VARTM Variability and Substantiation

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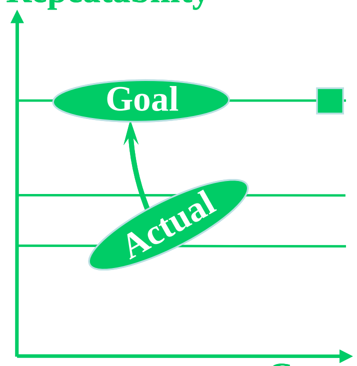
The Joint Advanced Materials and Structures Center of Excellence

FAA Sponsored Project Information

- Principal Investigators & Researchers
  - Dirk Heider
  - John W. Gillespie, Jr.
  - Crystal Newton
- FAA Technical Monitor
  - Curtis Davies
- Industry Participation
  - Gore (Munich, Germany)
    - Provided membrane materials, access to instrumentation and technical input
  - 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

MOTIVATION

- VARTM process: +/-
  - Main advantages: low cost, high fiber volume fraction, large scale parts
  - Still some limitations
    - High variability compared to autoclave process
      - From part to part
      - In the same part
- Following conditions have to be met to make VARTM viable for high-performance aerospace applications:

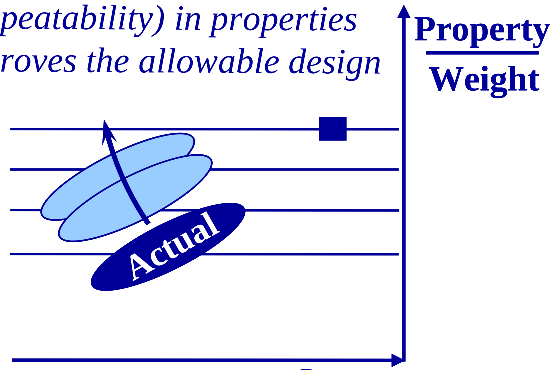


1) Process as repeatable as autoclave (reference)

VARTM
Autoclave

2) Slightly lower properties but for a much lower cost

A lower variation (higher repeatability) in properties improves the allowable design



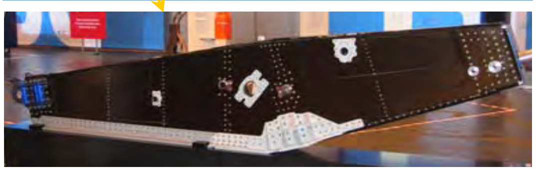
APPROACH

- Three VARTM processes will be evaluated on process repeatability, part quality, and mechanical performance
- Establish the fundamental understanding of the membrane/resin interaction
- Conduct model experiments to understand infusion and post-infusion stages of various VARTM processes
  - Implement novel characterization equipment
  - Model the thickness variation
  - Model the void formation
- Establish an elevated temperature VARTM workcell for toughened epoxies

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

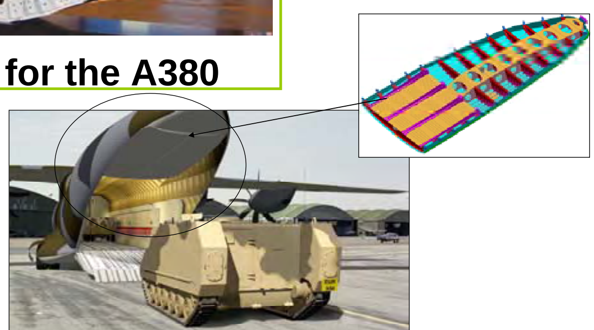
AEROSPACE VARTM'D COMPONENTS



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

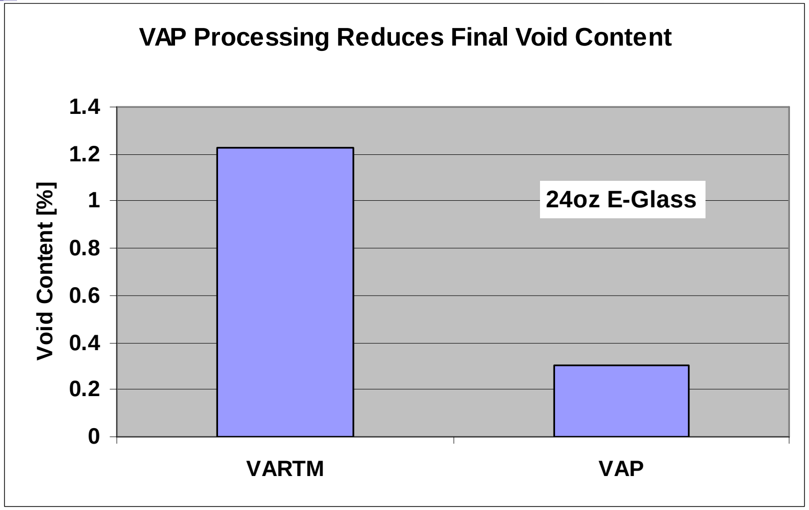
- LAIRCOM panels
- Leading edge 787
- Rear Bulkhead 787

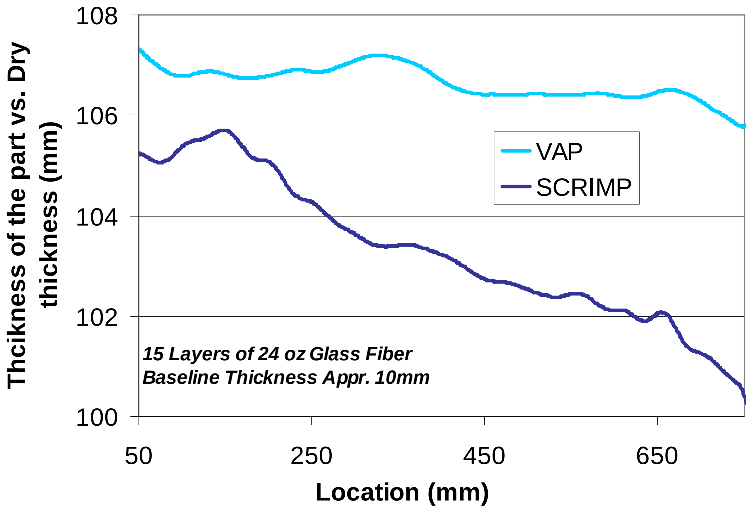
Liquid Injection Molding Simulation

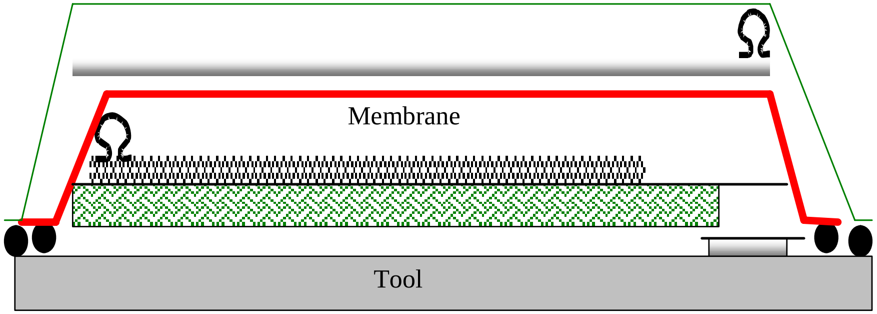
- **Developed since 1987**
  - Simulation of Liquid Composite Molding (LCM) processes such as
    - Resin Transfer Molding (RTM)
    - Vacuum-Assisted Resin Transfer Molding (VARTM)
  - Finite Element Model (FEM) allows
    - Simulation of large-scale complex structures
    - Optimization of injection and vent locations
    - Study of dry-spot and high void content areas
    - Integration of various materials (fabric, core, metal meshes, etc.)
    - Simulation of cure behavior
- **Successful virtual VARTM product development examples include**

MEMBRANE-BASED VARTM PROCESSING (VAP)

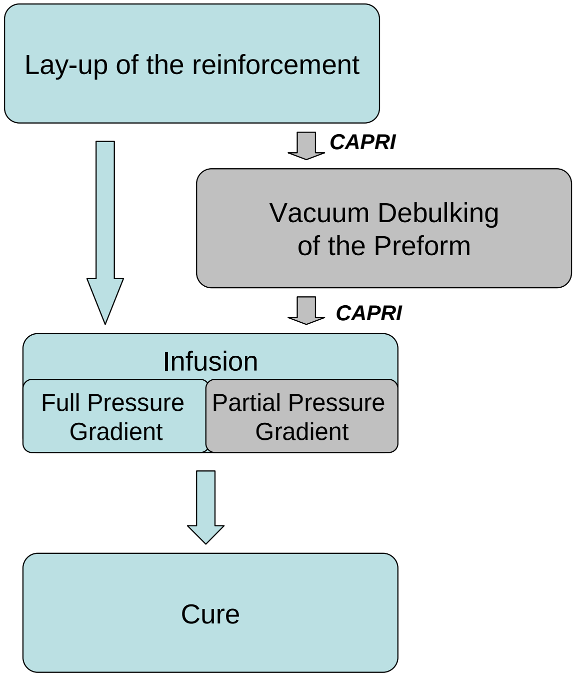
- Utilize membrane cover to allow continues degassing and uniform vacuum pressure during VARTM processing
  - Reduces void content
  - Improves uniformity (fiber volume fraction, thickness)
  - Eliminates dry-spots







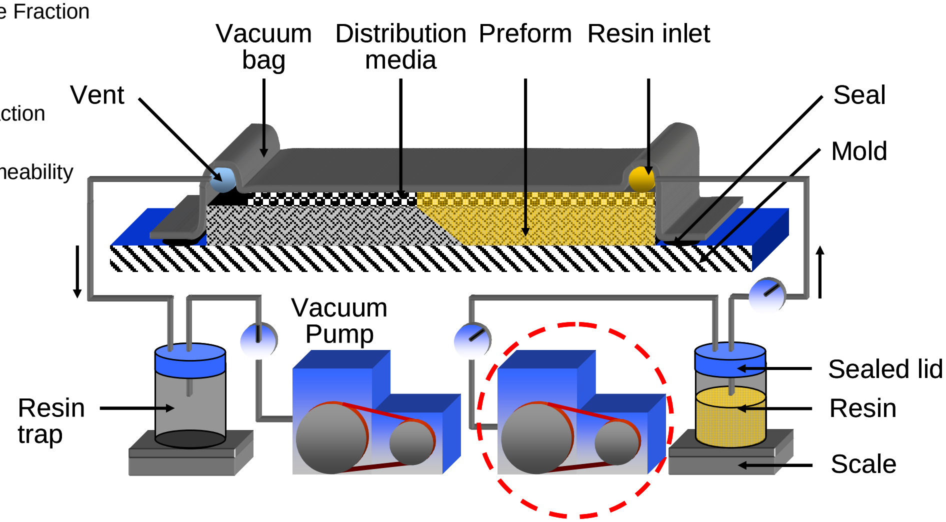
Process Variations: The CAPRI Process



- 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

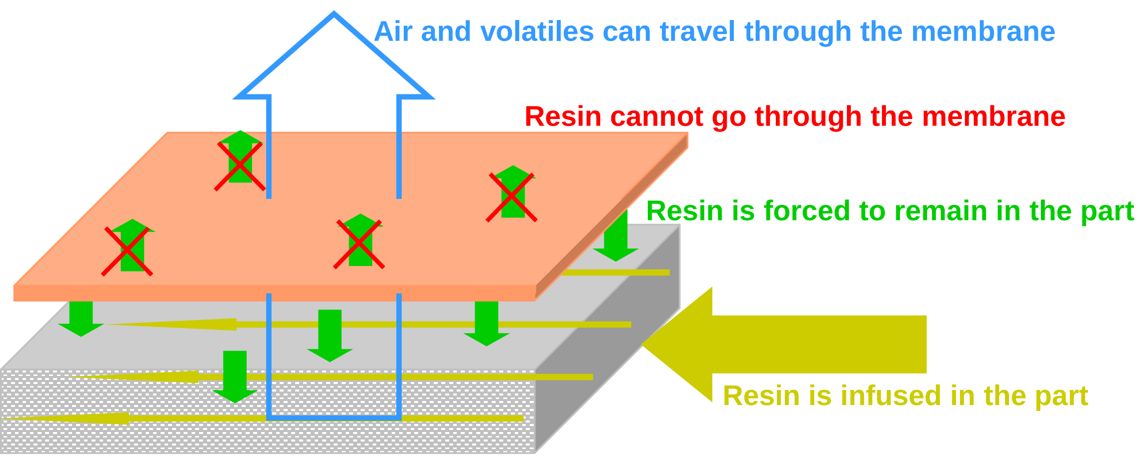


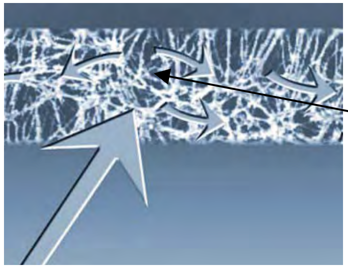
CAPRI Patent held by Boeing

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

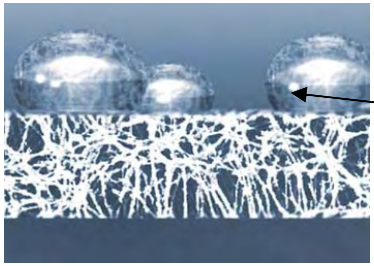
MAIN REQUIREMENTS OF THE MEMBRANE

- 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



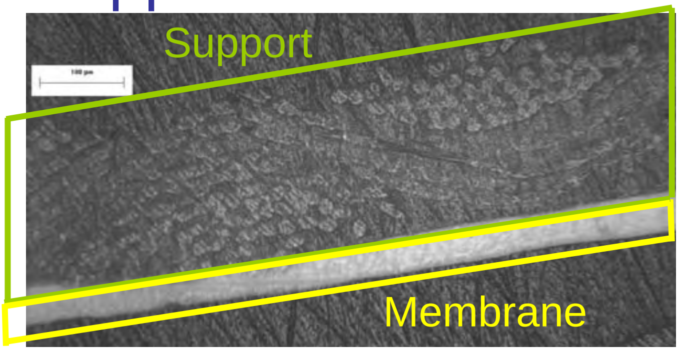


www.gore-tex.co.uk

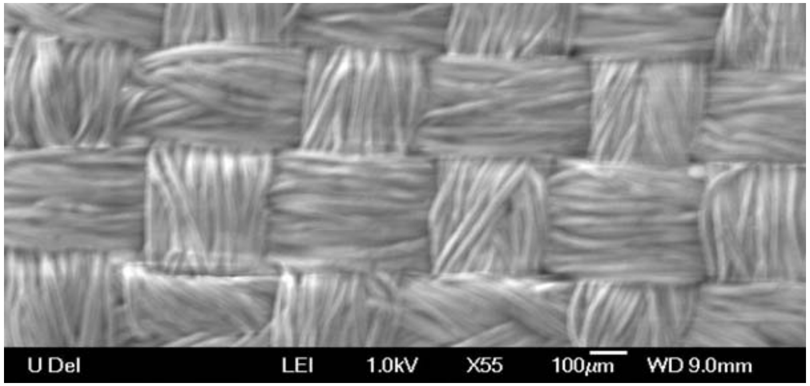


Membrane (from W. L. Gore & Associates, GmbH)

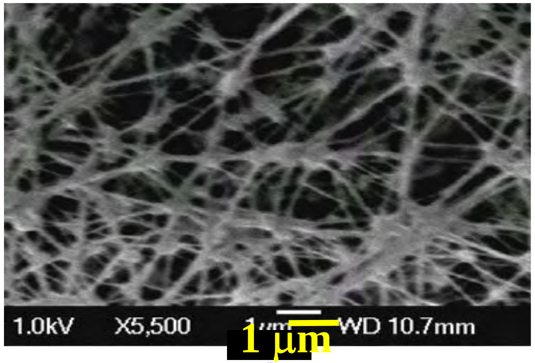
- Optical microscope
  - The membrane is mounted on a support



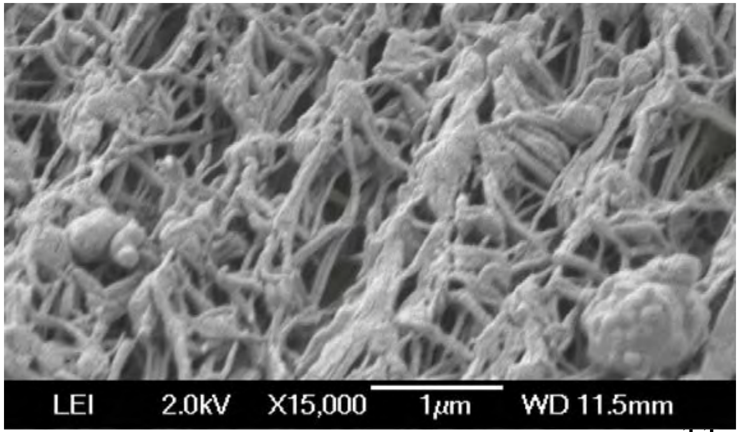
- SEM of the support



- SEM of the membrane
  - Top surface

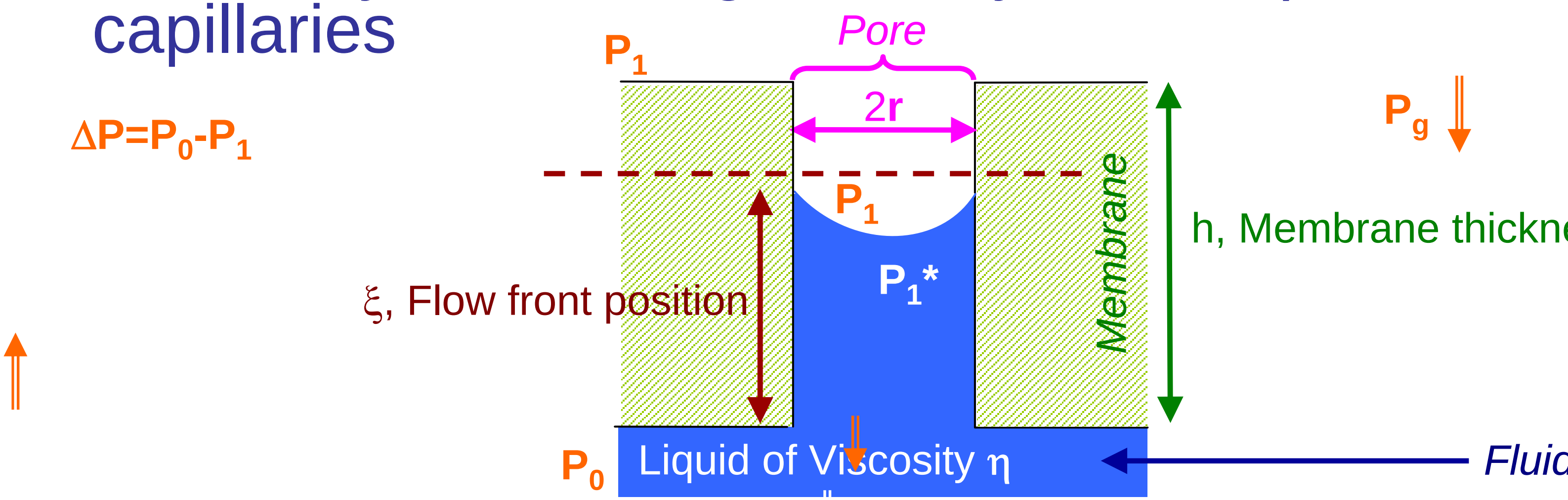


  - Cross-section



Modeling of Resin Transport Through Membrane

- <u>Goal</u>
  - Predict the impregnation time of the membrane by the resin to make sure that: $t_{impregnation} \geq t_{gel}$
- <u>Geometry</u>: thin, straight and cylindrical pores, called capillaries



- <u>Forces acting on the system</u>
  - Vacuum applied during the VARTM process ($\leq 10^5$ Pa)
  - Capillary effect
  - Gravity force

Expression of the Pressures

- Gravity: $P_g = \rho g \xi$
- Pressure in the fluid below the meniscus P_1*:

$$P_1* = P_1 + P_c$$

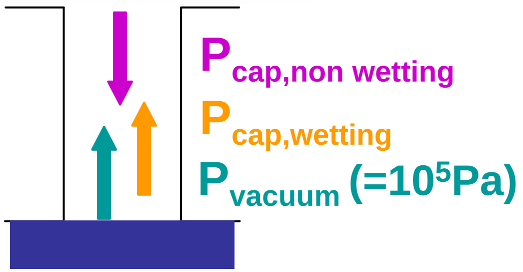
- **And** $P_c = -\dfrac{2\gamma\cos\theta}{r}$ (Laplace Equation), **so:**

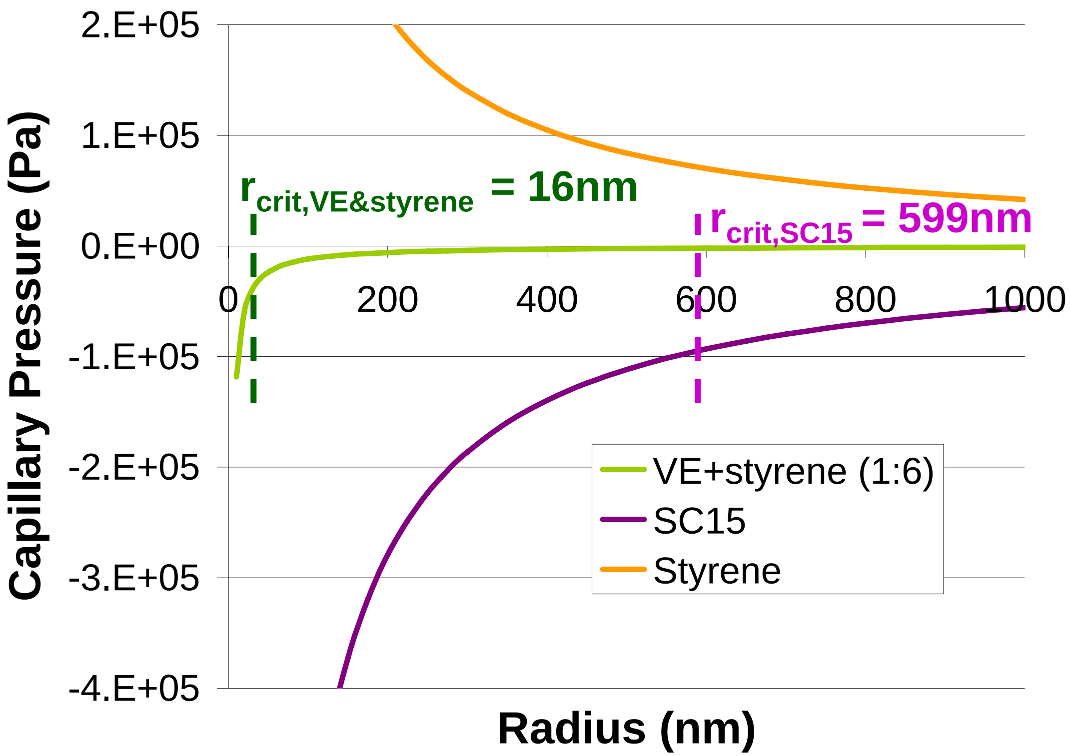
$$P_1* = P_1 - \frac{2\gamma\cos\theta}{r}$$

- **P_c: capillary pressure (Pa)**
- **γ: resin surface tension (N/m)**
- **θ: contact angle membrane/resin of interest**
- **r: pore radius (m)**
- **ρ: resin density (kg/m^3)**
- **g: gravitational acceleration (m/s^2)**
- **ξ: position of the flow front in the pore (m)**

Capillary pressure vs. nanoscale

•From the capillary pressure expression, interesting information about pore size vs. wetting characteristics can be provided





Wetting fluid ⇔ $\theta<90°$

⇒ $P_{cap}>0$ ⇒ Spontaneous wetting

NON-Wetting fluid ⇔ $\theta>90°$

If ∃ P_{vacuum}: Non-Wetting

⇔ $P_{cap}>P_{vacuum}$ or $r<r_{crit}$

$r_{crit,SC15}$ Critical radius for SC15

$r_{crit,VE}$ Critical radius for VE+Styrene

⇒ **Motivation for nanoporous materials**

Critical Time to go Through the Membrane

Darcy's law $$\dot{\xi} = \frac{K}{\eta}\frac{\Delta P^*}{\xi}$$

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

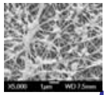
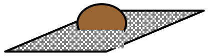
- The flow front position of the resin into the pore is given by <u>integration</u> of the flow front velocity
  - **As a result:** $$\xi = \sqrt{\frac{2t}{\eta}\frac{\varepsilon^3}{k\tau^2 S^{*2}}\left[\Delta P + \frac{2\gamma\cos\theta}{r} - P_g\right]}$$
- Time for t… membrane:
  - **Model** $$t = \frac{h^2}{\frac{2}{5}\frac{\varepsilon^3}{\eta S^{*2}}\left[\Delta P + \frac{2\gamma\cos\theta}{r} - P_g\right]}$$

Vacuum pressure applied during VARTM

Capillary effect

Gravity effect

Case Study of Membrane/Resin Interactions

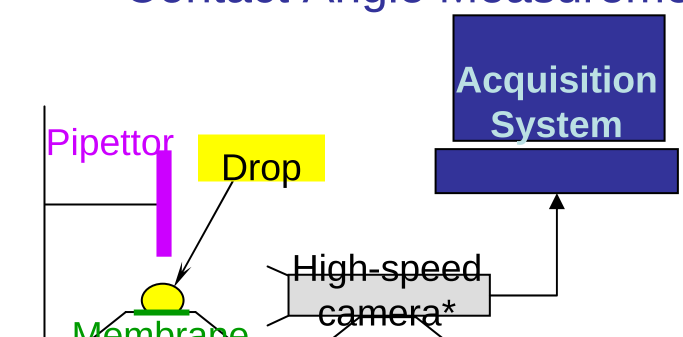
- 2 Systems
  - 1 membrane provided by W. L. Gore and Associates GmbH
  - 2 resins: 1 vinyl-ester and 1 epoxy
- Membrane characterization 
  - Porosity : weight and volume measurements $\Rightarrow \varepsilon_{vol} = 85.7 \pm 0.2$ %
  - Pore size : porometry $\Rightarrow$ mean flow pore diameter d = 130.5 $\pm$ 5.7nm
- Resins' characterization 
  - Density : from manufacturers
  - Viscosity : viscometer
  - Surface tension : dynamic contact angle apparatus
- Membrane/Resin characterization 
  - Contact angle : sessile drop/high-speed camera

Overview of Model Input

- Density, viscosity and surface tension of both resin systems:

Fluids	Density (kg/m³)	Viscosity (cP)	Surface tension (N/m)
Source	***From manufacturer***	***Measured***	***Measured***
Vinyl-ester resin system	**1024**	**106 ± 3.7**	**$3.39x10^{-2}$ ± $1.8x10^{-4}$**
Epoxy resin system	**1198**	**183 ± 4.8**	**$3.7x10^{-2}$ ± $2x10^{-4}$**

- Contact Angle Measurements:



*30-250 frames/s (max: 100.000) - 1024x1024 pixels

SC15 Part A

θ = 139º

VE411-350 + Styrene 1:6

θ = 91º

Evaluation of Capillary Effect and Gravity

- Evaluation of the different contributions
  - Vacuum pressure: $\Delta P = 98 \times 10^3 \pm 0.6 \times 10^3$ Pa
  - Capillary pressure: $$P_c = -\frac{2\gamma \cos\theta}{r}$$
  - Gravity effect: $$P_g = \rho g \xi$$

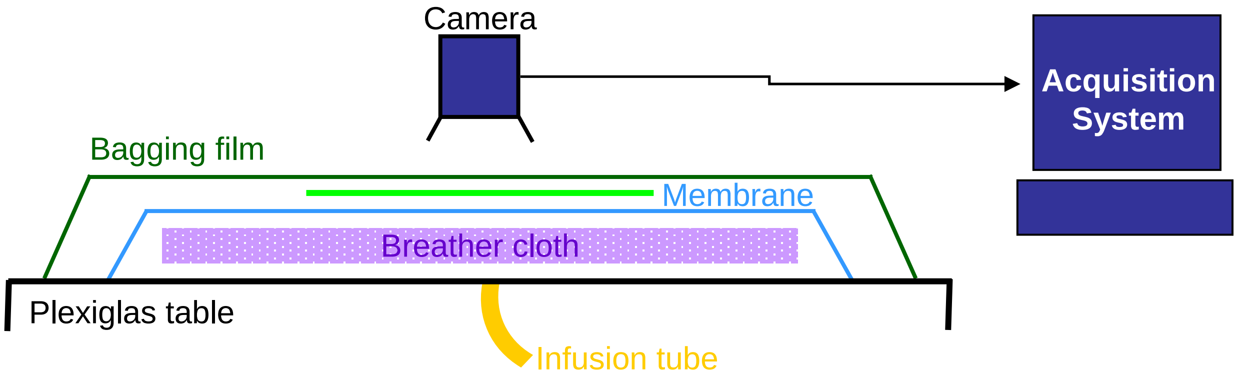
Fluids	**P_g (Pa)**	**$\lvert P_c \rvert$ (Pa)**
Epoxy resin system	**0.588**	**8.30×10^5**
Vinyl-ester resin system	**0.502**	**1.76×10^4**

$\Rightarrow$ The gravity term can be neglected

Experimental time to go through the membrane

- Setup
  - Central injection line
  - CCD (Charge-Coupled Device) camera to capture the wetting of the membrane

Paper to detect the flow of resin through membrane and create a strong contrast



Resin System	Reminder: gel time	Experimental	Model
VE + Styrene (1:6)	**30 minutes**	**11s ±30% ⇒INCOMpatible**	**1.7s (from 0.4s to 4s) ⇒ INCOMpatible**
SC15	**7 hours**	**About 10h ⇒ COMpatible**	**No impregnation ⇒ COMpatible**

Conclusions – Ongoing work

- A model based on:
  - Classical transport through porous medium
  - And surface science
- was built to address the issue of membrane/resin interactions

⇒ The model captures the predominant transport mechanisms but still needs refinement

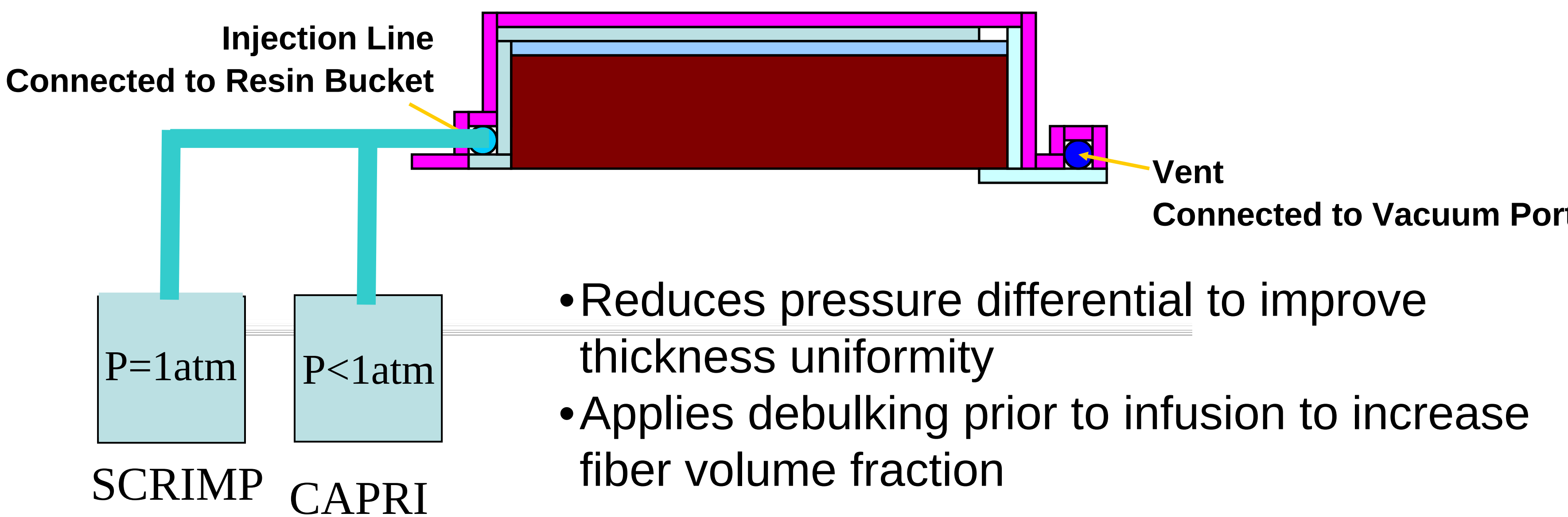
Ongoing work

- Model
  - Use the final model of resin transport through membrane to identify the critical parameters of membrane and resin
- Design a membrane
  - Create a design chart, which gives the adequate membrane for a specific resin system
  - Validate the design chart with various membranes
- Optimize membrane for toughened epoxies

Successful Membrane Research

- PhD Student (Solange Amouroux) won numerous awards including
  - R. L. McCullough Scholars Award, May 2006
  - Winner of the Student symposium at the 2006 Long Beach SAMPE Conference and Exhibition
  - 3rd place in the Student symposium at the 2005 Long Beach SAMPE Conference and Exhibition
- Technology highlighted in the JEC and SAMPE journal
- Following companies have shown interest in the membrane research:

Controlled Atmospheric Resin Infusion Process (CAPRI)

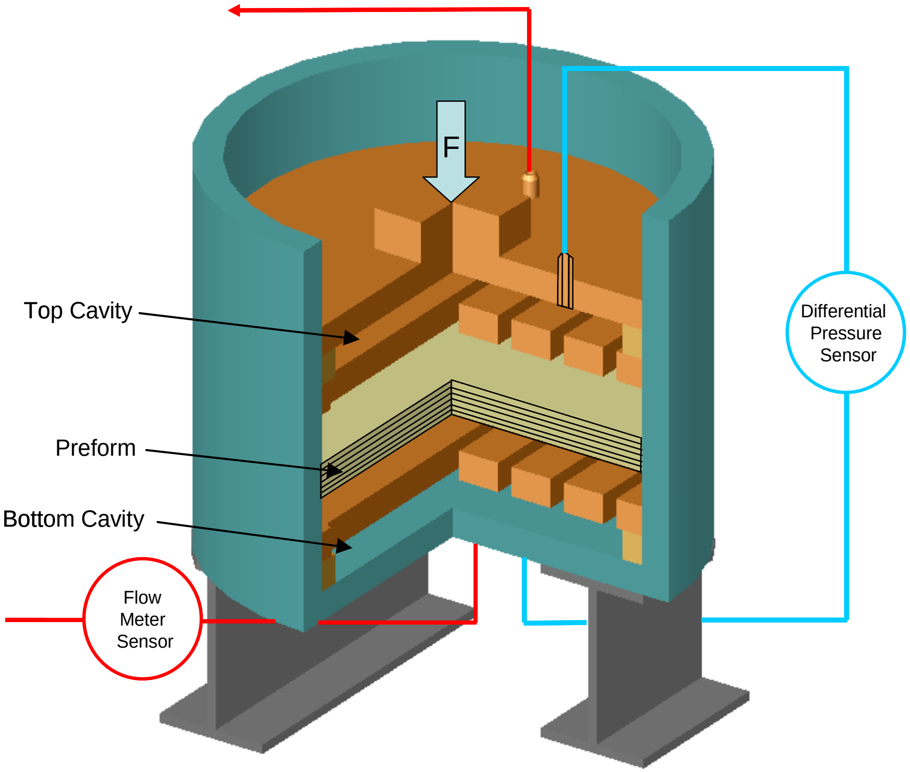


- Reduces pressure differential to improve thickness uniformity
- Applies debulking prior to infusion to increase fiber volume fraction

Approach:

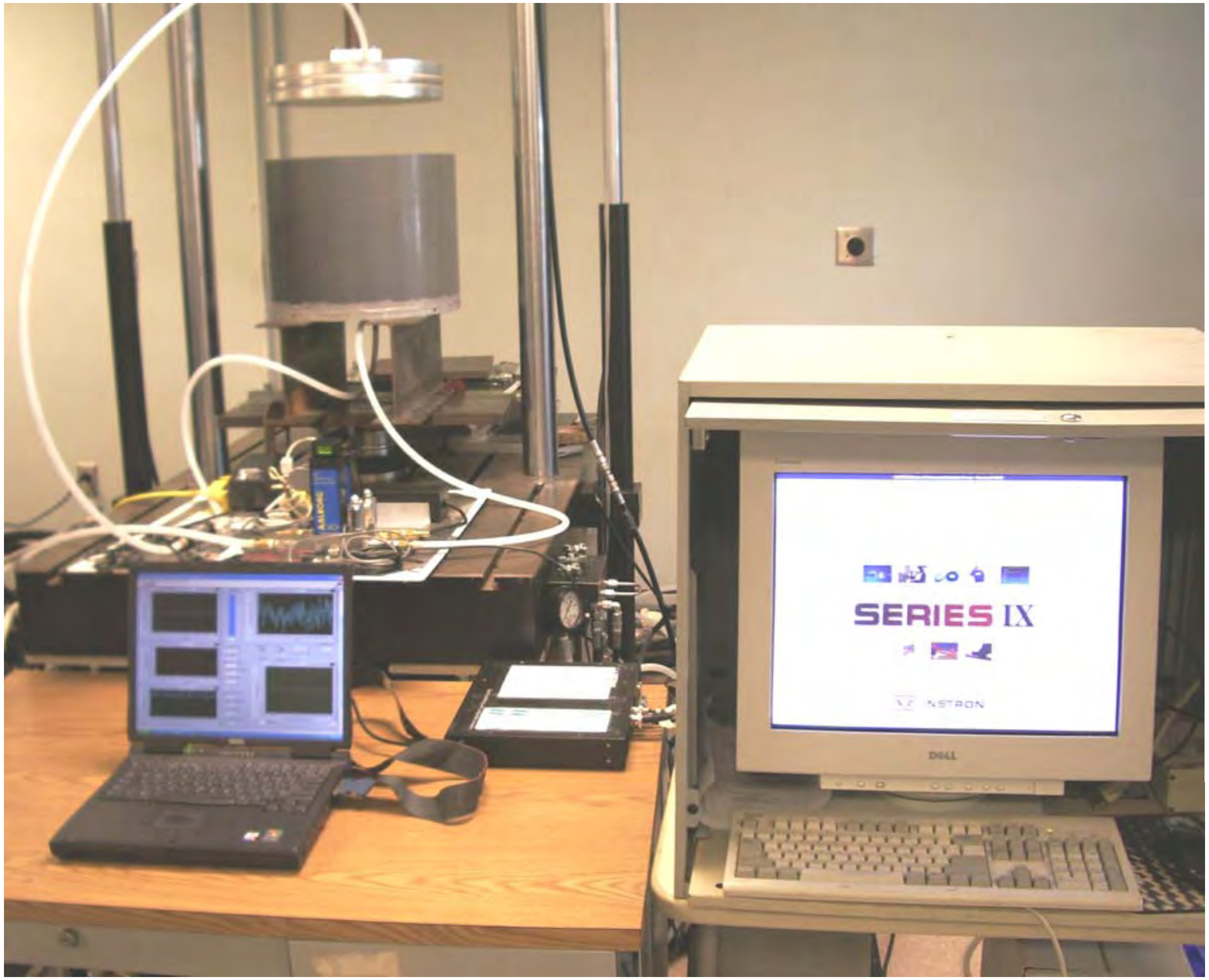
- Develop instrumentation to characterize compaction behavior and permeability as a function of compaction pressure and debulking cycle
- Conduct model experiments to evaluate process and use existing models to predict flow and thickness changes

Design of the Permeability Measurement Work Cell (PermCell)



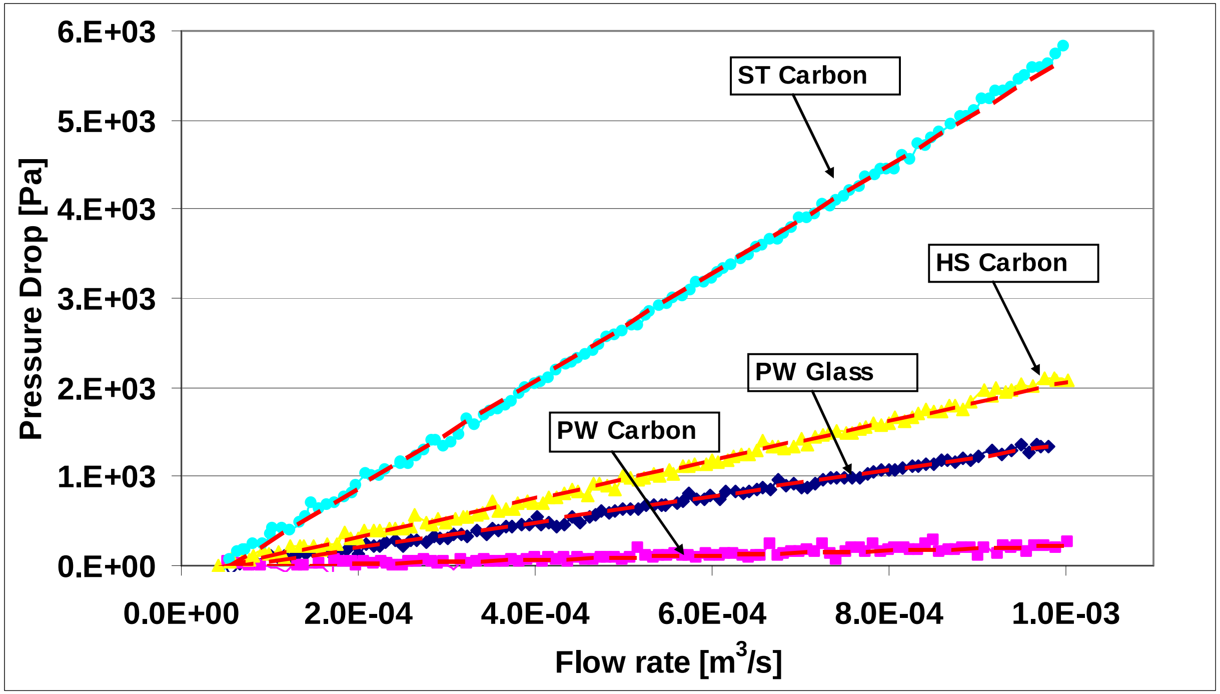
- Benefits of the PermCell
  - Rapid, clean and easy method to obtain permeability
  - Permeability can be obtained online as a function of compaction, fiber volume fraction and debulking cycle
  - Measurement Cell is capable for use of **gas** well as **liquid flow**
  - Dimension (14.5 inch diameter) minimizes errors from boundary effects

Experimental Set-Up



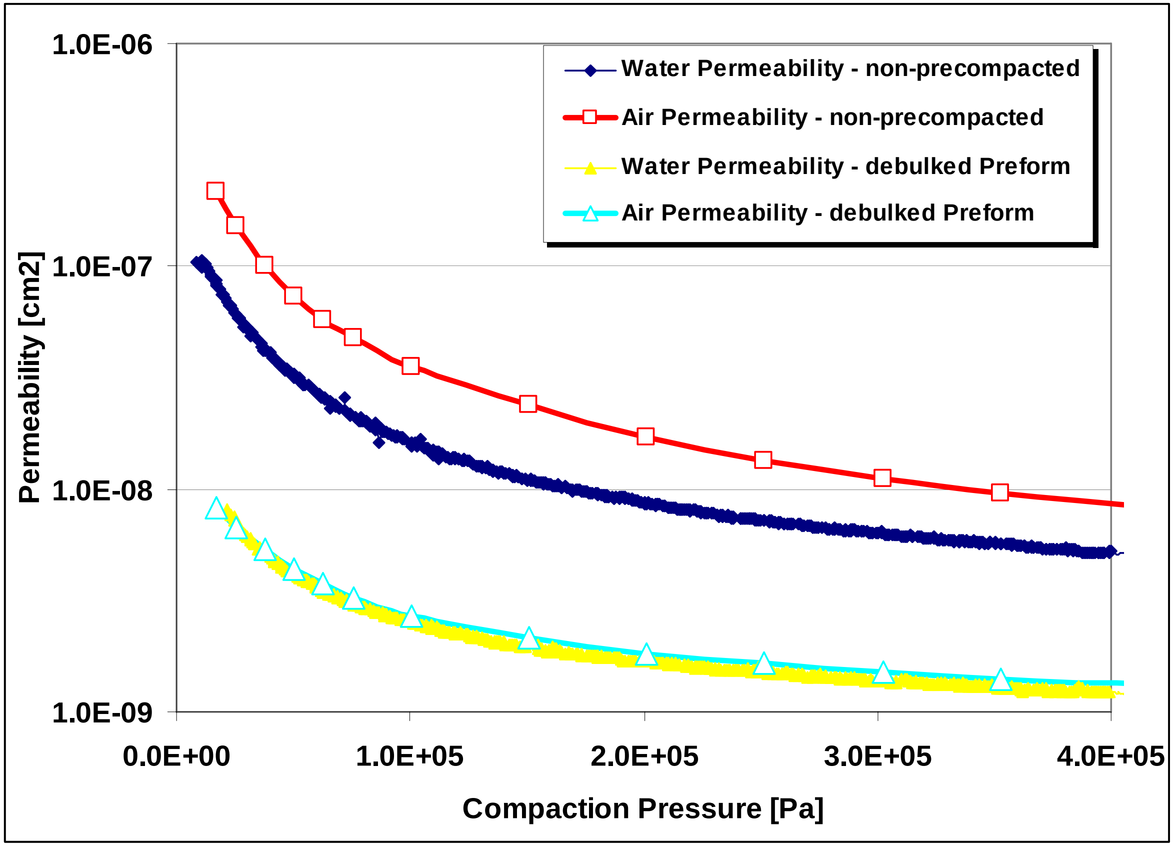
Validation of Darcy's Law

Measured Pressure Drop against increasing Flow Rate



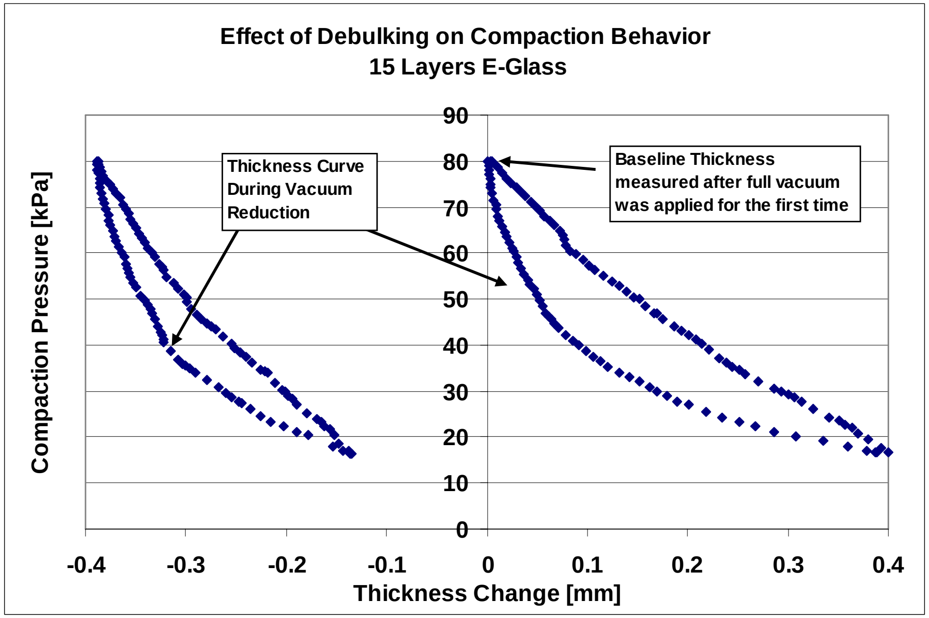
$\Delta P \sim Q$ → 1D-Darcy's Law can be applied → $v = \frac{Q}{A} = -K \frac{\Delta P}{\eta \cdot h}$

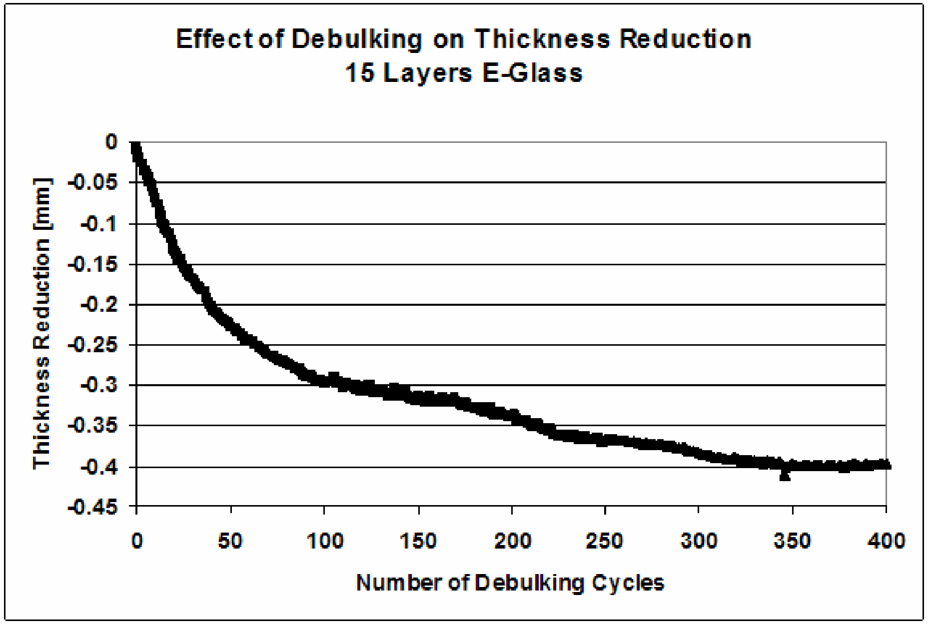
Water versus Air Permeability



- Water permeability is slightly lower compared to air permeability
  - Lubrication may allow add. sliding during infusion
- After debulking the permeability is reduced and identical

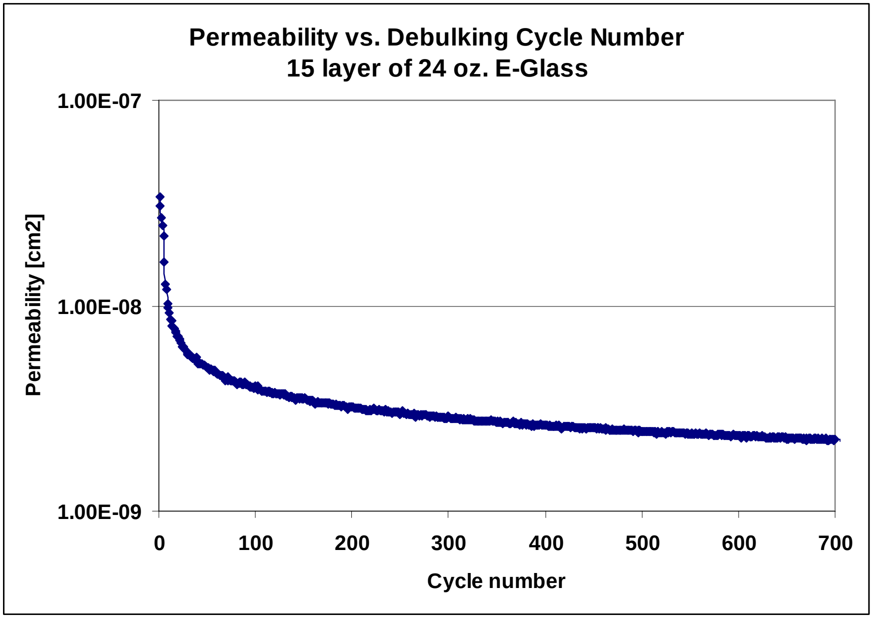
Effect of Debulking on Thickness and Fiber Volume Fraction

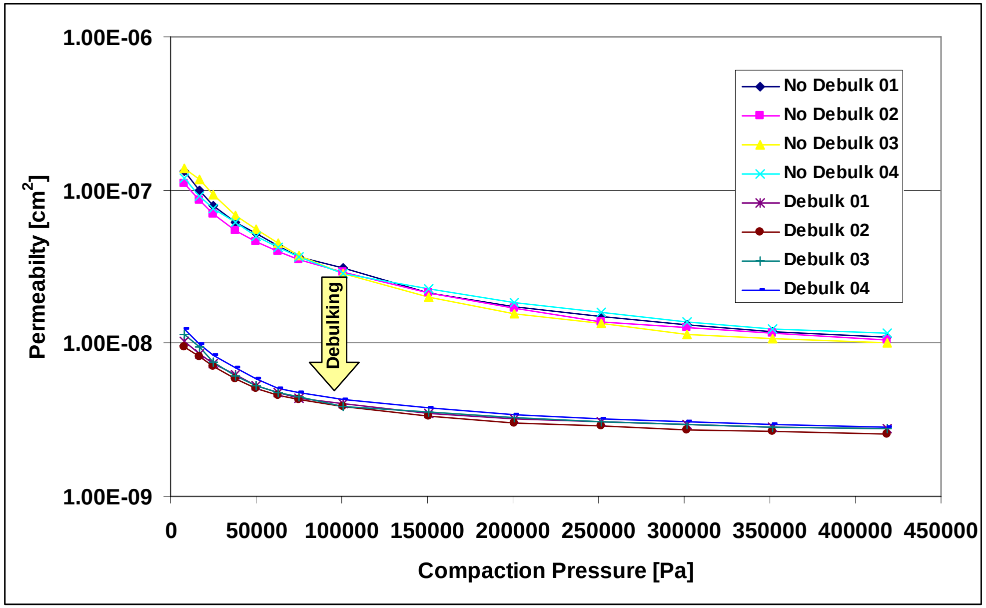




- The thickness and spring-back behavior is greatly reduced during debulking
  - Increases Fv
  - Reduces thickness gradient

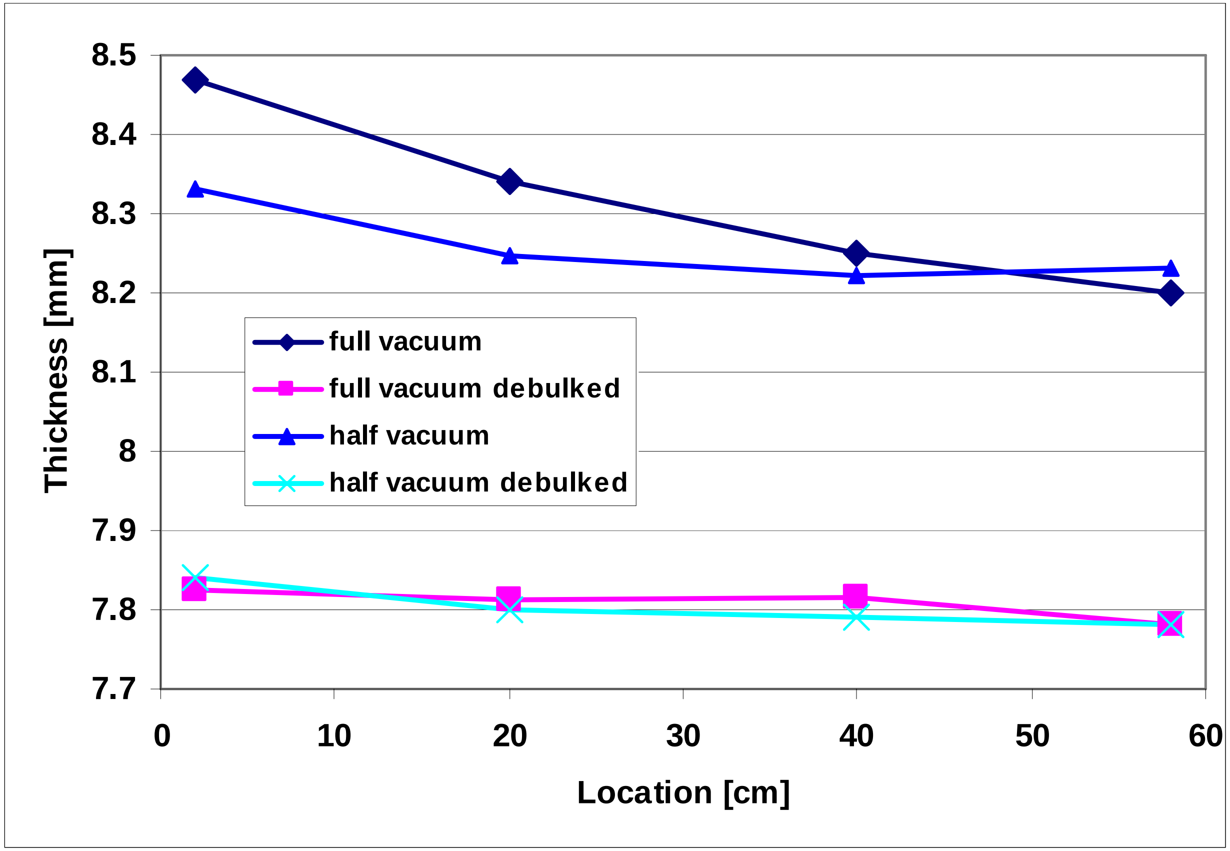
Effect of Debulking on Permeability





- Debulking also reduces the permeability (up to a factor of 10 times) and thus flow behavior

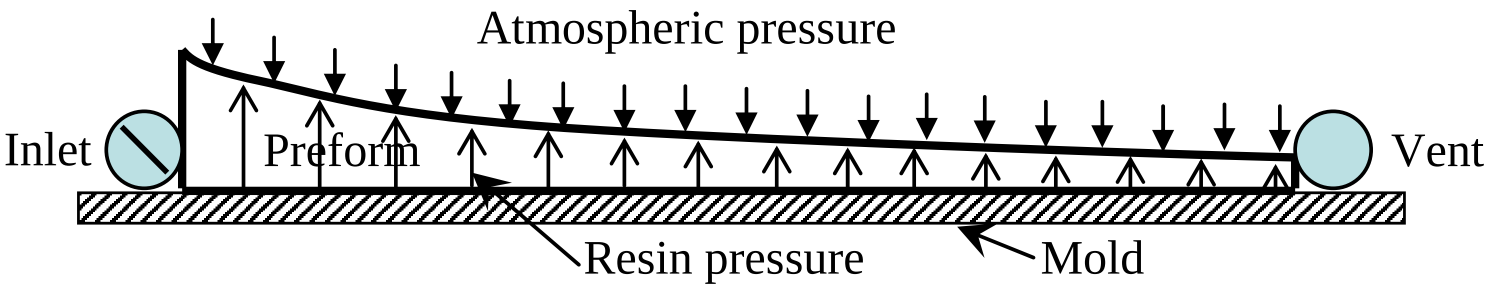
Thickness Behavior Comparison between CAPRI and SCRIMP



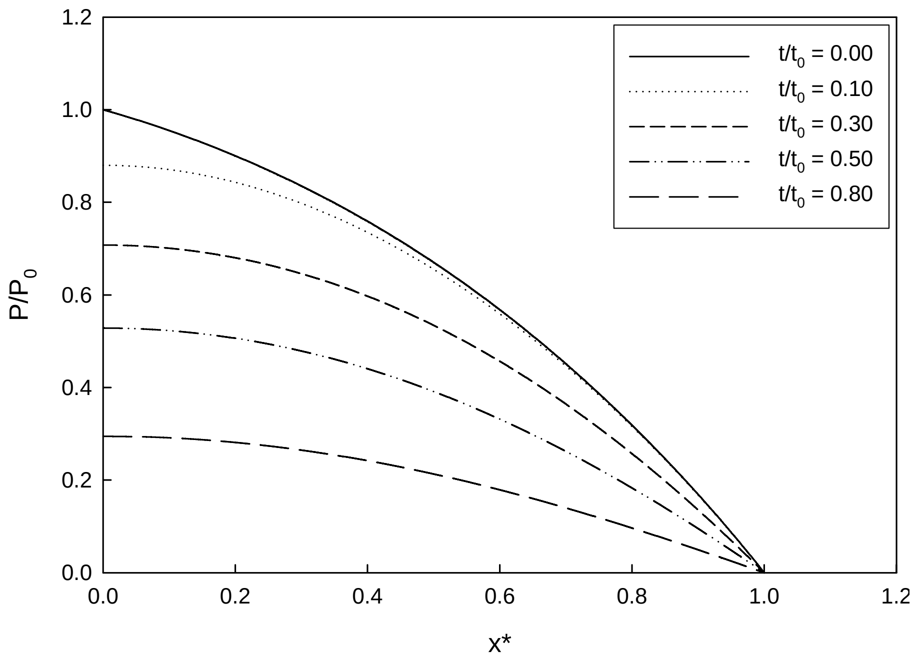
- Debulking can greatly increase final fiber volume fraction
- The thickness gradient is reduced when the CAPRI pressure is applied (insignificant for the debulked case)

Model to Predict Thickness Variation

- Considers infusion and resin bleeding behavior
- Requires compaction and permeability behavior of fabric
- Provides anticipated thickness after infusion and during resin bleeding

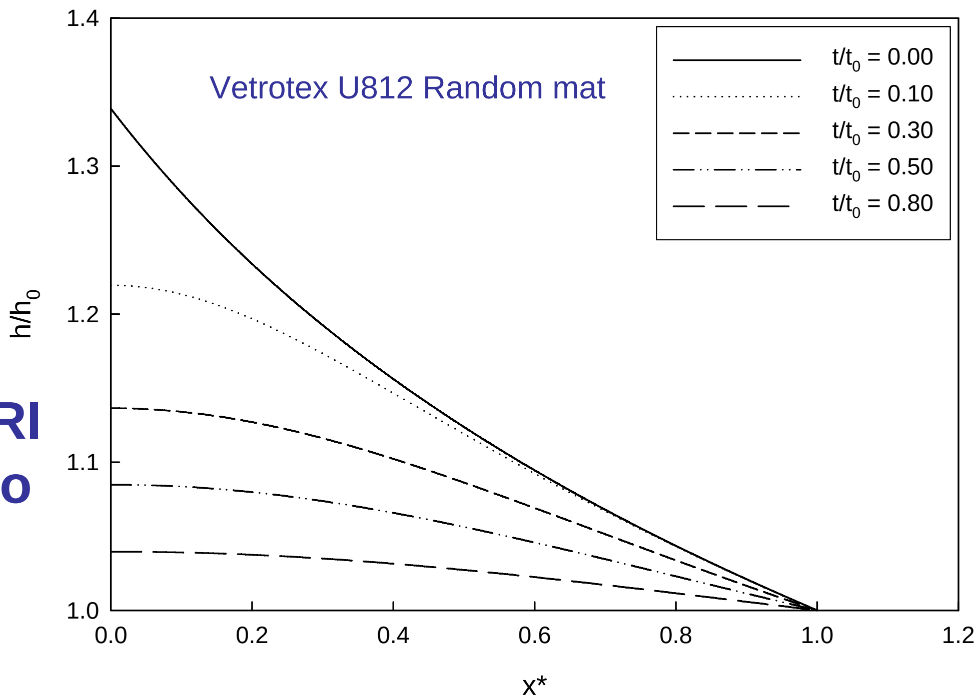


Thickness Field During Typical SCRIMP Processing

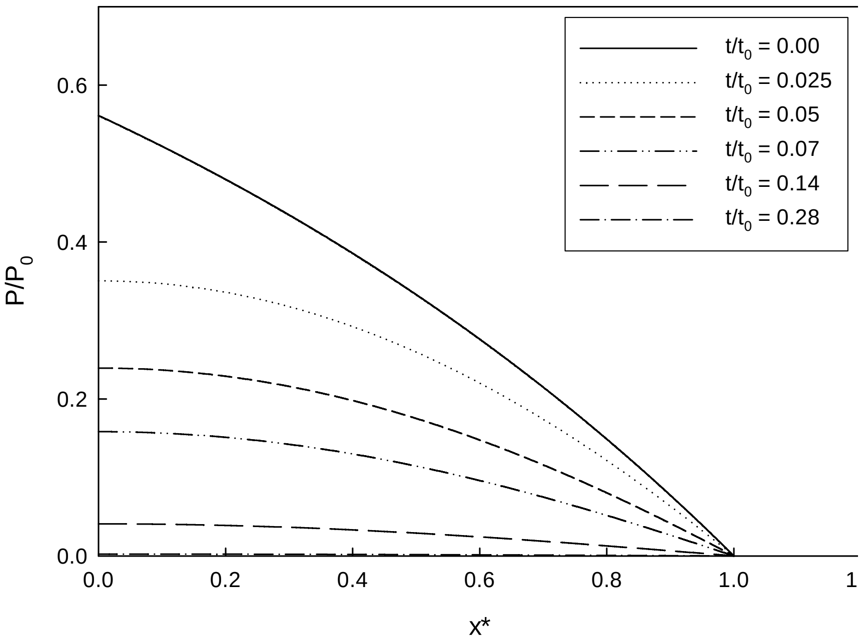


- **Model can be used to predict thickness and pressure variation during and after infusion**

- **It can be used to optimize CAPRI pressure and gel time of resin to minimize thickness gradient**



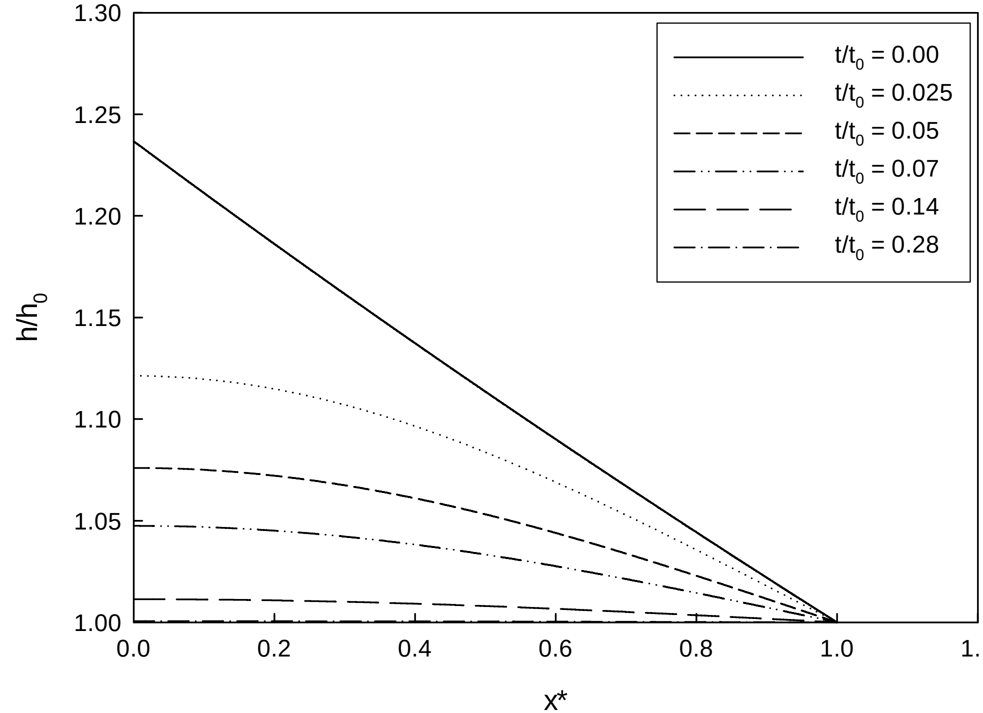
Thickness Field During CAPRI Processing



CAPRI Process

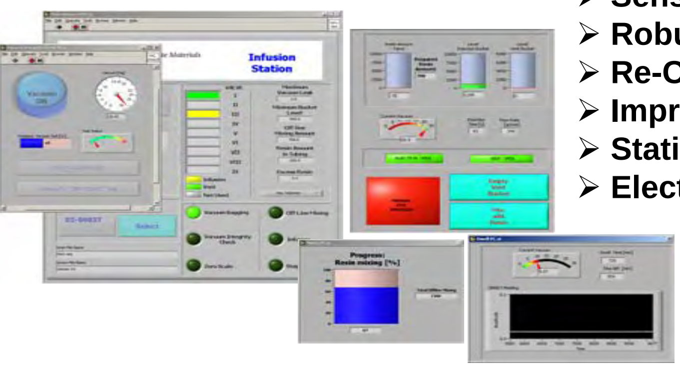
➔ **This resulted in 30% reduction in thickness gradient directly after infusion**

➔ **The resin bleeding time reduced by 80% to obtain a 5% thickness gradient**

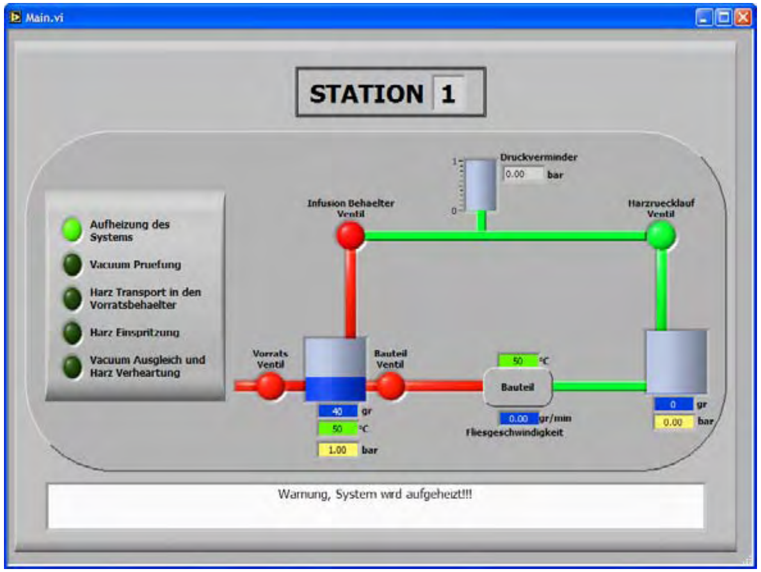


- **The infusion bucket was evacuated to 0.5atm (CAPRI pressure)**

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



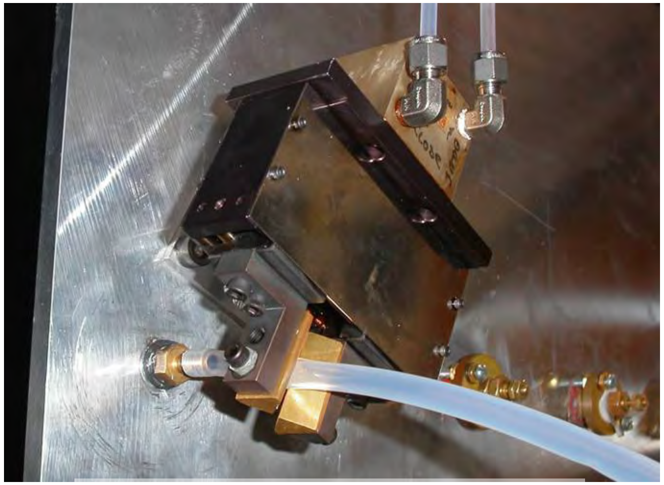
ELEVATED PROCESSING REQ

- Heated External Resin Supply
- Heated Tooling
- Adapt IPC capabilities to elevated temperature processing

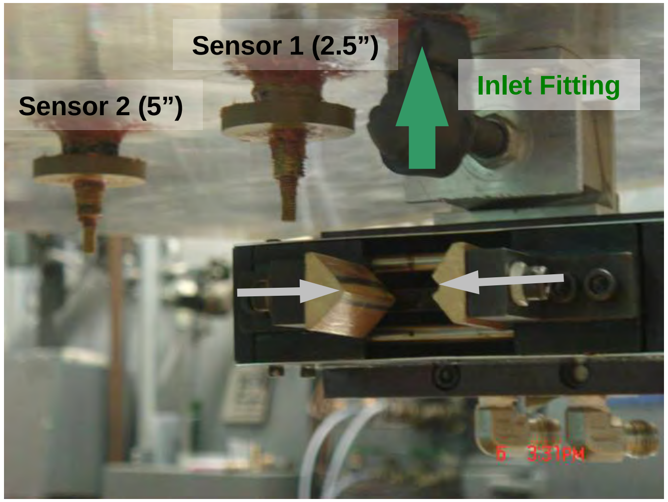
CONSIDER TWO AEROSPACE TOUGHENED EPOXY SYSTEMS

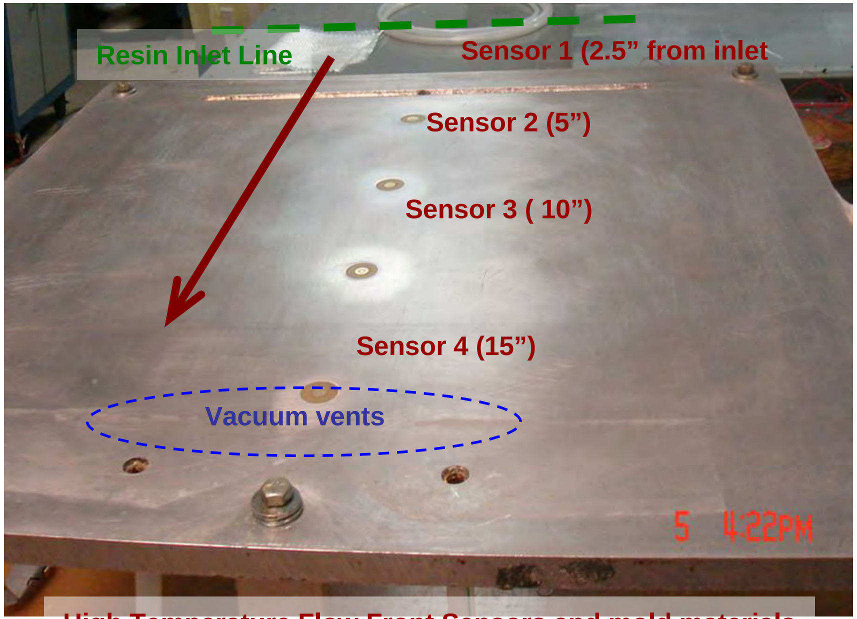
- **Cytec Epoxy Cycom 977-20**
  - **Viscosity = 120 cps @ 167°F**
  - **Ramp with 4°F/min to 355 cure for 3 hours, cool to 140°F @ 5°F/min**
  - **Cured Resin Density = 1.31g/cm^2**
  - **Tg = 212°C**
- **Hexcel Epoxy RTM 6**
  - **Viscosity = 180 cps @ 177°F / 40 cps @ 248°F**
  - **Ramp with 5°F/min to 320 °F, cure for 75 minutes**
  - **Cured Density = 1.14g/cm^2**
  - **Tg = 183°C (Hexcel Datasheet)**

Elevated VARTM Requires New Grippers and Sensors



Pneumatic High Temperature Gripper

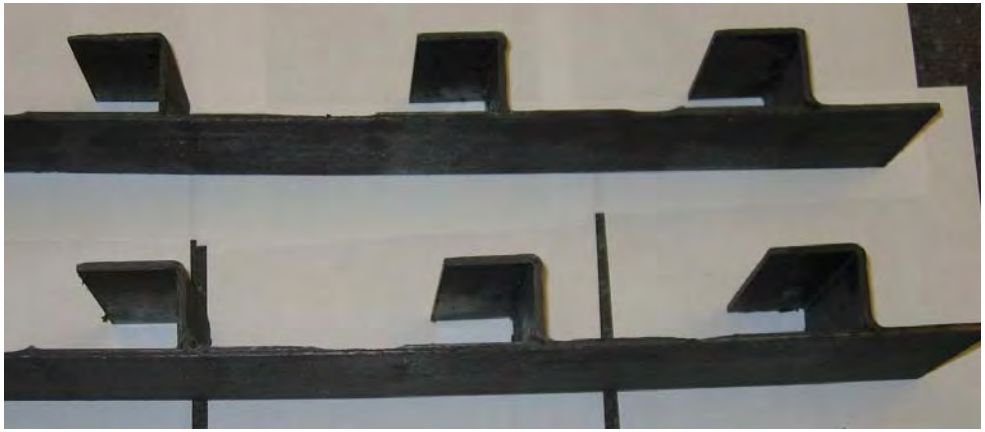




High Temperature Flow Front Sensors and mold materials

Component Fabrication

- Consistent fiber volume fraction of > 56% is achievable
  - AS4-GP-6K-5HS 377g/m^2 carbon fabric
  - Higher performance fibers are being considered
- Void Content below 1%
- Unitized structures can be fabricated
  - Stiffened Structures
  - Cored Structures
- Automation has been implemented



Develop Property Database

- Compare various processes
  - Fiber Volume Fraction
  - Void Content
  - Dimensional Tolerances
- Structural
  - Tension, compression, bending
  - Damage tolerance
    - Open-hole compression
    - Compression after impact

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 fiber volume fraction
  - Investigate more complex geometries / unitized structures