VARTM Variability and Substantiation

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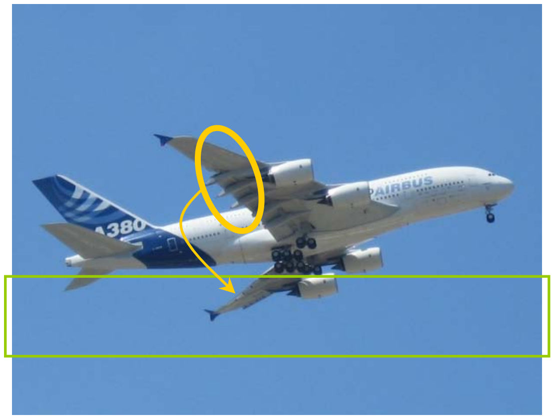
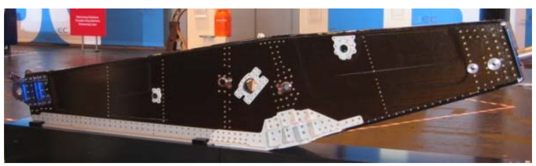
FAA Sponsored Project Information

- 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
  - Embraer (São José dos Campos, Brazil)
    - Provided technical input

AEROSPACE VARTM'D COMPONENTS

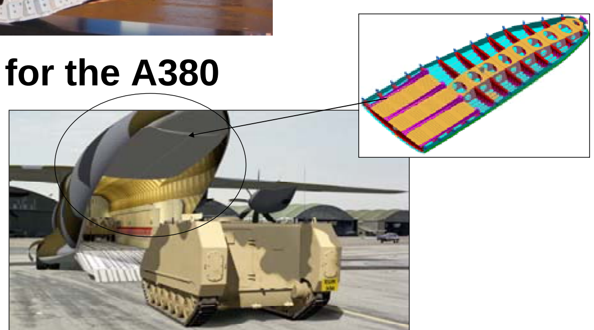




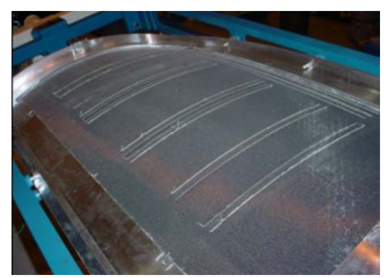
Flap tracks for the A380

Pressure Dome

CH-47 Chinook Forward Pylon



A400M CFC Cargo Door



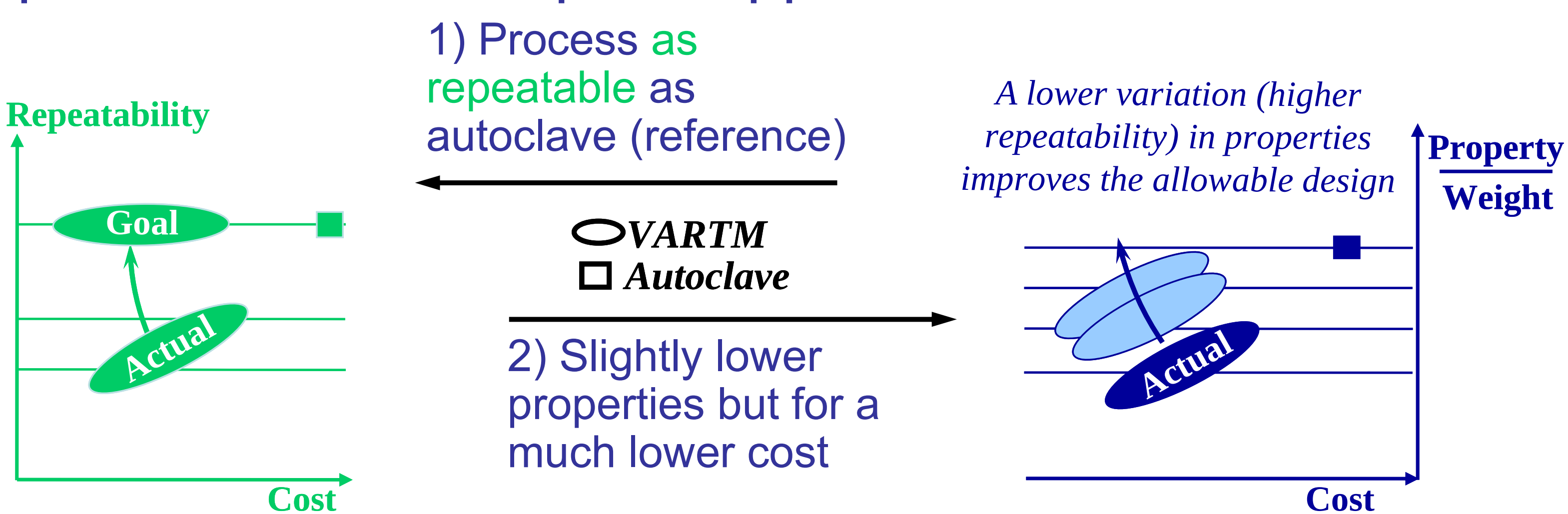
C-17 Main Landing Gear Door

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
    - 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:



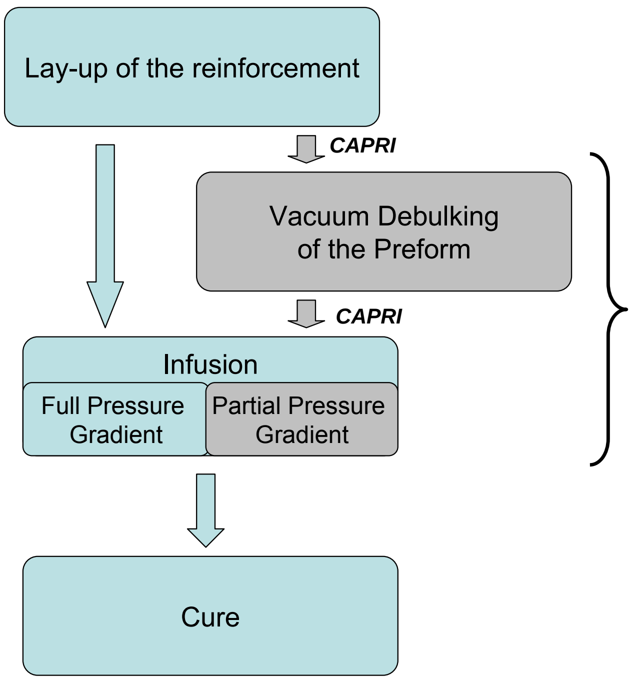
APPROACH

- Three VARTM processes will be evaluated on process repeatability, part quality, and mechanical performance
- Establish the fundamental understanding of the VAP process
- 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

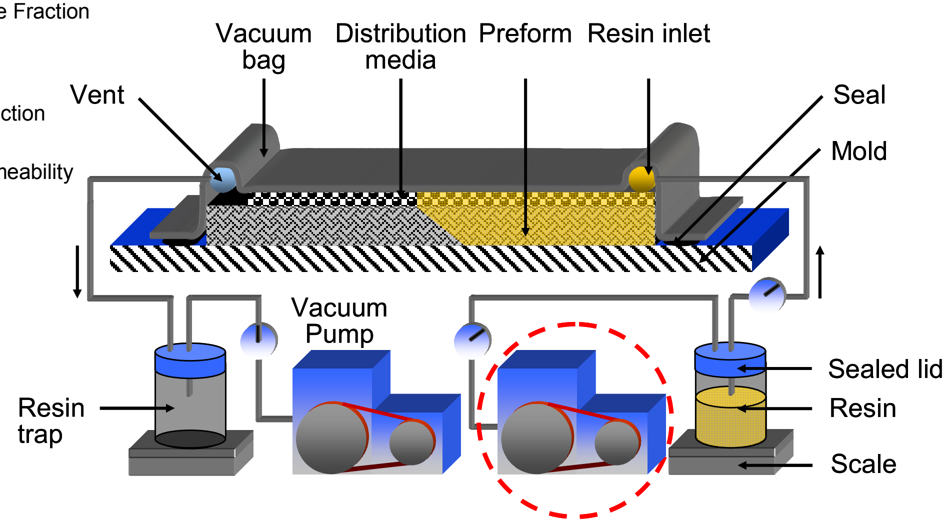
Process Variations: The CAPRI Process



- 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

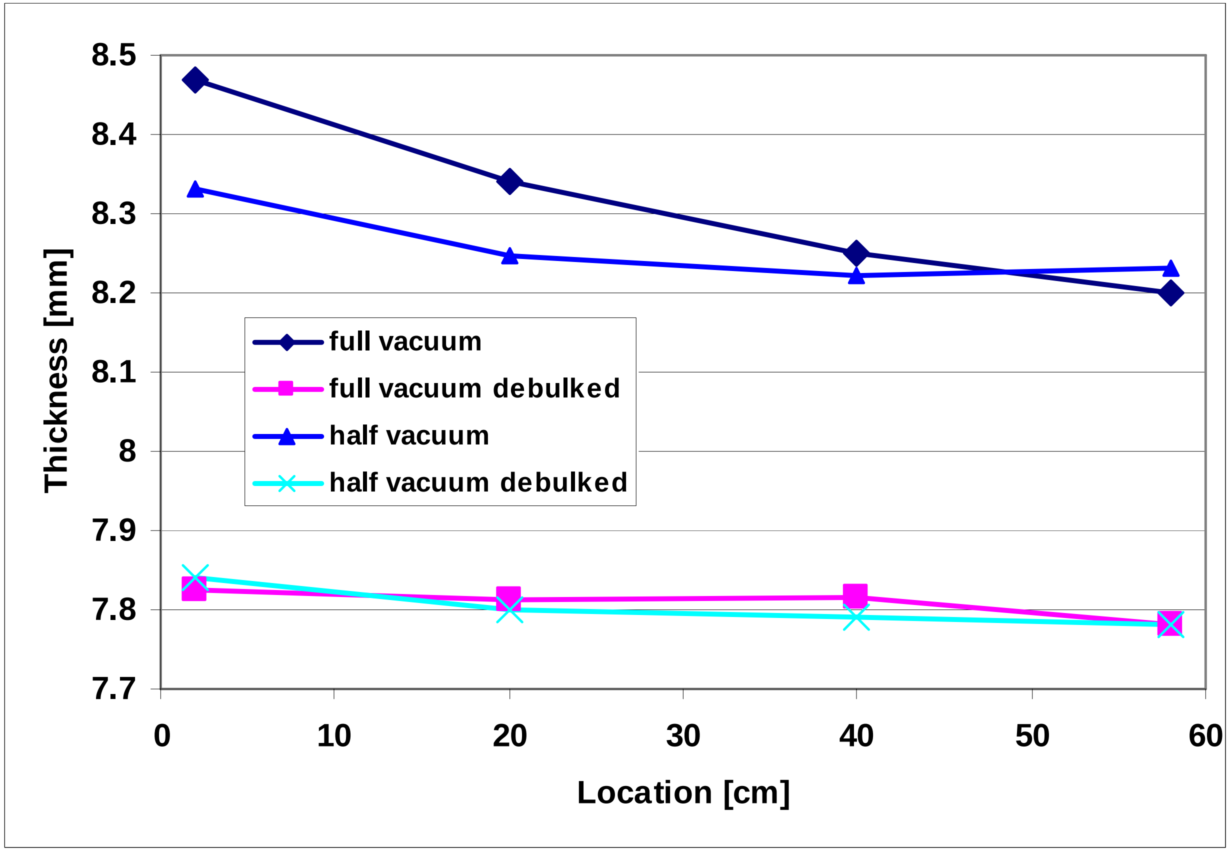
Disadvantages
- Decrease in fabric permeability
- Increase in flow times
- Increase in lead length



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.

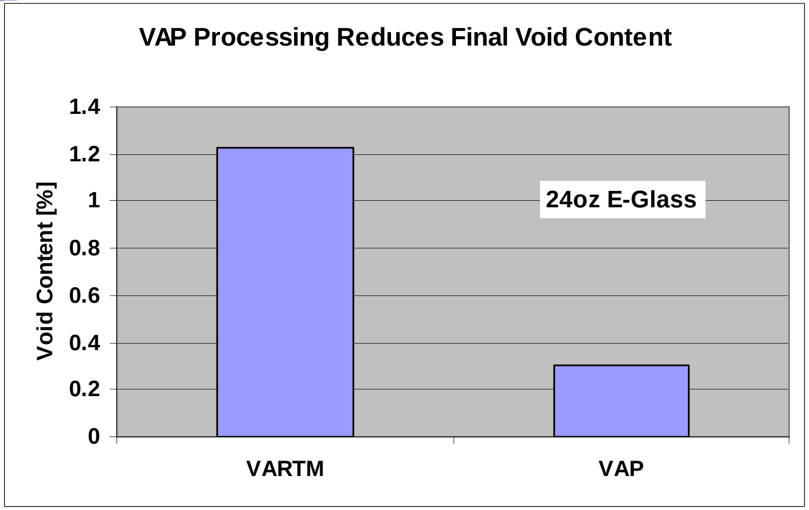
Thickness Behavior Comparison between CAPRI and SCRIMP

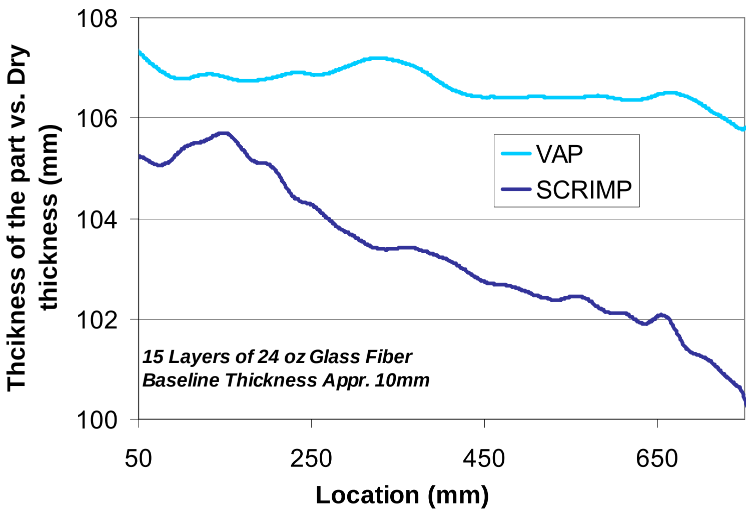


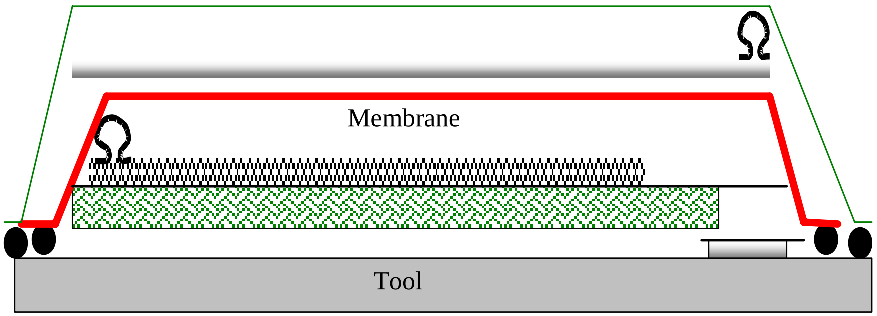
- Debulking can greatly increase final fiber volume fraction
- The thickness gradient is reduced when the CAPRI pressure is applied (insignificant for the debulked case)

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

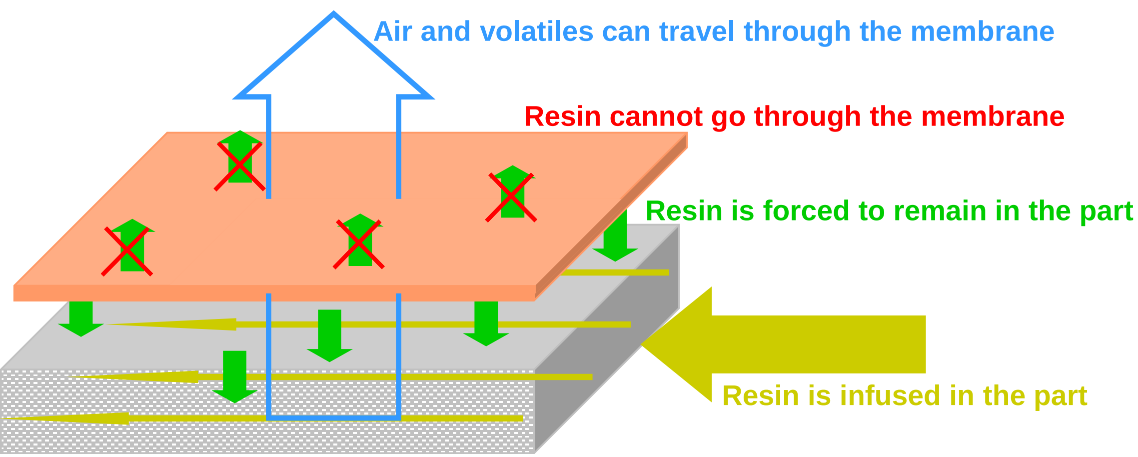


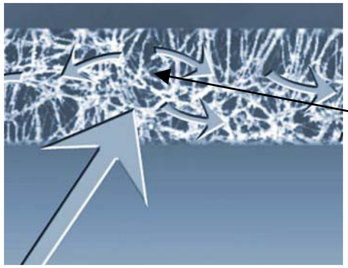




MAIN REQUIREMENTS OF THE MEMBRANE

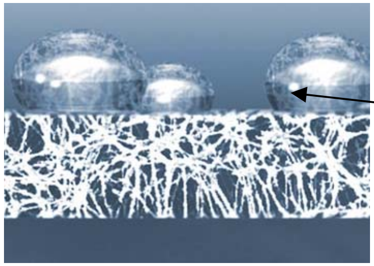
- Desirable Characteristics for a membrane used in VARTM:
  - Gas permeable material
    - OR High air permeability through the thickness
  - Resin-proof material
    - OR Low liquid/resin permeability through the thickness
- Compatibility with resin
  - Compatible: The resin does not go through the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





High air permeability

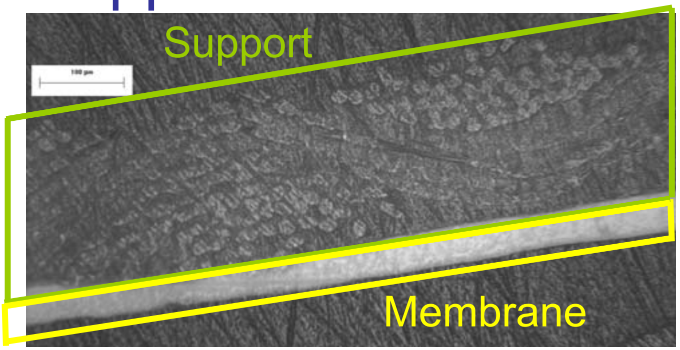
www.gore-tex.co.uk



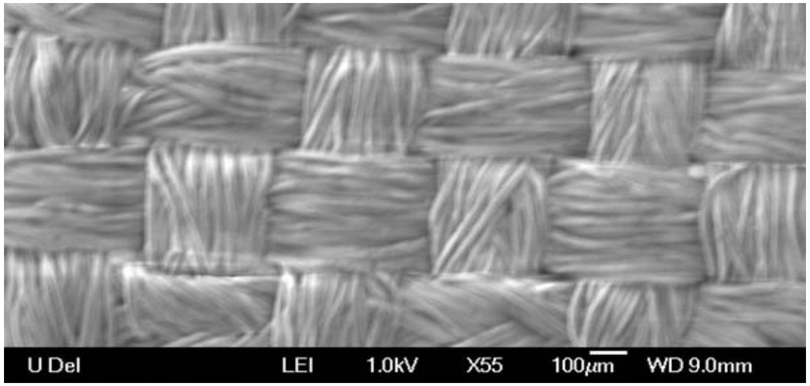
Low liquid permeability

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

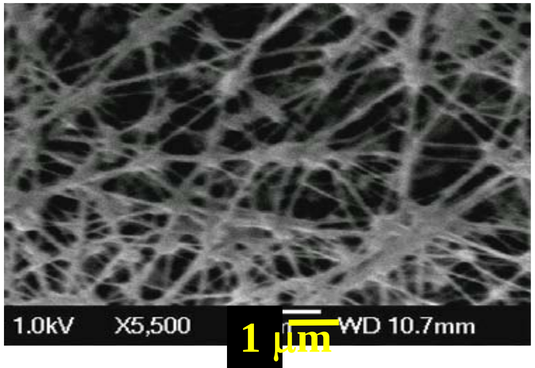
- Optical microscope
  - The membrane is mounted on a support



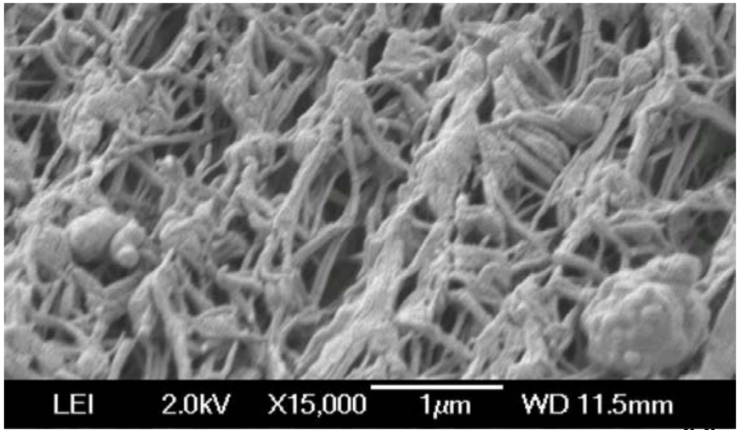
- SEM of the support



- SEM of the membrane
  - Top surface

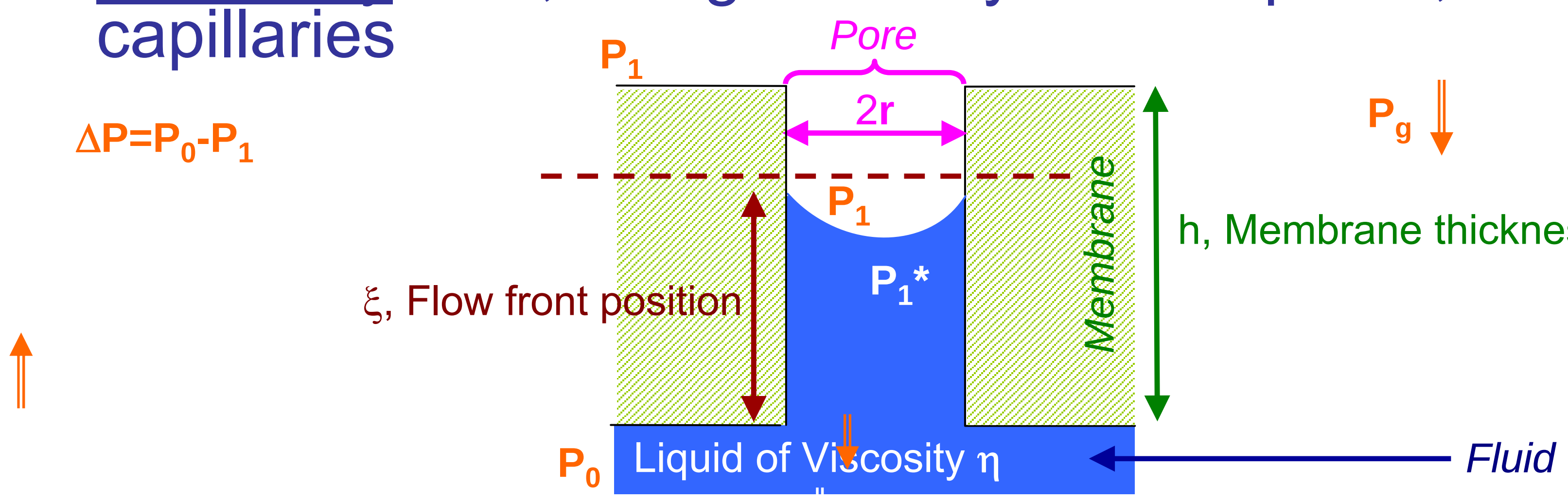


  - Cross-section



Modeling of Resin Transport Through Membrane

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



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

Building blocks the model

- $\dot{\xi}$: Flow front velocity (m/s)
- ξ : Position of the flow front in the pore (m)
- η : Viscosity of the liquid/resin (Pa.s)
- ε : Porosity of the membrane (%)
- k : Kozeny's constant, originally stated at 5.0
- τ : Tortuosity of the pores

τ = pore real length/membrane thickness

For a straight capillary: τ=1.0

- S* : Specific surface area

For a cylindrical capillary: S*=2/r

- P_0 : pressure below the membrane, created by a pump (Pa)
- P_g : pressure due to the gravity effect acting on the fluid in the pore (Pa)
- P_1 : pressure above the meniscus (Pa)
- γ : Resin surface tension (N/m)
- θ : Contact angle membrane/resin
- r : Pore radius (m)

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

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

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

vt for ξ=h

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

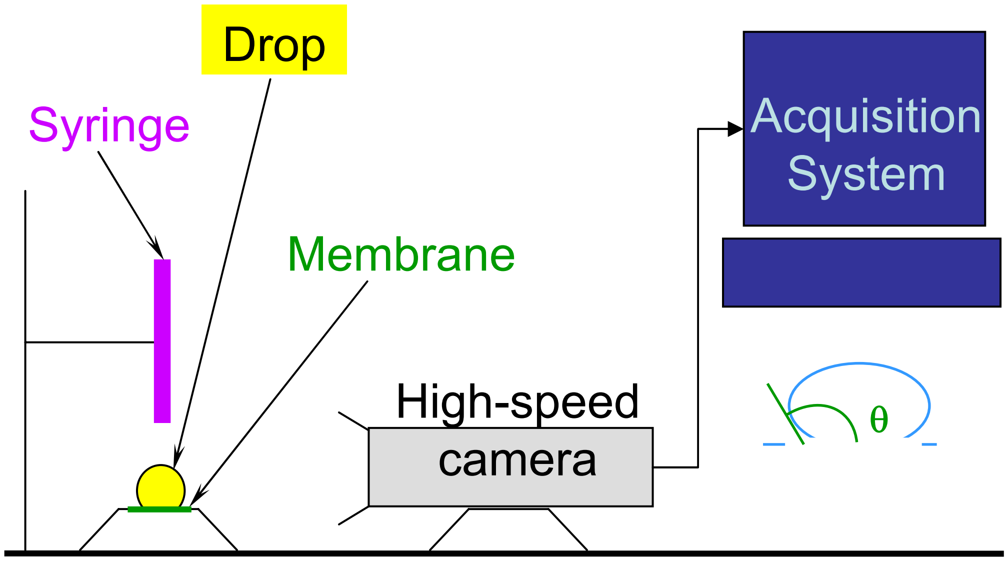
Materials' Characterization

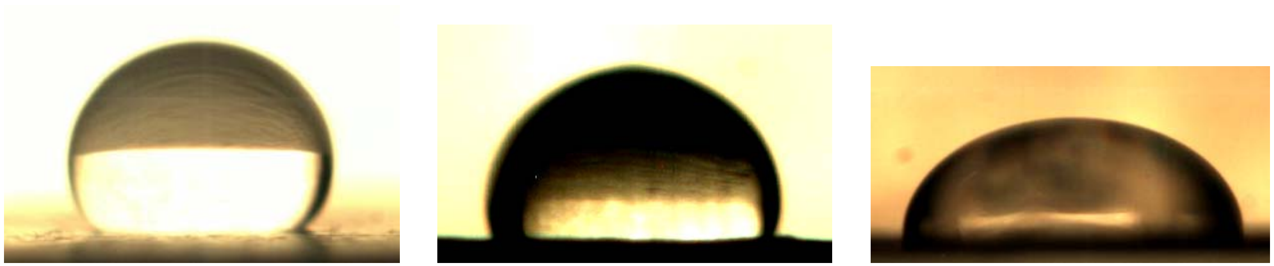
- Membrane's pore size distribution by Porometry
- Fluids' surface tension with the DCA
- Contact angle between fluids and the membrane using a sessile drop method

Fluids	Density (kg/m^3)	Viscosity (cP)	Surface tension (N/m)	Contact angle (°)
HPLC	1000	1	$7.2 \times 10^{-2} \pm 0.7 \times 10^{-4}$	$\theta = 118° \pm 5°$
Vinyl-ester resin system	1024	115 ± 15	$3.3 \times 10^{-2} \pm 0.7 \times 10^{-4}$	$\theta = 83° \pm 8°$
Epoxy resin system	1198	360 ± 7	$3.6 \times 10^{-2} \pm 1 \times 10^{-4}$	$\theta = 98° \pm 7°$

Contact Angle Measurements

- Set-up
  - High-speed camera
  - Speed: 30 frames/s
  - Resolution: 1500x1100 pixels
- 3 systems
  - HPLC water (1)
  - Epoxy SC15 (2)
  - VE411-350 (3)





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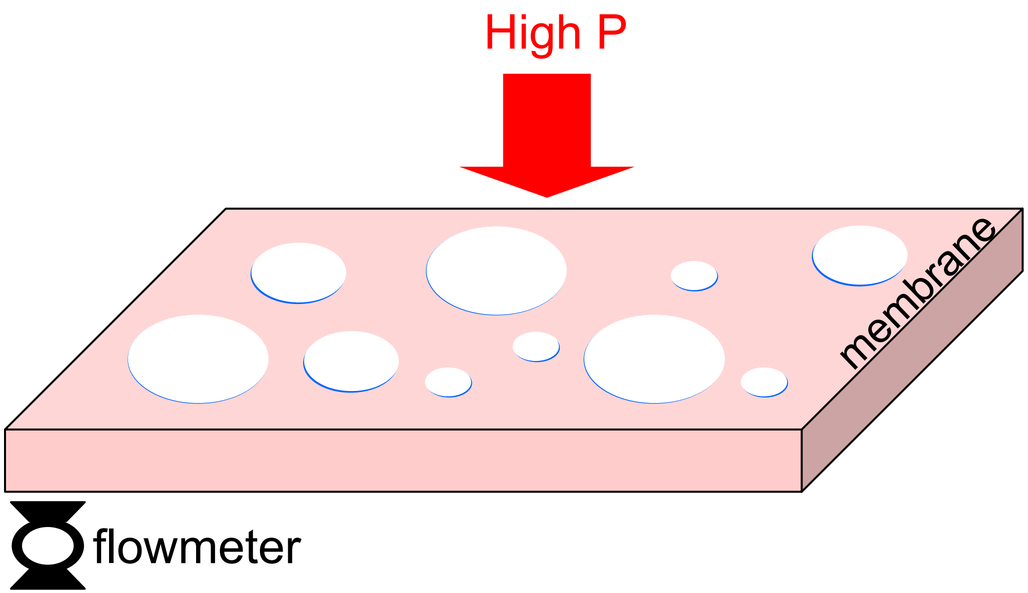
Capillary Porometry

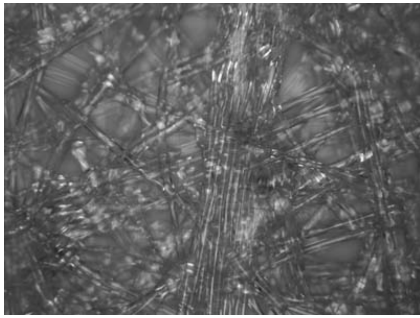
- Provides semi-quantitative data, difficult to obtain by optical means
  - Pore size distribution
  - Maximum pore size, mean flow pore size, minimum detectable pore size
- Measurements performed at W. L. Gore & Associates (Elkton, MD)

- Principle: the air flow is recorded as a function of pressure

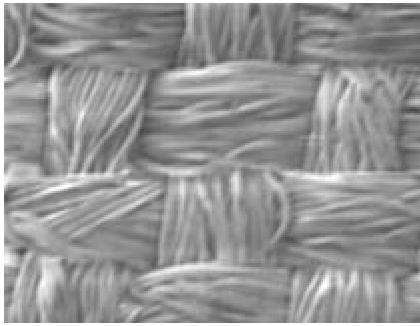


General characteristics

	Material of the membrane	Thickness	Bubble point		Mean Flow Pore	
		μm	Pore size (diam) (nm)		Pore size (diam) (nm)	
		Approximation	average	std dev	average	std dev
W1	ePTFE	50	**247**	6	**130**	6
WA	ePTFE	75	**606**	10	**255**	3
WB	ePTFE	30	**469**	4	**221**	6
WC	ePTFE	7	**337**	13	**188**	8
D6501	ePTFE	230	**351**	15	**150**	1.1
D6504	ePTFE	200	**219**	13	**101**	2.4
D1302	ePTFE	250?	**566**	19	**256**	10



Support of the Donaldson membrane

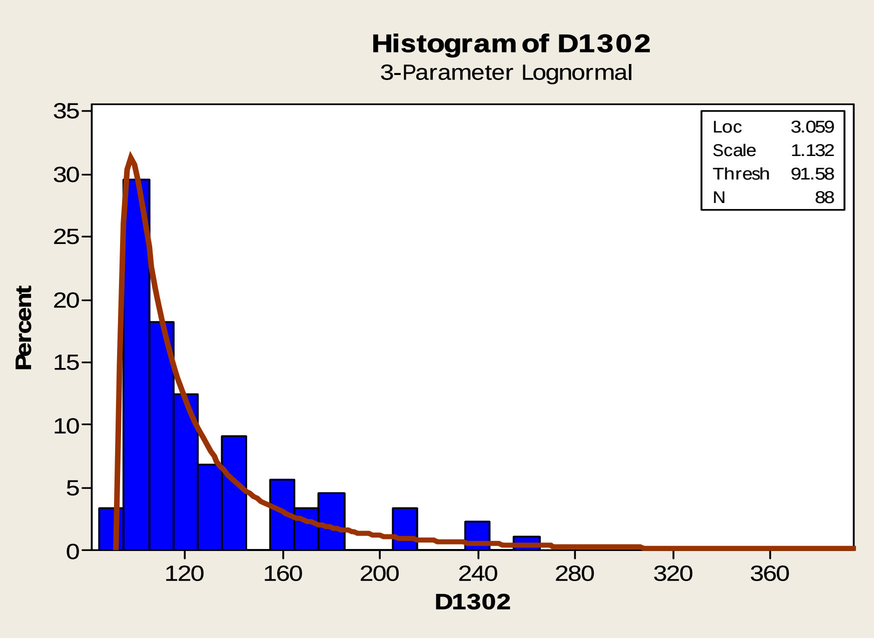


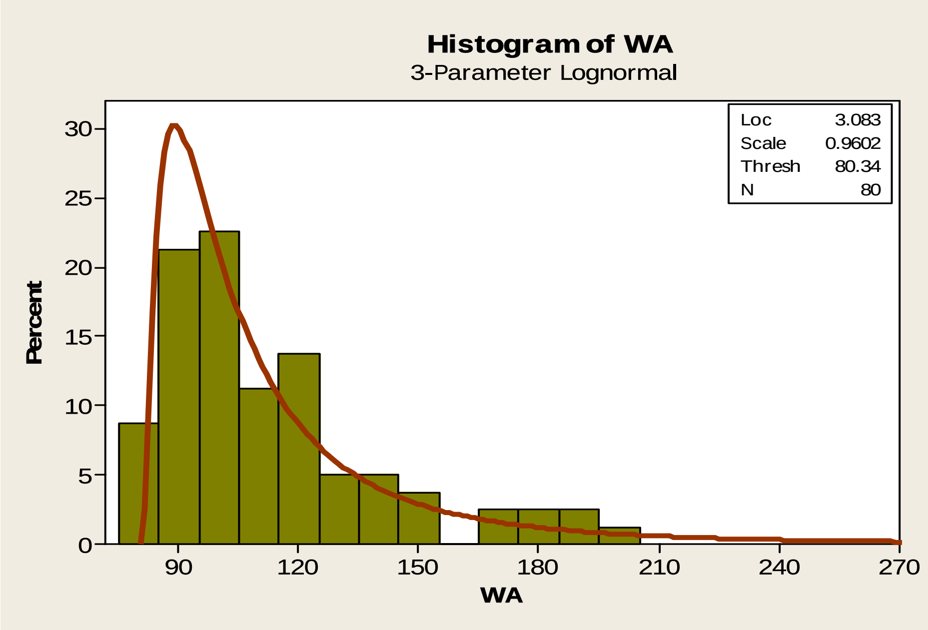
Support of the membrane by W. L. Gore and Associates

- Three membranes from Gore
- Two membranes from Donaldson

Pore size distribution

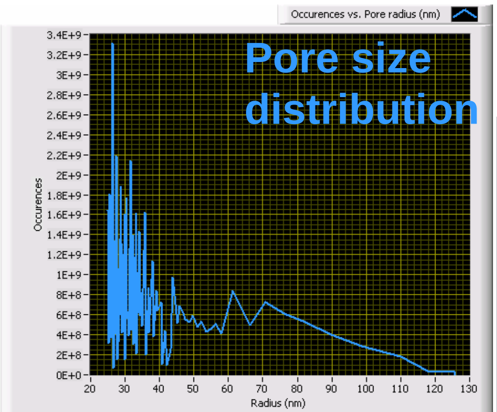
- The pore size distributions of the different membranes seem to match a 3-parameters lognormal fit; this finding will be used at the end of the project to provide membrane's users with guidelines, which correlate porometry data with membrane performance
- Examples with D1302 and WA



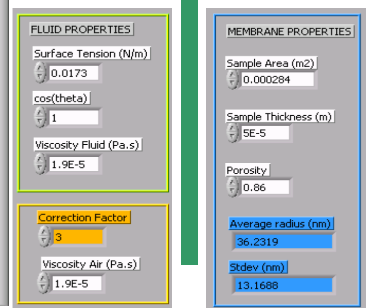


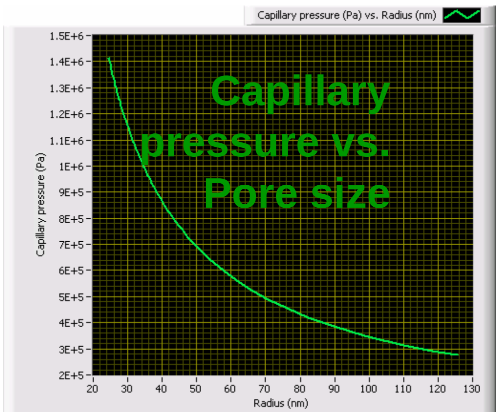
Membrane Flow and Permeability Simulation

Porometry data



Resin properties





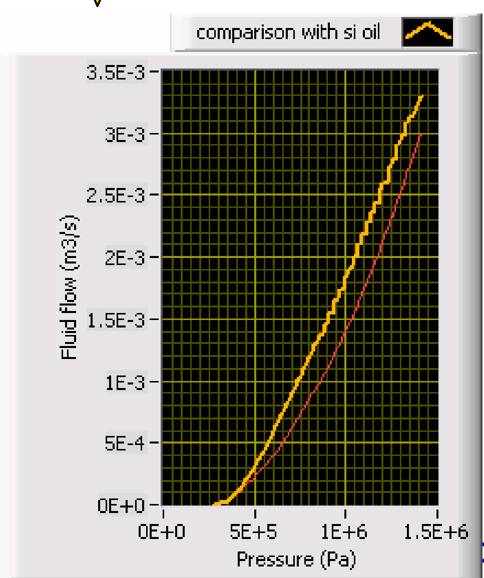
(1) Number of pores of each size

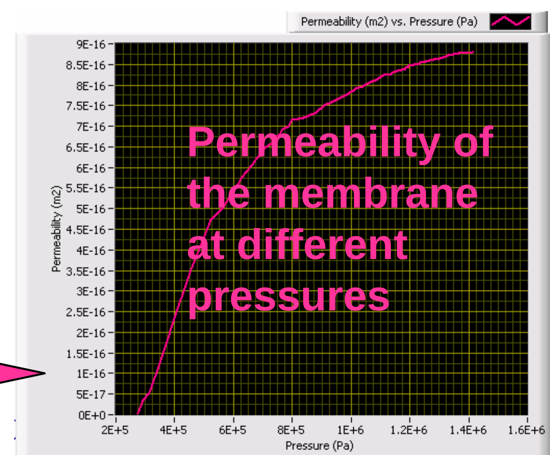
(2) Hagen Poiseuille in all pores

(3) Correction factor for air flow

(4) Calculation of flow with fluid of interest and correction factor

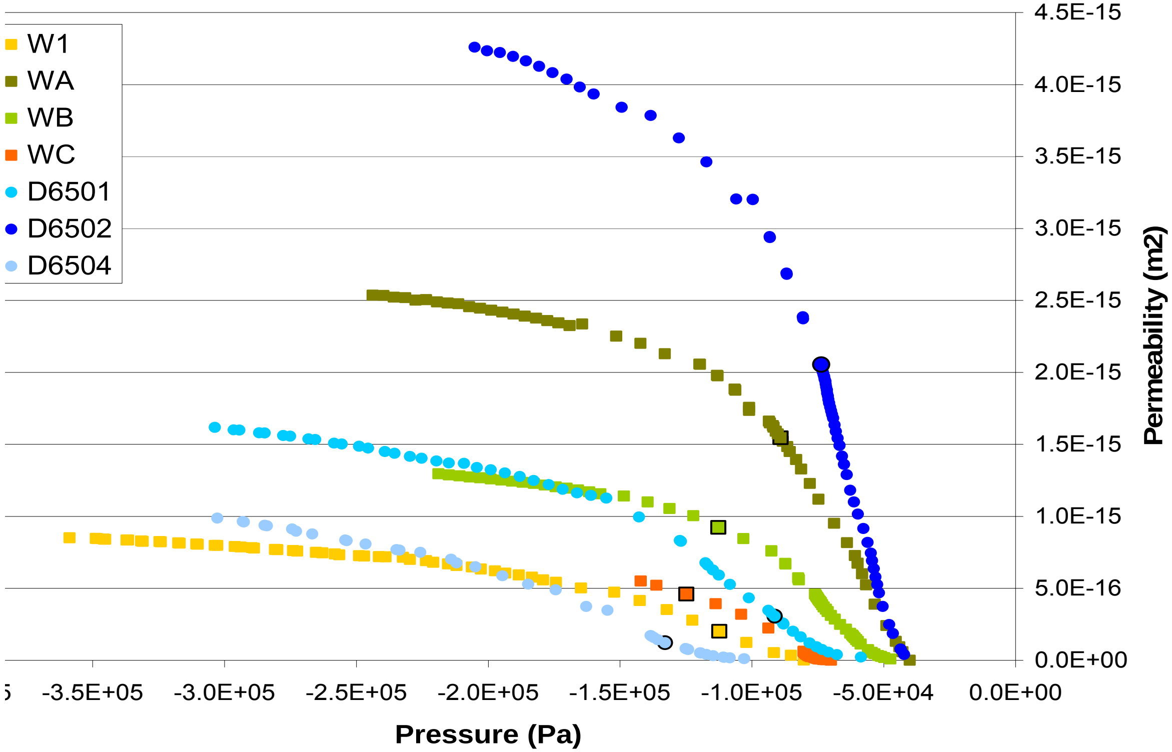
(5) Calculation of permeability using Darcy's law





Permeability of W and D membranes and SC15-epoxy

- Example with SC15 (the results show, again, that there is no agreement between all membranes)
- For water, the plots would be similar but would present lower permeabilities at similar pressures



Autoclave experiments

Motivation

Prove that the impregnation is driven by the capillary pressure of the largest pore.

Principle

Model:

$$t = \frac{10\eta h^2}{\varepsilon^3 r^2 \left[\Delta P + P_{capillary}\right]}$$

ΔP is the pressure applied during the process (vacuum for VARTM)

From the model:

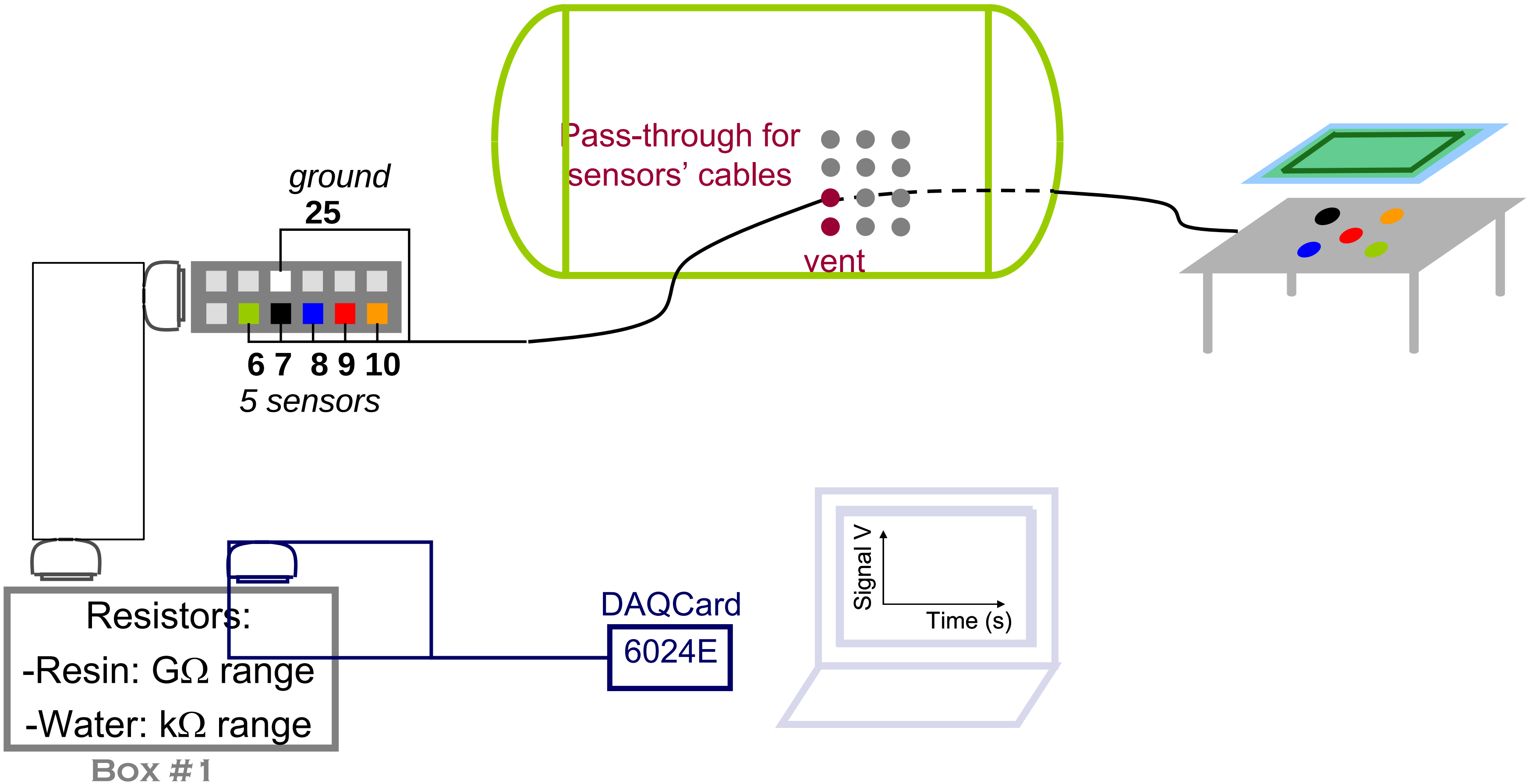
Considering a non-wetting resin ($P_{capillary} < 0$)

If $|\Delta P| > |P_{capillary}|$ $\Rightarrow$ Impregnation of the membrane by the resin

If we apply a positive pressure to force impregnation

$\Rightarrow$ This critical value should be equal to the capillary pressure of the membrane's largest pore

Autoclave Setup



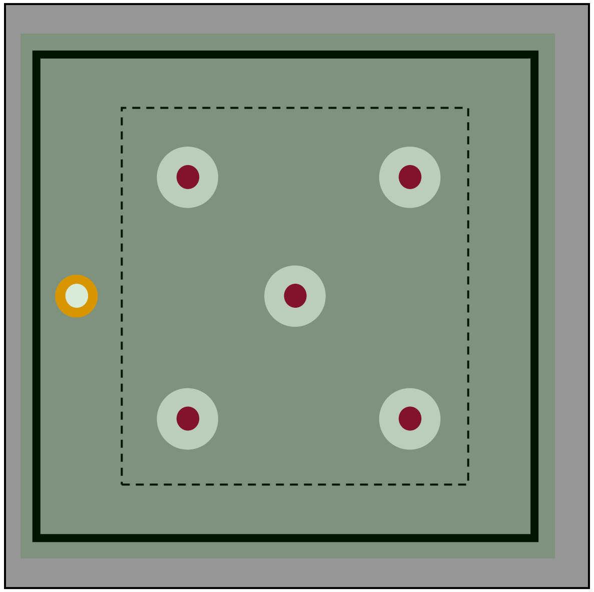
Sample placement

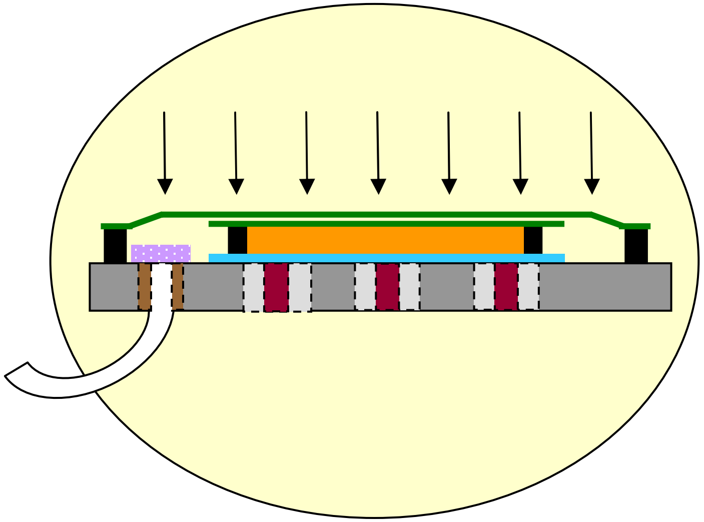
Setup

Sensors in the mold to measure resin's resistivity

The signal goes up when the resin goes through the membrane

top view





side view

Bagging film

Membrane

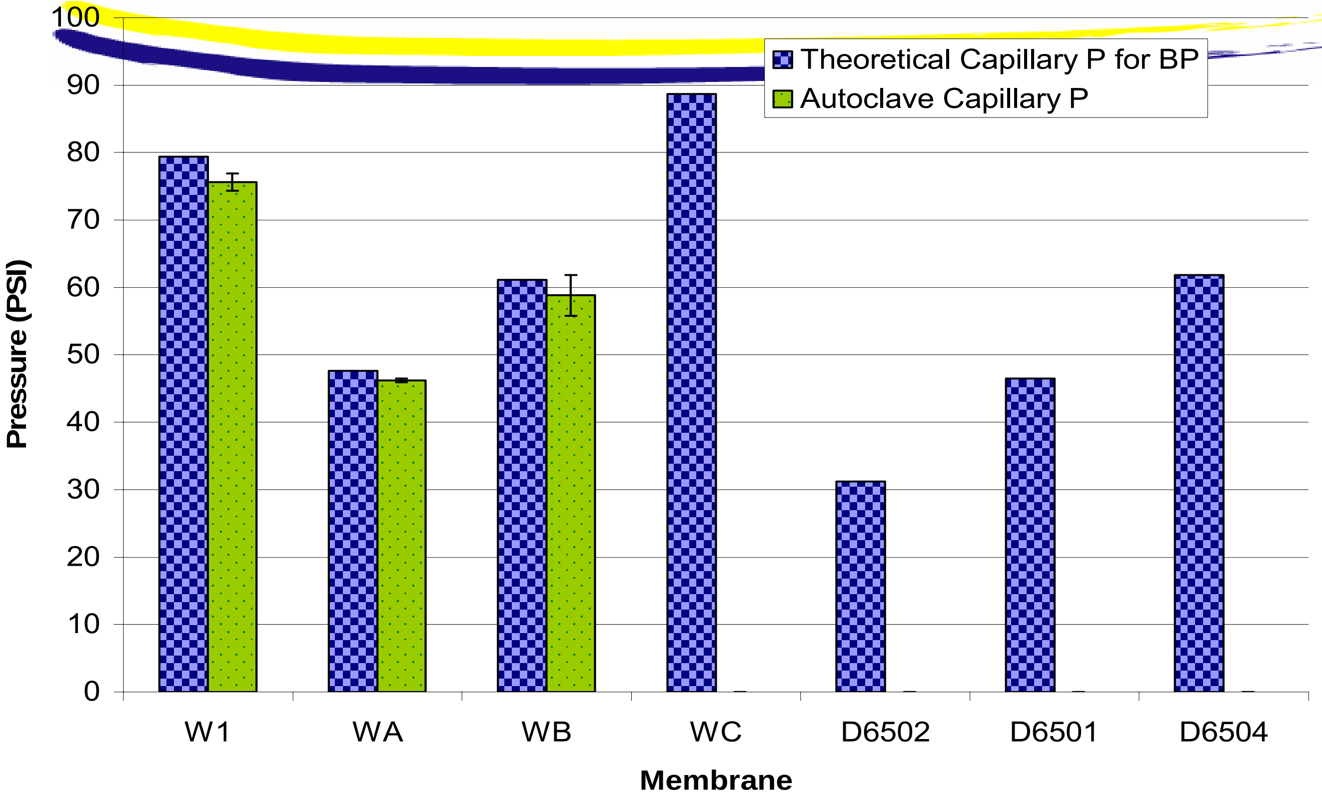
Breather cloth

Tacky tape

Resin

Sensors

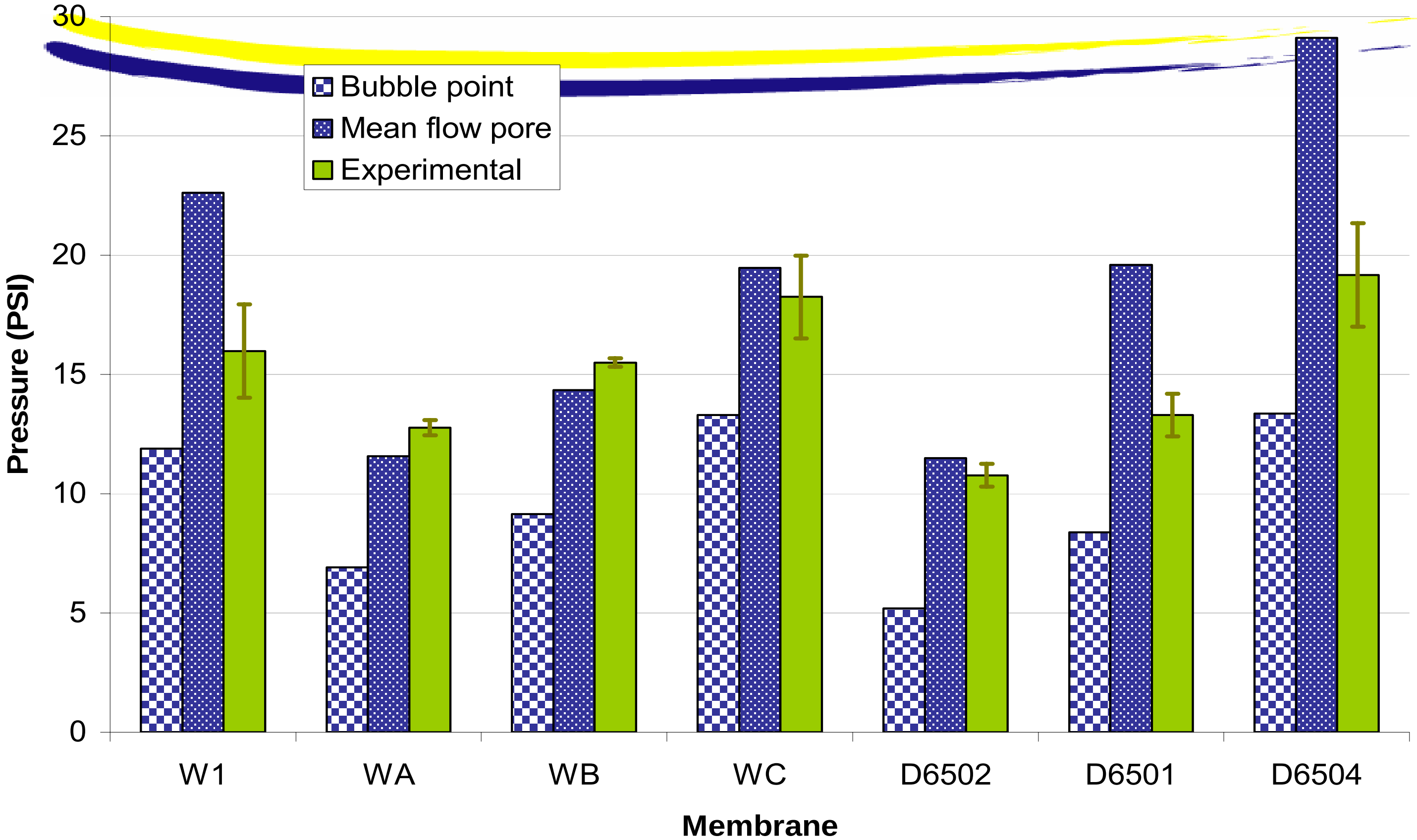
Autoclave: HPLC



Good correlation between the theoretical capillary pressure measured for the bubble point and the experimental results.

Ongoing work includes the experimental evaluation of the capillary pressure of the membranes WC, D6501, D6502 and D6504.

Autoclave: SC15



The experimental results are <u>not conclusive</u> since they do not match neither the capillary pressure with the mean flow pore or the bubble point.

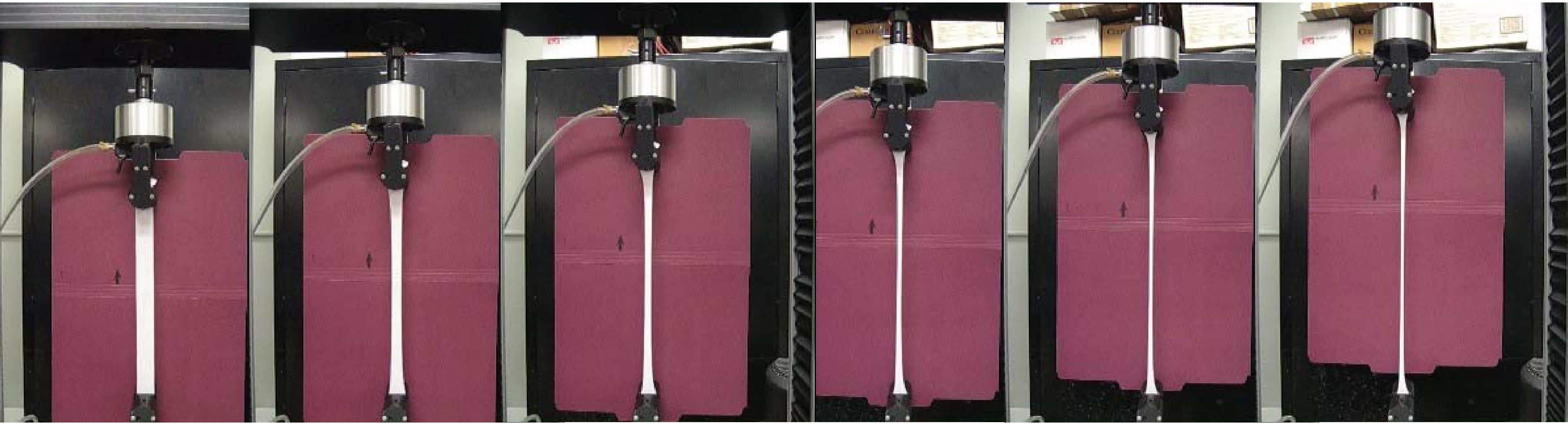
<u>Potential explanation</u>: the SC15 epoxy is a multi-component resin system which could allow penetration of it constituents at different pressure levels.

On-Going Work
Draping Investigations

EADS 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.

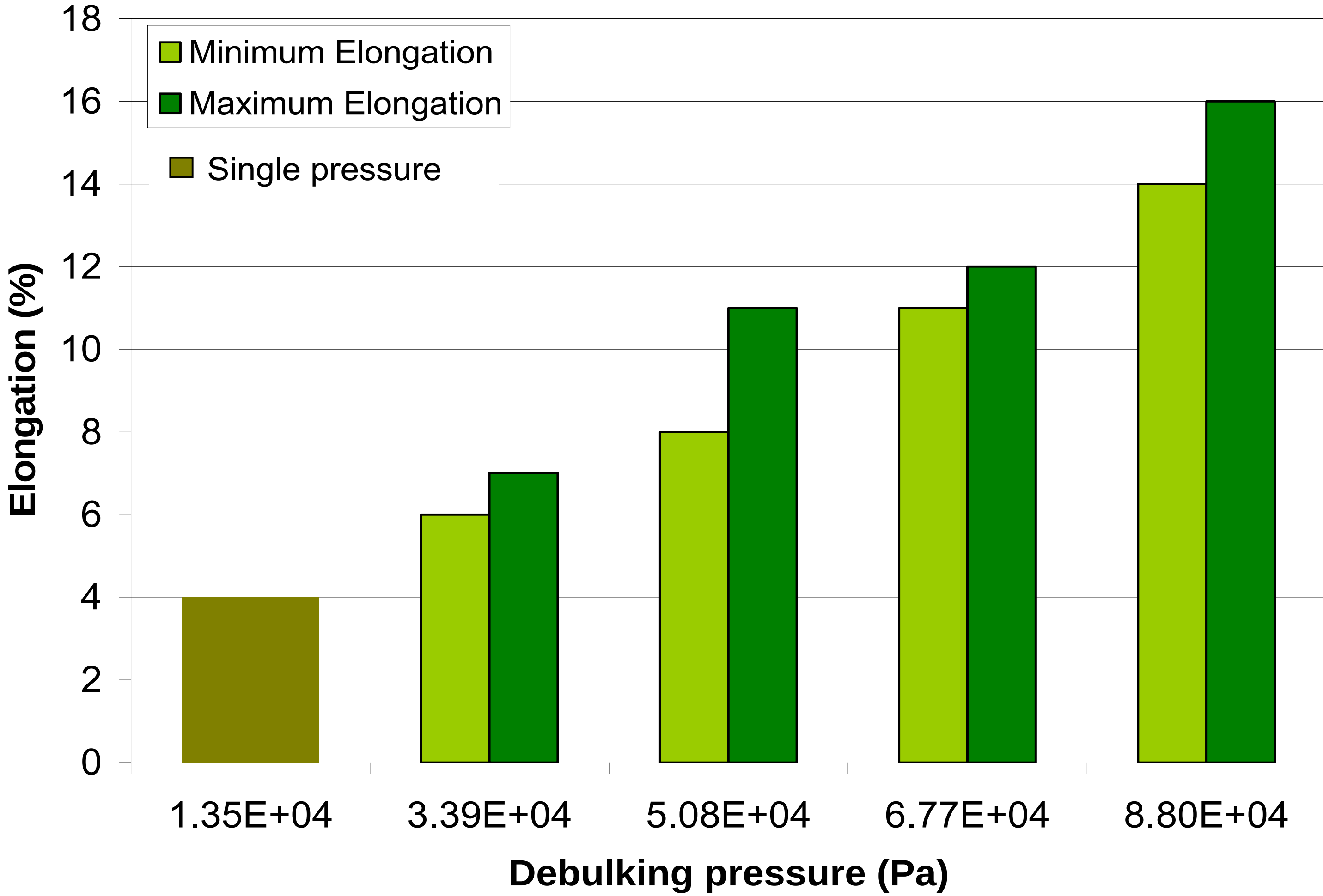
- Basic characterization of the membrane was conducted to obtain its Young's modulus, strain at break…
- Because the membrane is made of PTFE, we suspected that its mechanical behavior was strain rate dependent, which was confirmed. Therefore, it appeared crucial to choose the right strain rate to conduct 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.

Illustration of the membrane stretching



Stretching Behavior During Vacuum Application

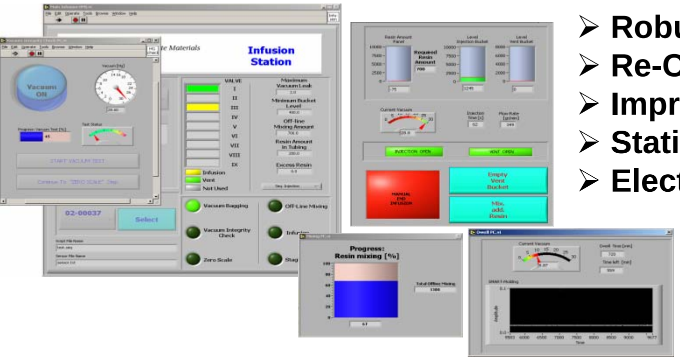
-Signifcant Elongation is observed potentially resulting in microstructure changes and local breakages of the membrane



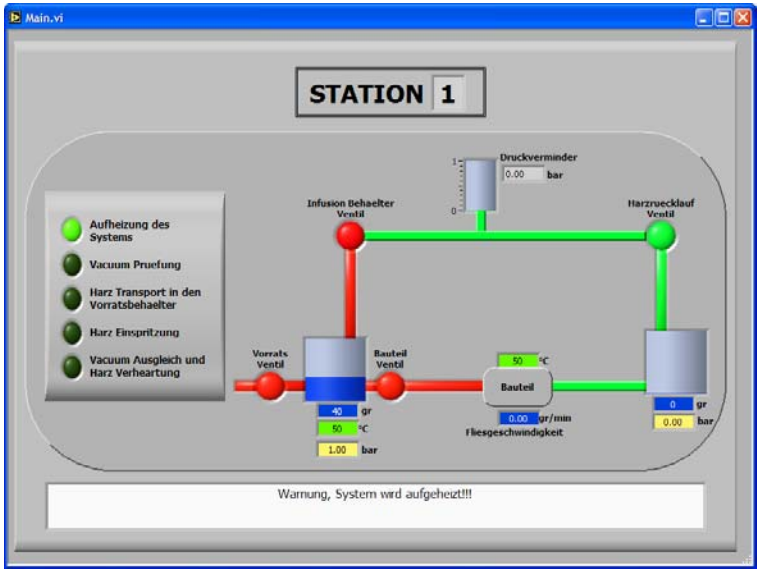
Conclusions and Future Work

- A model was introduced to predict the impregnation time of the membrane by different resins
  - There is a good match between experiments and theory, given that the input parameters present variations
- An experimental procedure was developed to investigate the driving force responsible for the success/breakdown of the membrane using the autoclave
  - The tests with water seem to be convincing, although it is not the case for the epoxy SC15
- Mechanical testing of the membrane was conducted to address the deformation encountered by the membrane while being used during manufacturing
  - Basic characterization and a strain rate dependency study give the basis of this study
  - A unique setup was built to promote biaxial stretching and evaluate its impact on membrane's performances

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 & Stag0
- Electronic Work Instruction



TRANSITIONED FOR R&D AND PRODUCTION AT DASAULT AVIATION (Paris, France)

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)**

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

NAVAIR P3-Orion Replacement Project

•Leverage FAA and ONR funded design, process, materials, and prototyping technologies to develop flight worthy replacement article(s) for the P3 surveillance aircraft.

- Exploit / Develop Composite Design & Analysis Capabilities
- Develop Elevated Temperature VARTM (ETV) Process
- Produce test article for flight testing of trailing edge panel
- Lay groundwork for certification of composite part for P3 replacement

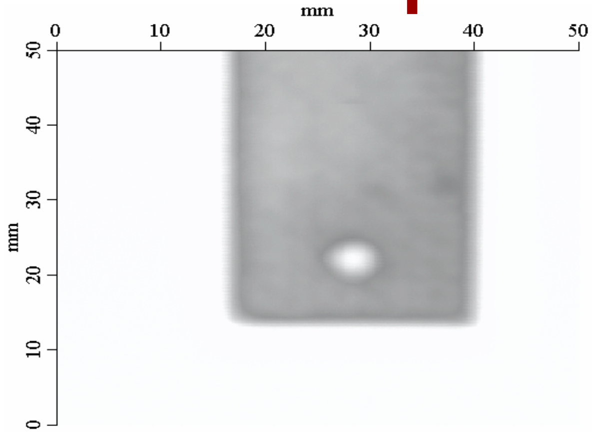
•Develop a <u>model</u> program to establish a parts replacements initiative to reduce maintenance/part costs for P3 and other aircraft.

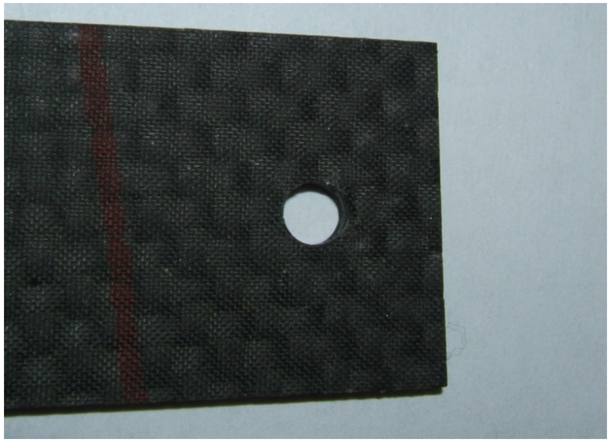
A Look Forward

- 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

Pin Bearing Test
ASTM D 5961

Sample Numbered and Drilled





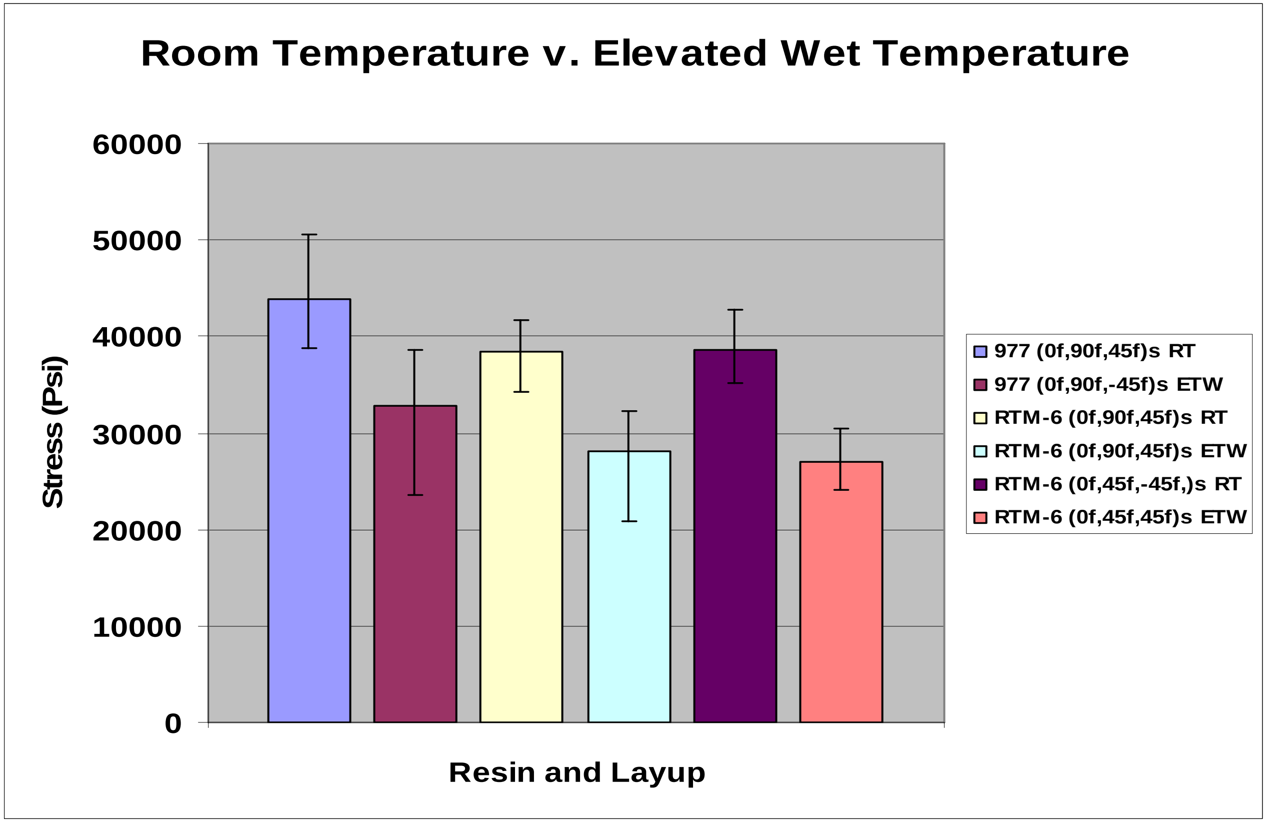
C-scan of hole to identify drilling damage or local impurities.

Post testing hole damage.

P3 Trailing Edge Flap

- 802753 Trailing Edge Panel
- E10-09971 is the NADEP Jax Bead Cross Section

Bearing Test Results



- Typical reduction for elevated temperature wet conditions (180F, 80% wet) are observed
- Cycom 977-20 pin bearing strength is slightly better than RTM6 system

Development Team

Leveraging of Technology

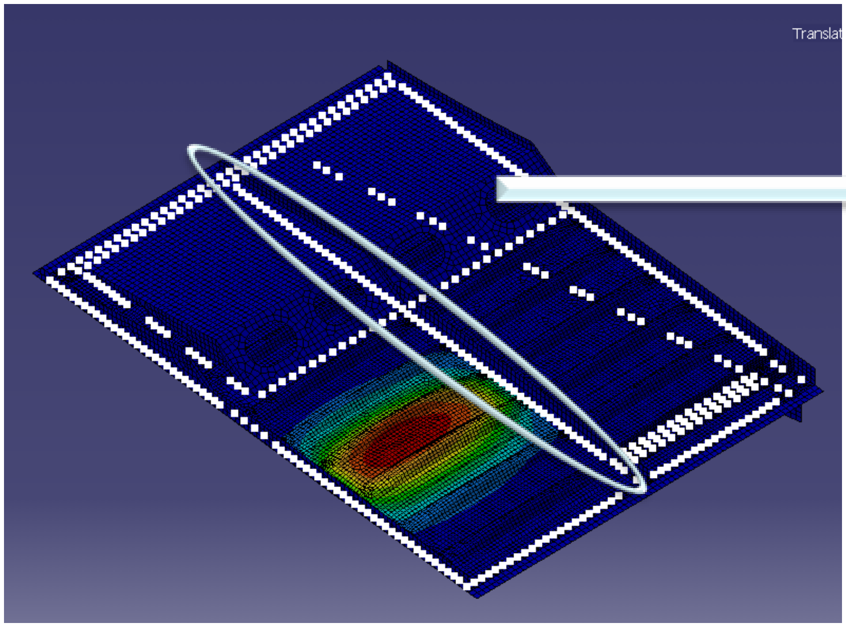
NAVAIR Structures Group
- Provide Structural Requirements
- Define Requirements for Structural Certification

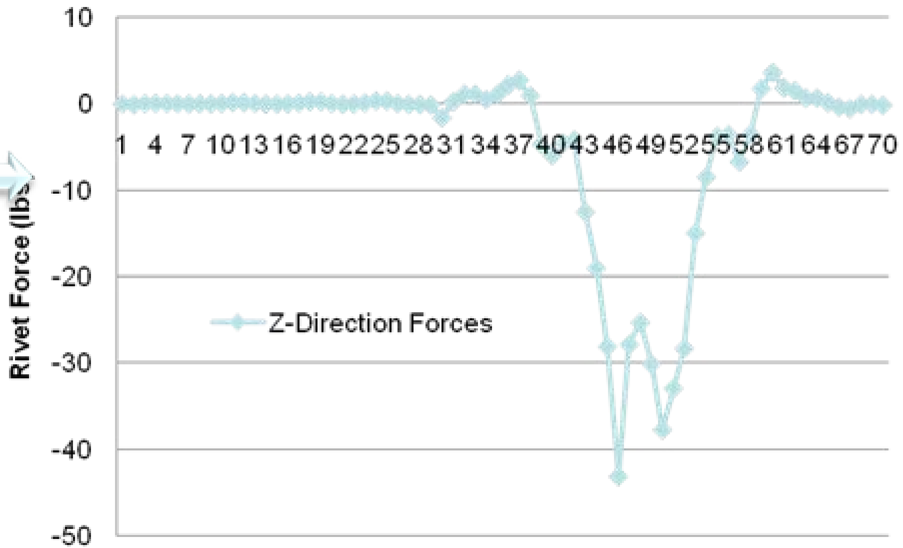
Trailing Edge Design
- Part Design and Analysis
- Process Development
- Prototype Fabrication
- Materials Selection / Testing

LOCKHEED MARTIN
We never forget who we're working for™

Oversee Trailing Edge Design
- P3 – Design & Manufacture

Full Design and Analysis for Carbon Replacement Part





Rivet Loads from Concentrated Force (3x200lb)

- Critical load case is the thermal expansion difference between the new carbon replacement panel and the aluminum rib structure