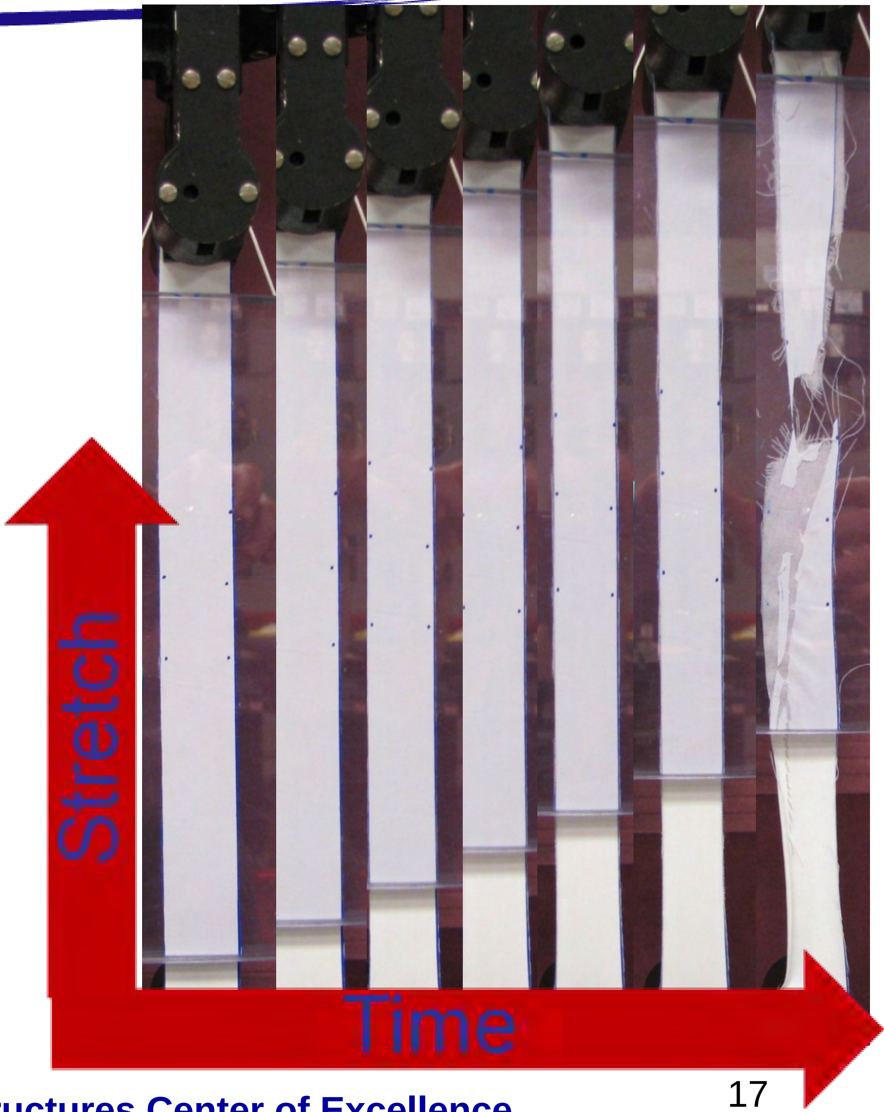




Stretching Behavior

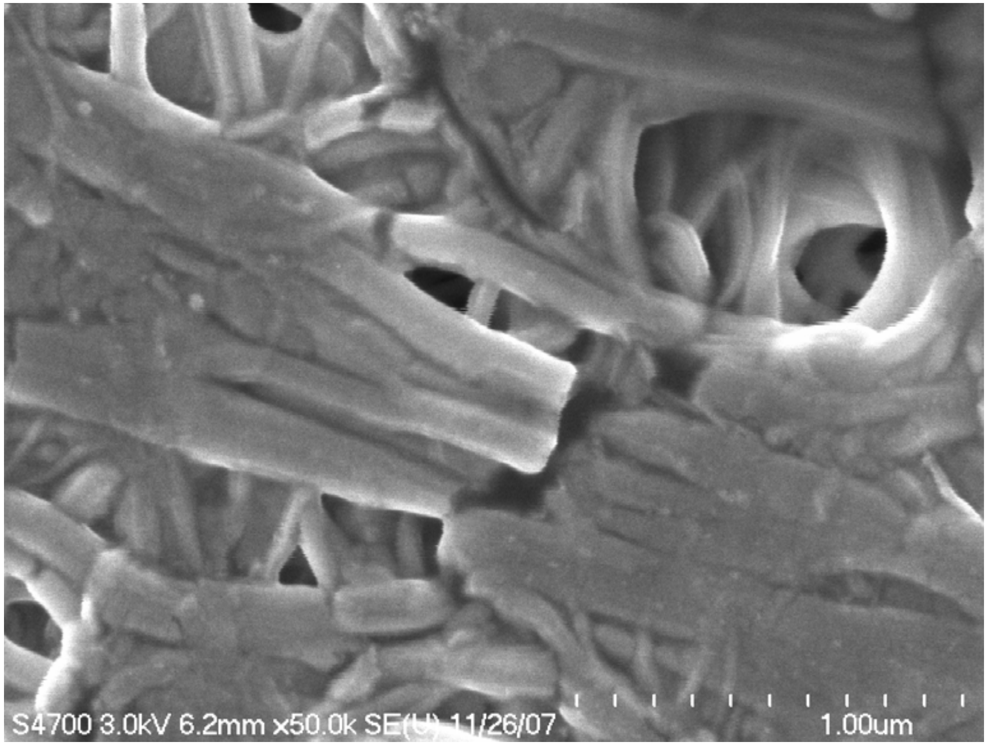
♦The hybrid construction of the Composite Manufacturing Membrane (ePTFE Membrane and Fabric Support) has long been believed to be the cause of premature tearing of the ePTFE membrane.

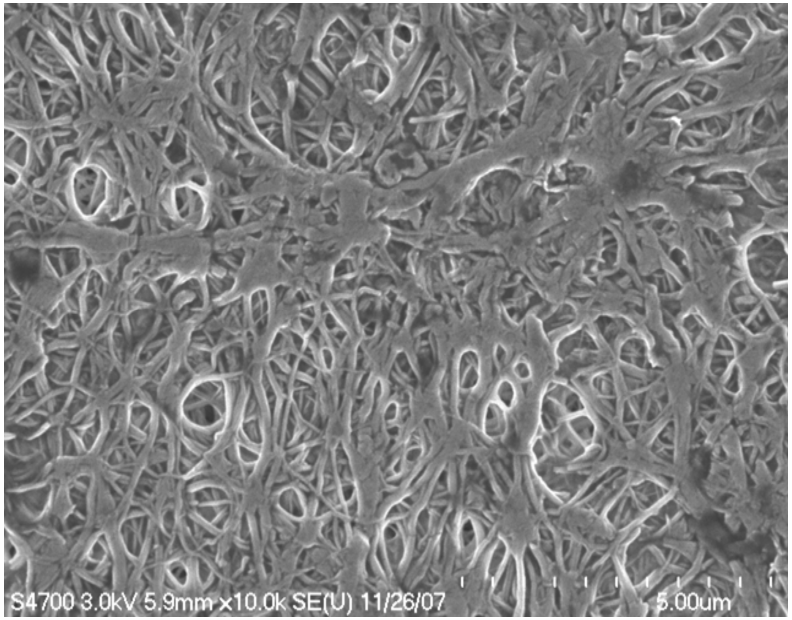
- ✧The ePTFE Membrane is transversely isotropic while the support is orthotropic (a plain weave fabric).
- ✧A study of the Poisson Ratio of the Membrane and the support was undertook to analyze if the strain differences between the support and the membrane were sufficient to cause localized tears in the membrane and thus leaks.



SEM Images
Stretch Damage

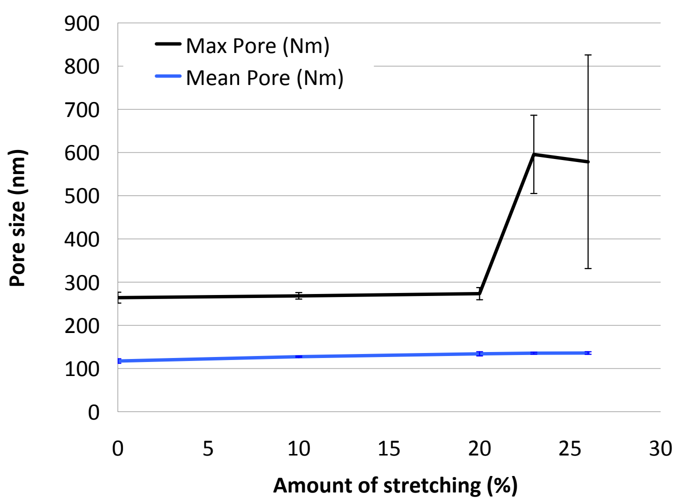
- SEM Images of stretched samples show visible affects of fibril tearing
  - At 23% Unidirectional Strain, fibrils were dislocated from nodes and visible cracks and damage were present.
  - The membrane alone does not exhibit this behavior, so there must be some support limitations causing the damage.

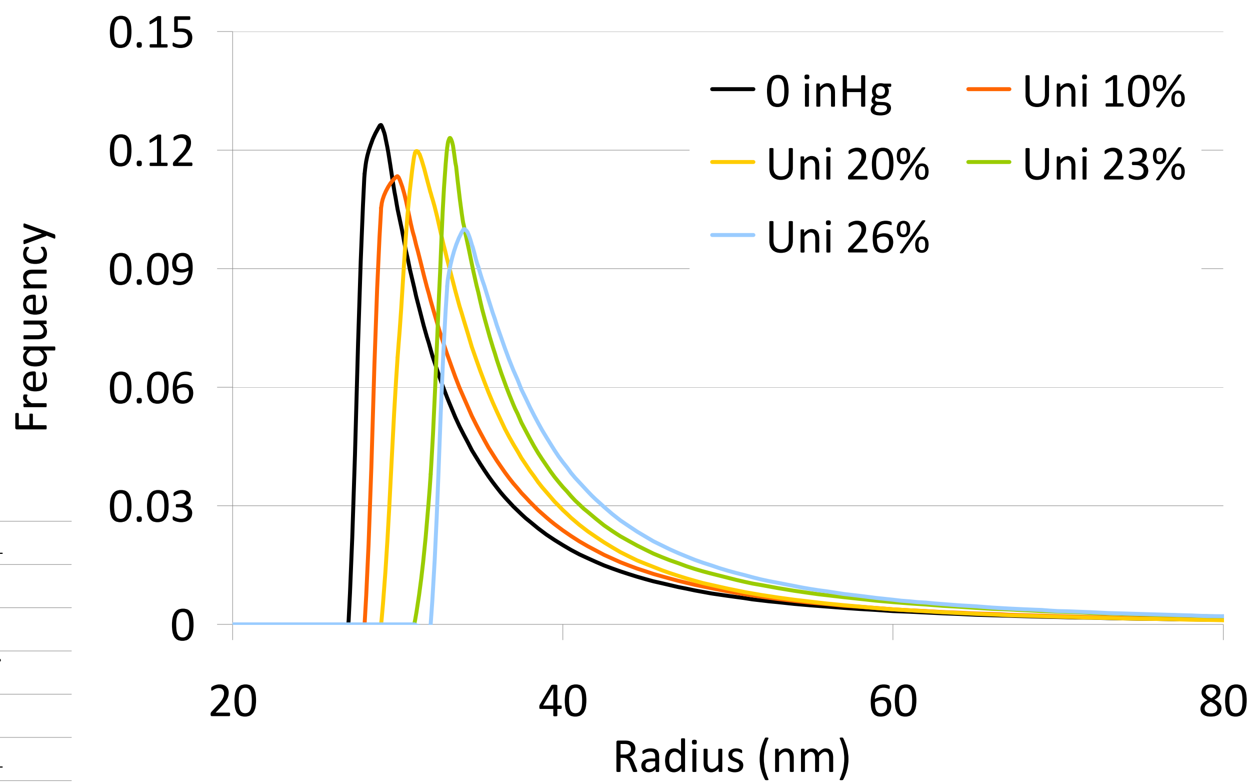




Effect of Stretch on Pore Size

- Stretching the membrane changes the distribution of pores.
  - The jump around 20% is verified by the damage seen in the stretched SEM images.



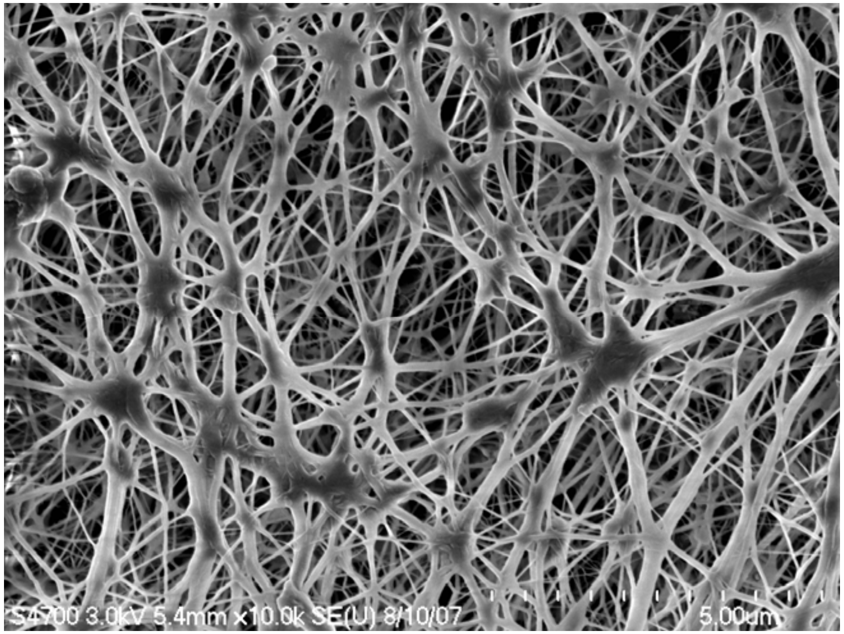


Strain Behavior: Membrane v. Membrane & Support

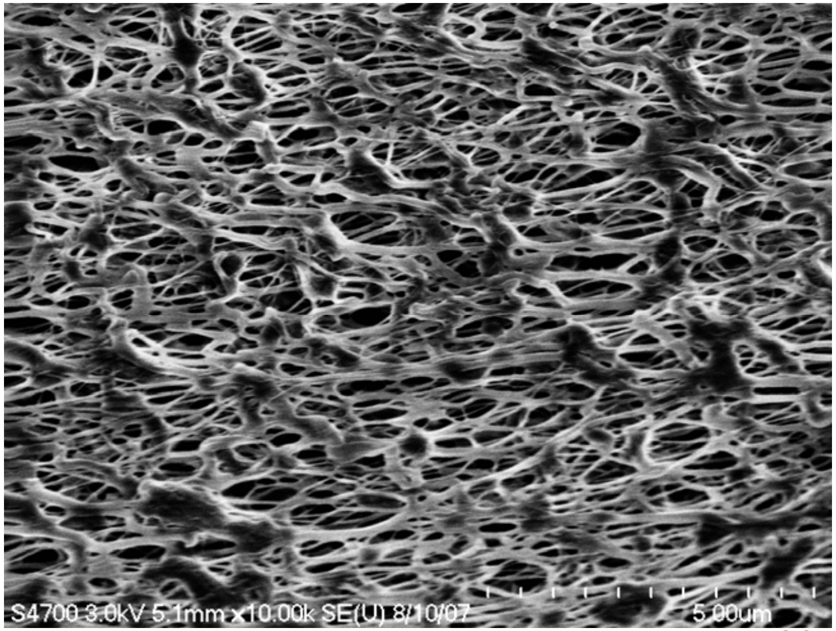
- Different Microstructures are observed when the membrane is stretched (both stretched to 20%) with and without the support.
  - The stretching direction is horizontal and in the sample stretched without the support, significant scissoring was observed.

Stretching Direction

Membrane and Support

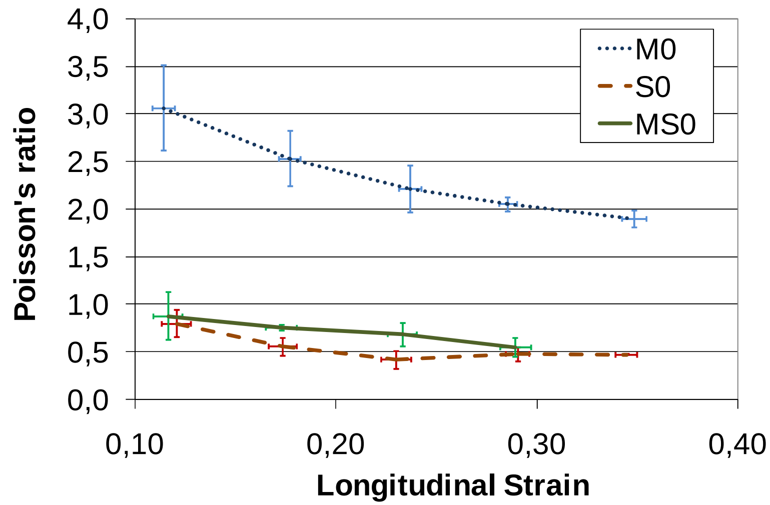


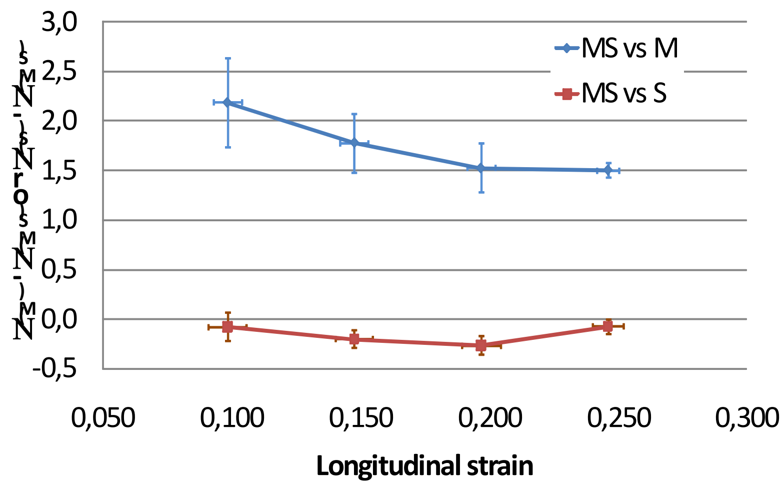
Membrane Alone

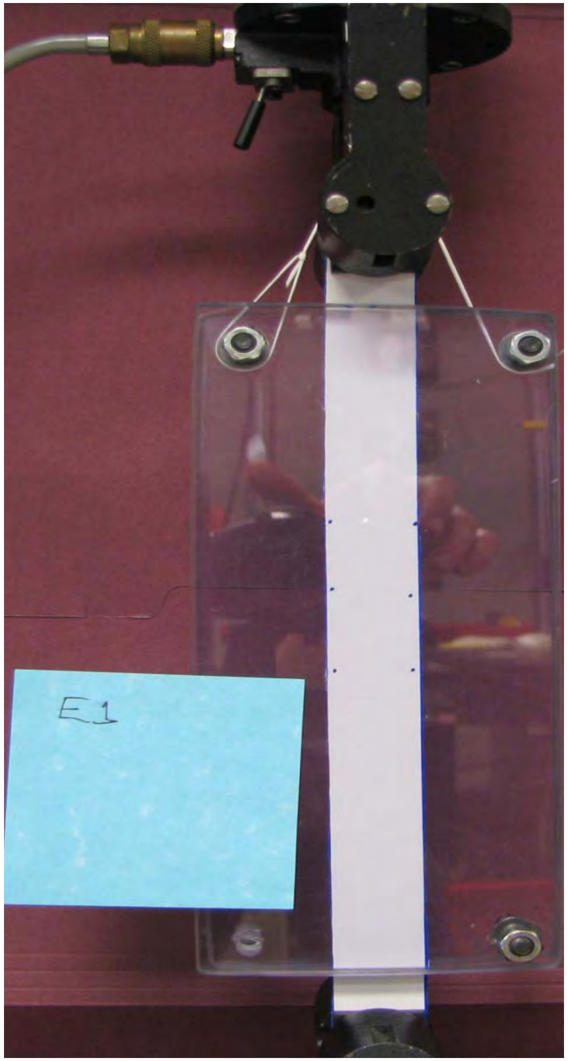


Poisson Ratio Mismatch

- ♦The Poisson Ratio of the Membrane (Transversely Isotropic) and the Support (Orthotropic) create orthogonal strains in a standard tensile sample.
- ♦The membrane is far more elastic than the support.
  - ✧The damage is believed to be a result of the support tearing, not the membrane being over-strained.

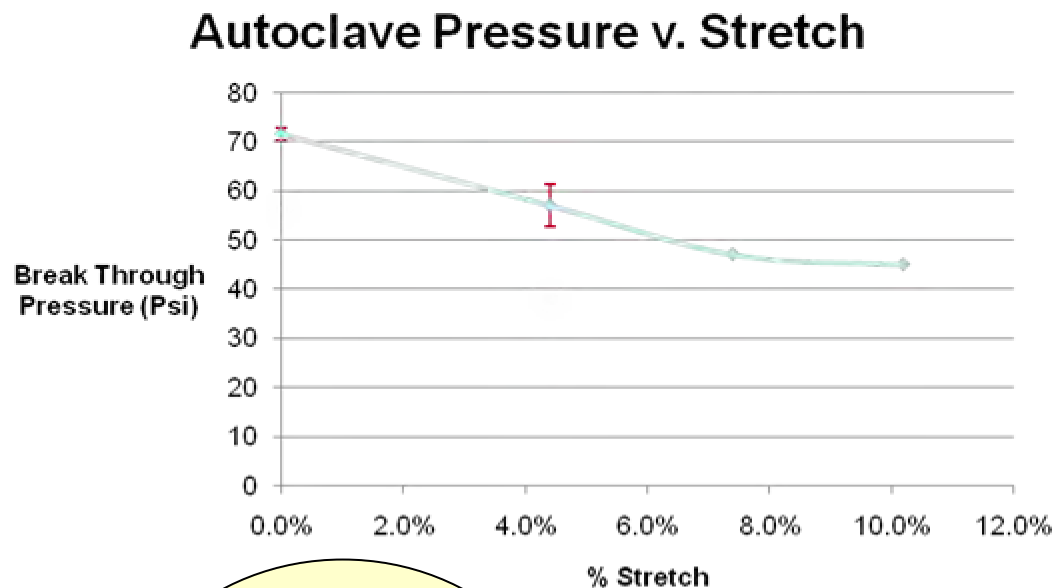




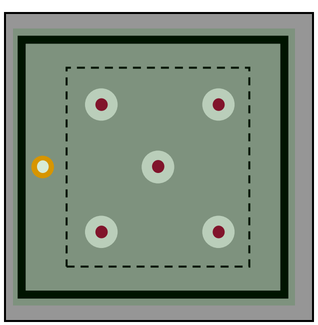


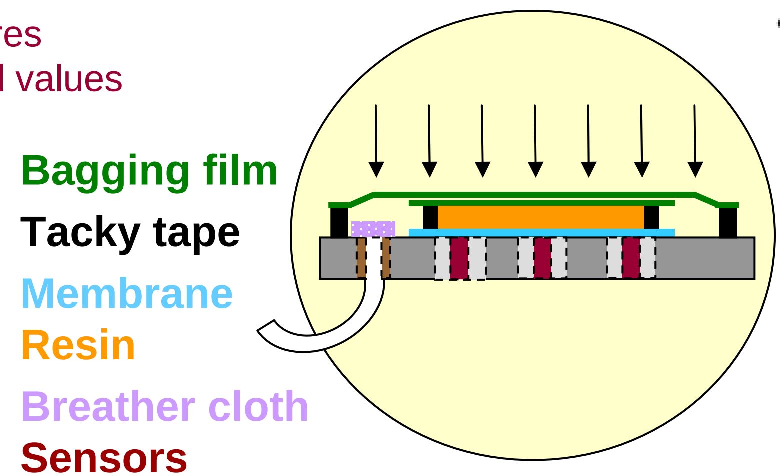
Autoclave

- Some autoclave experiments have been performed to demonstrate the change in capillary pressure at various strains.
- The membranes were characterized using the porometer and contact angle experiments.
  - The values for the stretched membranes were used as inputs to determine the experimental capillary pressure.
  - The analytical capillary pressures were compared to experimental values obtained in the autoclave.

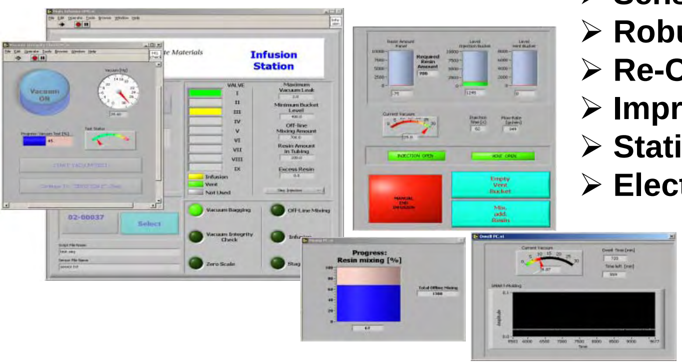


top view

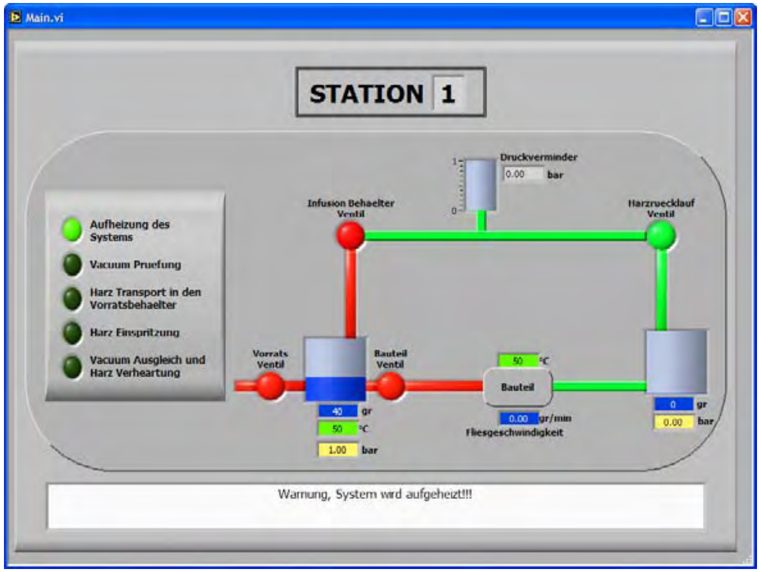




Aerospace VARTM Requires Elevated Temperature Processing



- Sensor Based Infusion Technology
- Robust System Construction
- Re-Configurable Infusion Schemes
- Improved Resin Mixing System
- Statistical Data Sampling During Infusion & Stage
- Electronic Work Instruction



TRANSITIONED FOR R&D AND PRODUCTION AT DASAULT AVIATION (Paris, France)
Also available to other companies

Develop Property Database

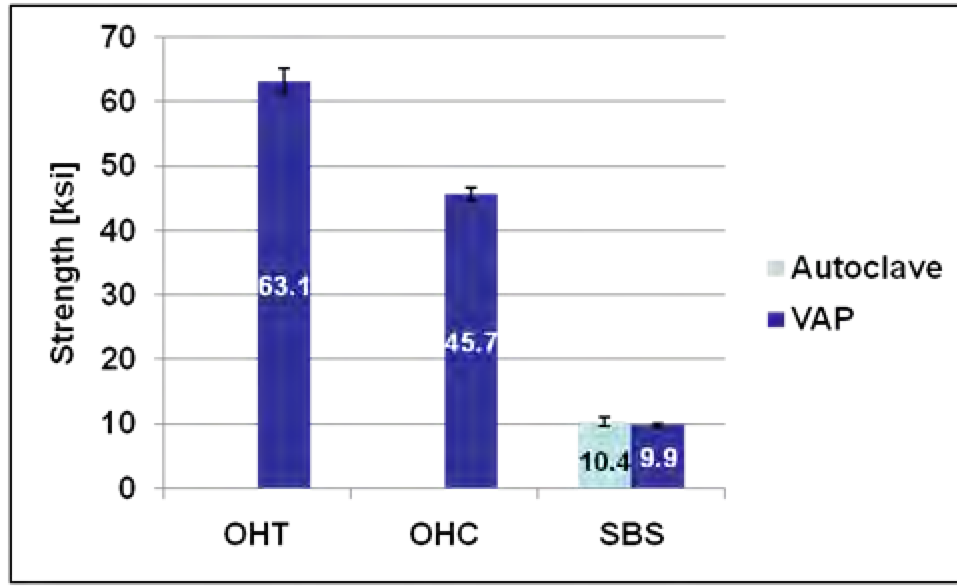
1. Unnotched Tensile D-5766
2. Unnotched Compression D6484
3. Open hole compression D-6484
4. Filled Hole Compression D-6742-02
5. Pin Bearing D-5961
6. Short Beam Shear D-2344
7. Drop weight Impact D 7136
8. Compression after Impact (CAI) D-7137
9. Interlaminar Tension (D-5415)

ALL Tests will be conducted at room temperature and 180F/80% hot/wet conditions using Cytec Epoxy Cycom 977-20 and T700 PW fabric

Mechanical Property Evaluation

Panel Geometry

and specimen location



Preliminary Data

Will be compared with autoclave processed panels

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