A 12 PART WEBINAR SERIES ON:

COMPOSITE MATERIALS ENGINEERING

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- Ph.D. and M.A.Sc. in Composite Materials Engineering
- Over 15 years experience in industry and academia working on polymer matrix composites in aerospace, automotive, marine, energy, recreation and others
- Experience working with over 150 companies from SME to major international corporations
- Expertise in liquid composite moulding and thermal management

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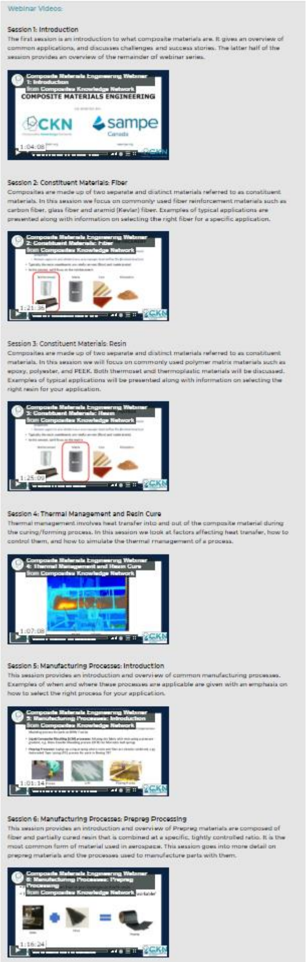

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OVERVIEW OF WEBINAR SERIES

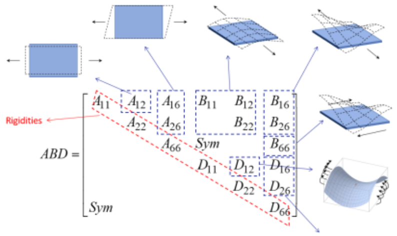
- **Series of 12 webinars, 1 hour each**

Introduction
Constituent Materials
Thermal Management

Processing (Manufacturing)
Prepreg Processing
Liquid Composite Moulding

Mechanics of Composites
Micromechanics
Lamina and Laminate Level
Failure

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon_0 \\ \kappa \end{Bmatrix}$$



Testing Composites
Common Defects

- **For more information on dates and times visit:**
  https://compositeskn.org/aimevents/

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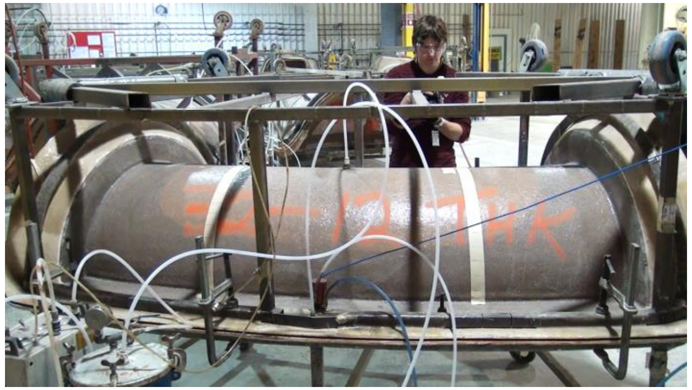
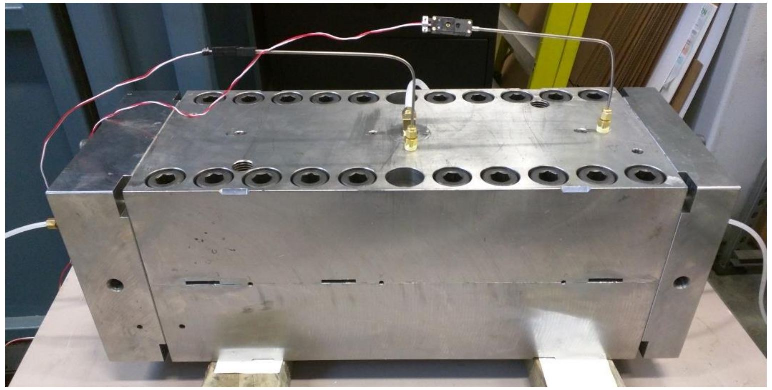
INTRODUCTION: LIQUID COMPOSITE MOULDING

- Liquid composite moulding (LCM) refers to processes that saturate a dry reinforcement that is on/in the mould by means of a pressure differential (injection pressure, vacuum, combination of both)
- There are three main sub-processes:
  - Vacuum infusion process (VIP), sometimes referred to as (VARTM)
  - Resin transfer moulding process (RTM)
  - Light resin transfer moulding process (LRTM)

Vacuum infusion (VIP, VARTM)



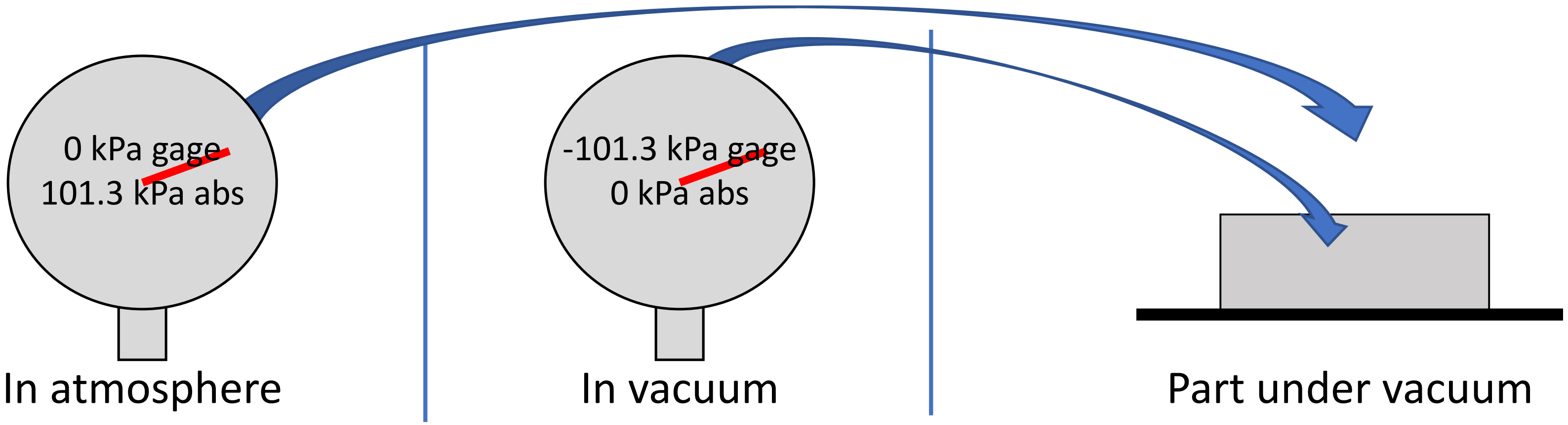
Light resin transfer moulding (LRTM)



Resin transfer moulding (RTM)

IMPORTANT CONCEPTS: VACUUM

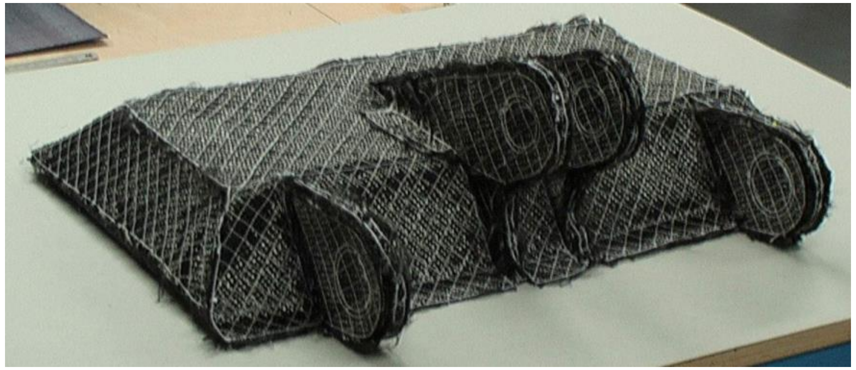
- Vacuum simply means ‘devoid of matter’
  - ie. nothing is occupying the space
- At sea level, atmospheric pressure is 101.3 kPa (14.7 psi)
- We refer to this as zero pressure (zero *gage* pressure)
- A full vacuum would be zero *absolute* pressure or -101.3 kPa
- When we pull vacuum on a part, we’re simply drawing out the air
- When we allow resin to be drawn into the part, it is atmospheric pressure that is forcing it in



IMPORTANT CONCEPTS: PREFORM

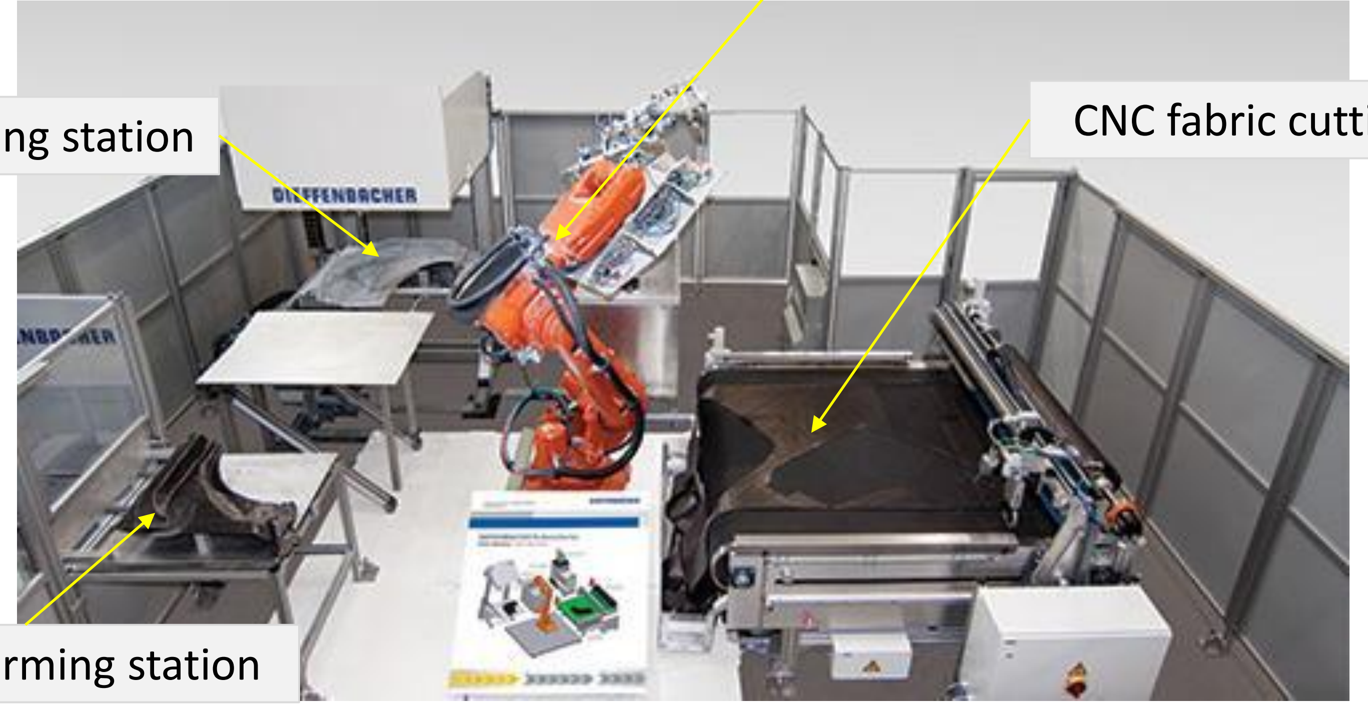
- 'Preform' is the term for the fibre reinforcement
- This is the stage between the raw material form after it is processed into an architecture (fabric, mat, etc.) and becoming a composite
- 'Preforming' refers to the task of preparing the fibre
  - Cutting it out
  - Assembling a number of pieces (stitching, bonding, etc.)
  - Forming on a (heated) tool

Basic preforms assembled over mandrels



Advanced preform (stitched together)

IMPORTANT CONCEPTS: PREFORM



Preforming workcell

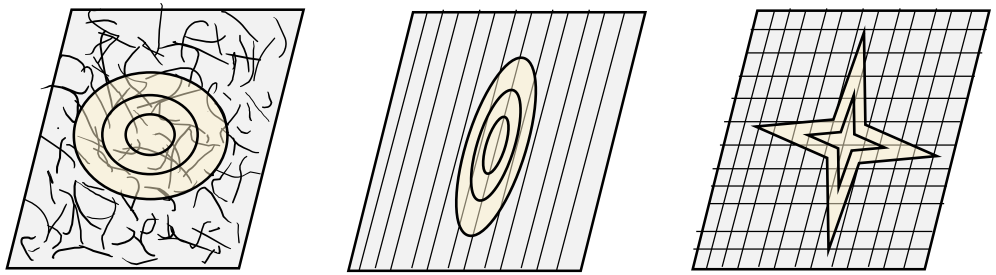
IMPORTANT CONCEPTS: PREMEABILITY (*K*)

- Permeability refers to the resistance of fluid flow through a porous medium
- Analogous to conductivity in an electrical circuit
- *K* is a 3X3 tensor
- Often used as a scalar (one value)

$$K = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$$

If aligned with principal axis of preform

$$K = \begin{bmatrix} K_{11} & 0 & 0 \\ 0 & K_{22} & 0 \\ 0 & 0 & K_{33} \end{bmatrix}$$



Multidirectional Unidirectional Bidirectional

Flow pattern through various fibre architectures

IMPORTANT CONCEPTS: PERMEABILITY (*K*)

Permeability values of various materials

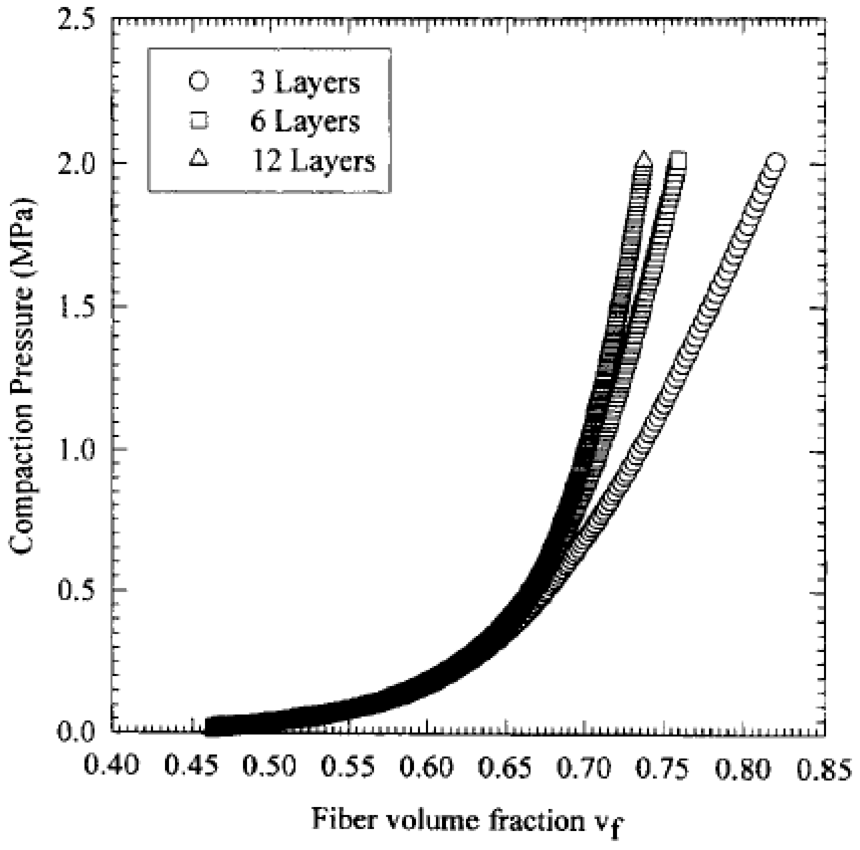
[1]

Material	Permeability, 10^{-9} m^2
Glass reinforcement	
Multiaxial	0.05–0.30
Woven roving	0.05–0.30
Random mat	1–4
Combination mat	4–8
Cores and flow layers	
Contoured balsa (25 mm, or 1 in.)	3
Flow layer grid	10
Flow layer braiding	50
Tubes	
Internal diameter 5 mm (0.2 in.)	800
Internal diameter 10 mm (0.4 in.)	3000
Internal diameter 25 mm (1 in.)	20,000

Ref [1]: Hoebergen, A., Vacuum Infusion, ASM Handbook, Vol 21, 2001

IMPORTANT CONCEPTS: FIBRE BED COMPACTION

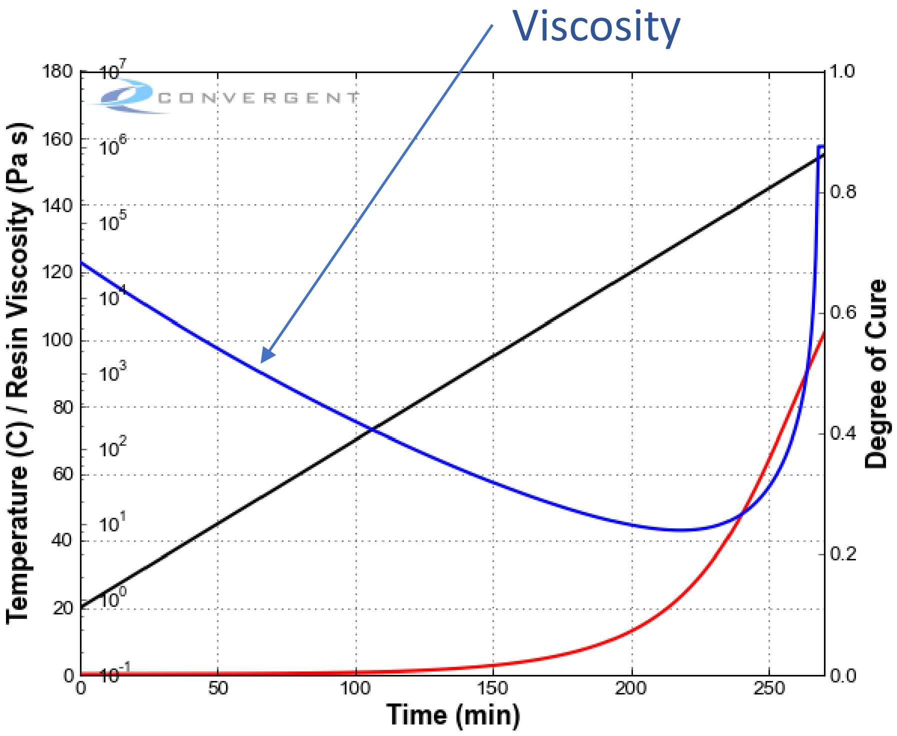
- In an unconstrained state, fibre has loft (springiness), when it goes into a mould it must be compacted to obtain the desired V_f
- With VIP, the compaction pressure comes from atmospheric pressure acting on the vacuum bag
- With RTM, the compaction comes from the tool
- As the compaction increases, the permeability decreases



Compaction pressure vs. V_f

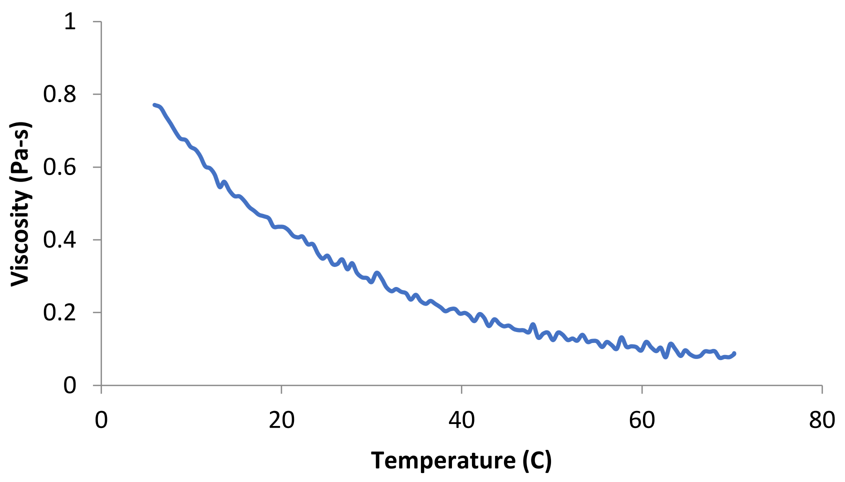
IMPORTANT CONCEPTS: RESIN PROPERTIES

- Resin processing parameters:
  - **Working time:** must be long enough for resin to fully saturate the fibre, yet short enough to make the process efficient
  - **Viscosity:** must be low enough so that resin can fully saturate the fibre within the working time
- Typical viscosity range:
  - For VIP: up to ~500 mPa-s
  - For RTM: up to ~800 mPa-s
- Typical working times:
  - For VIP: ~1 to 6 hours
  - For RTM: ~15 minutes to 1 hour
    - New resins with very short working times are being developed for automotive industry (~1 minute)

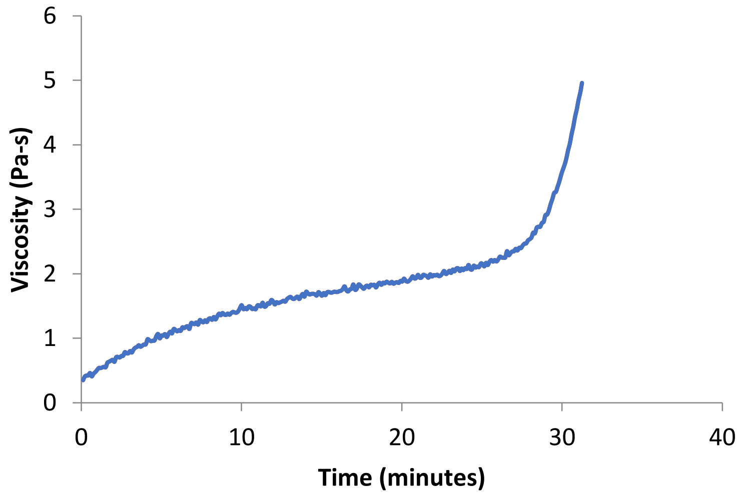


IMPORTANT CONCEPTS: RESIN PROPERTIES

- Process control: Temperature
  - Increase in temperature reduces viscosity (= faster resin flow)
  - Increase in temperature reduces working time (= faster chemical reaction)



Viscosity vs. Temperature



Viscosity vs. Time

IMPORTANT CONCEPTS: FLOW FRONT

- Flow front refers to the leading edge of the resin as it is flowing into the preform
    - The interface between resin and dry fibre/free space

IMPORTANT CONCEPTS: RACETRACKING

- Racetracking occurs when resin takes the path of least resistance
- This typically occurs at the outer edges of the reinforcement (between the fibre and tool)
- Depending on the severity, this can lead to dry spots (resin starved regions)
- Racetracking is not consistent and difficult to predict accurately
  - A 'range' of racetracking effects is often considered

IMPORTANT CONCEPTS: RACETRACKING

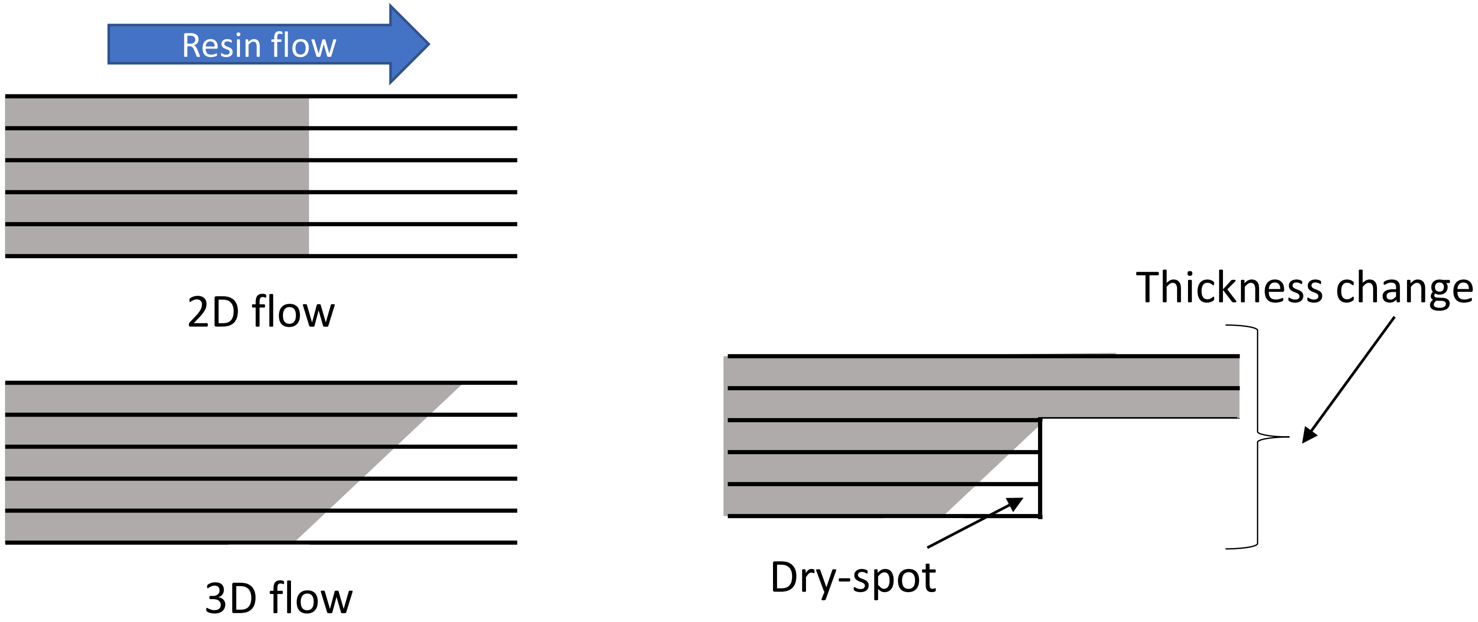
IMPORTANT CONCEPTS: DRY-SPOTS

- All LCM process are susceptible to flow induced dry-spots
- Dry-spots are typically caused by one or all of the following:
  - An inadequate flow strategy (inlet/outlet port placement) that allows the resin to reach the outlet before it has fully saturated the mould
  - Racetracking, which allows resin to reach the outlet before resin has fully saturated the mould
  - Inadequate working time, which causes the resin to gel before the mould is fully saturated
  - A change in laminate thickness, which causes the resin to trap dry fibre under the surface

Dry spots in RTM’d part

IMPORTANT CONCEPTS: 2D AND 3D FLOW

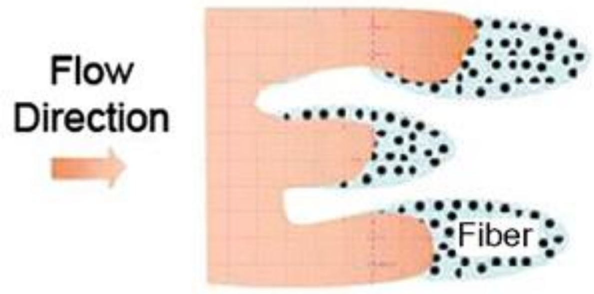
- With typical laminate thicknesses (<5 mm), flow is considered to be 2D (ie. constant through the laminate thickness)
- When a laminate becomes thicker, flow may become 3D when the upper flow front and lower flow front do not progress at the same rate typically because resin is introduced from the upper surface
  - This becomes problematic when the laminate thickness changes and creates hidden dry-spots within the laminate



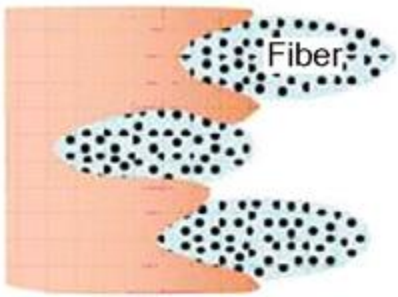
IMPORTANT CONCEPTS: MICRO AND MACROSCOPIC FLOW

- There are two different flow scales that come into play
  - **Macroscopic flow:** flow in between tows
  - **Microscopic flow:** flow in between fibres

Microscopic flow



Macroscopic flow



- These two flow scales should progress at the same rate otherwise one will over take the other, potentially resulting in porosity
  – If flow is *too fast*, macroscopic flow will overtake, resulting in dry spots within the tow
  – If flow is *too slow*, microscopic flow will overtake, resulting in dry spots between the tows

Leclerc, S.J., Ruiz, E., Porosity reduction using optimized flow velocity in Resin Transfer Molding, Composites Part A, 2008

IMPORTANT CONCEPTS: MICRO AND MACROSCOPIC FLOW

- 'Sweet spot' for resin flow to reduce porosity based on optimal capillary number (*Ca*)

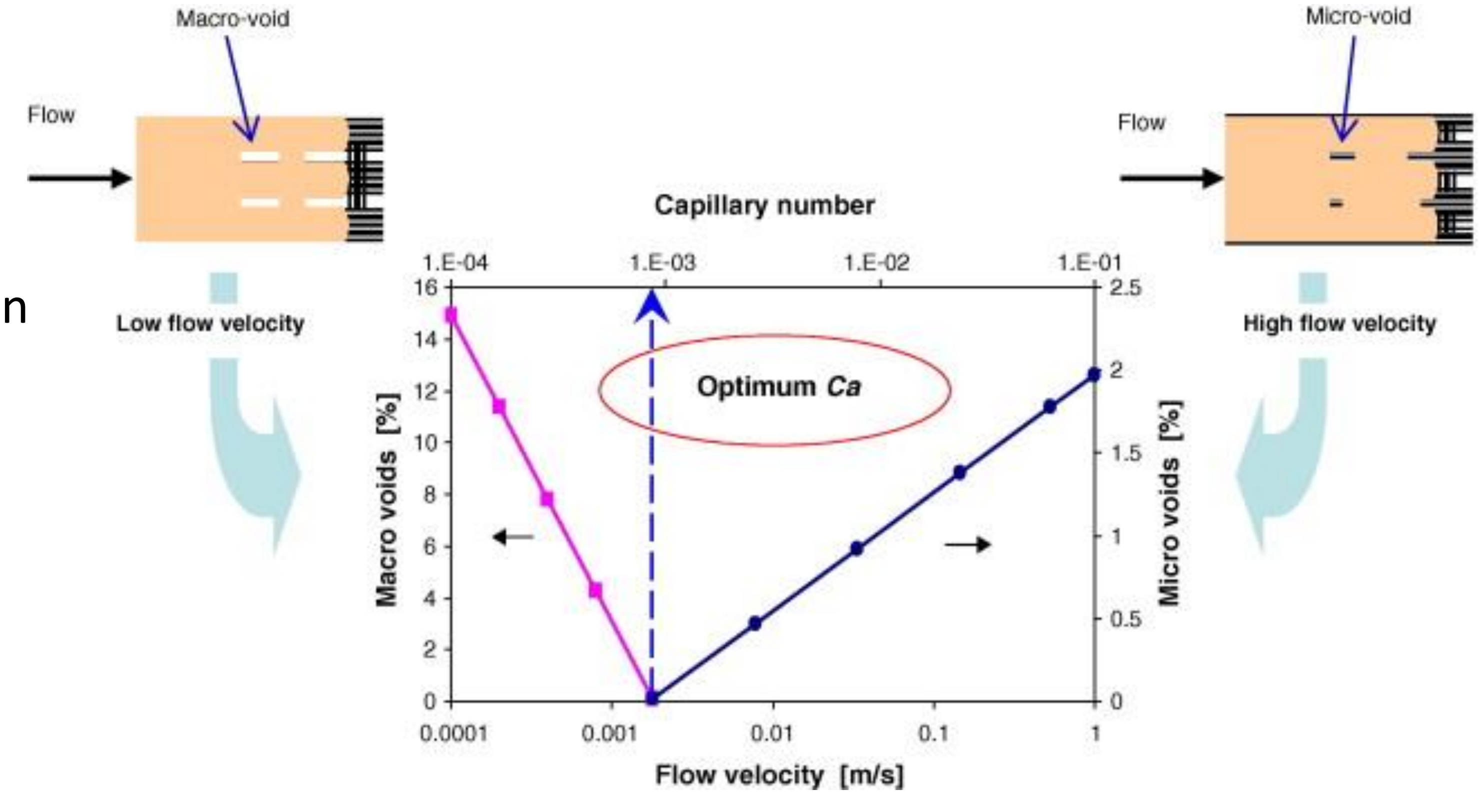
$$Ca = \frac{\mu v}{\gamma}$$

- Where:

  μ is resin viscosity

  γ is surface tension at air/resin interface

  v is resin velocity



Leclerc, S.J., Ruiz, E., Porosity reduction using optimized flow velocity in Resin Transfer Molding, Composites Part A, 2008

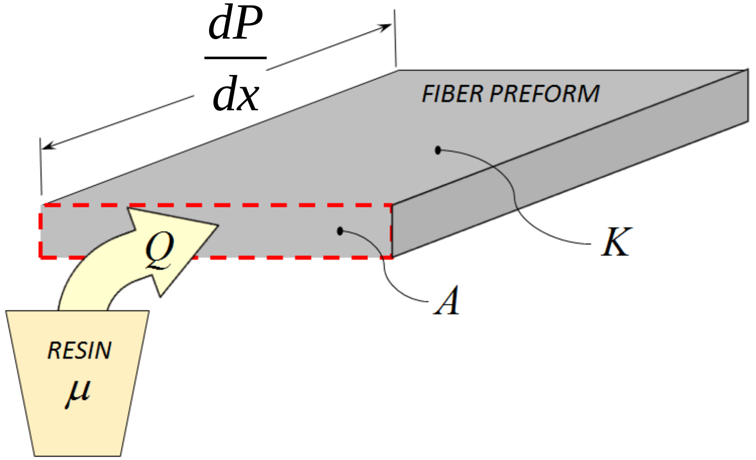
IMPORTANT CONCEPTS: FIBRE WASHOUT

- Fibre washout refers to the displacement of fibre by resin due to excessive shear stress
- This can occur locally (ie. in a small, contained region) or throughout the whole preform (ie. sliding the preform and/or wrinkling it)
- Commonly occurs near injection ports
- Typically an indication of:
  - Low V_f
  - Flexible mould

FLOW THEORY

- Flow through porous media is governed by Darcy's law:

$$Q = -\frac{KA}{\mu}\frac{dP}{dx}$$ … Eq. (1)



- Where:
  - Q is the volume flow rate
  - K is the preform permeability
  - μ is the resin viscosity
  - A is the area the resin is entering (edge area of preform)
  - P is the resin pressure
  - x is the distance across the preform (pressure difference length)

FLOW THEORY

- Let's derive the filling time for a rectangular panel
- First, we need to define superficial velocity, v_s:

$$v_s = v \frac{A_{FLOW}}{A_{MOULD}} = v\phi \qquad \text{... Eq. (2)}$$

- Where v is the seepage velocity or actual velocity, and ϕ is the porosity (ϕ=1-V_f), this is due to the fact that the fibre preform is porous and the actual volume the resin flows through is not the cross section of the laminate
- Now we can relate the volume flow rate, Q and laminate cross sectional area, A with:

$$Q = v_s A \qquad \text{... Eq. (3)}$$

FLOW THEORY

- Now we can substitute Eq. (3) into Eq. (1) to get (note that *A* cancels out):

$$v_s = -\frac{K}{\mu}\frac{dP}{dx} \quad \text{... Eq. (4)}$$

- Now we can substitute Eq. (2) into Eq. (4) to get:

$$v\phi = -\frac{K}{\mu}\frac{dP}{dx} \quad \text{... Eq. (5)}$$

- By definition, $v=dx/dt$, this can be substituted into Eq. (5):

$$\phi\frac{dx}{dt} = -\frac{K}{\mu}\frac{dP}{dx} \quad \text{... Eq. (6)}$$

FLOW THEORY

- Studies have shown that there is a linear pressure gradient from the inlet to the resin flow front, therefore:

$$\frac{dP}{dx} = -\frac{(P_0 - P_x)}{x} \quad \text{... Eq. (7)}$$

- Where P_0 and P_x are the pressures at the inlet and flow front, respectively
- Eq. (7) can be substituted into into Eq. (6) to get:

$$\phi \frac{dx}{dt} = \frac{K}{\mu} \frac{(P_0 - P_x)}{x} \quad \text{... Eq. (8)}$$

FLOW THEORY

- Eq. (8) can be rearranged and integrated to solve for time:

$$\int_0^x x\,dx = \frac{K}{\mu\phi}(P_0 - P_x)\int_0^t dt$$

⬇

$$\frac{x^2}{2} = \frac{K}{\mu\phi}(P_0 - P_x)t$$

⬇

Fill time of a rectangular laminate:

$$t = \frac{x^2 \mu\phi}{2K(P_0 - P_x)}$$

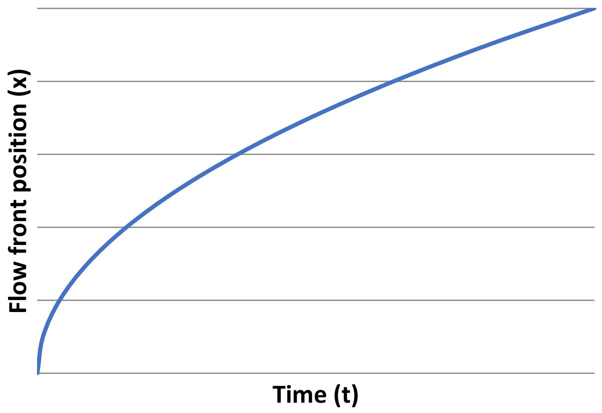
… Eq. (9)

FLOW THEORY

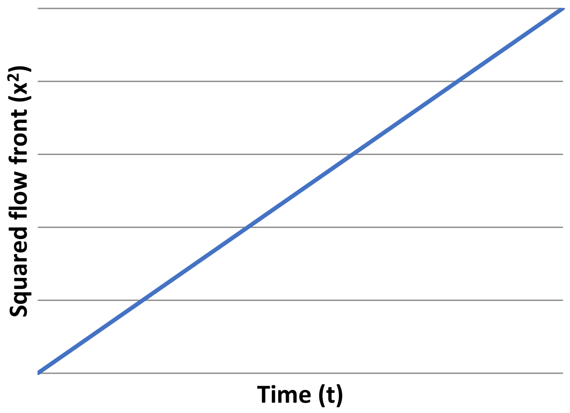
- From Eq. (9), we can observe the relationship between flow front position and time

$$t = \frac{x^2 \mu \phi}{2K(P_0 - P_x)} \quad \text{... Eq. (9)}$$

Flow front position vs. time



Squared flow front position vs. time

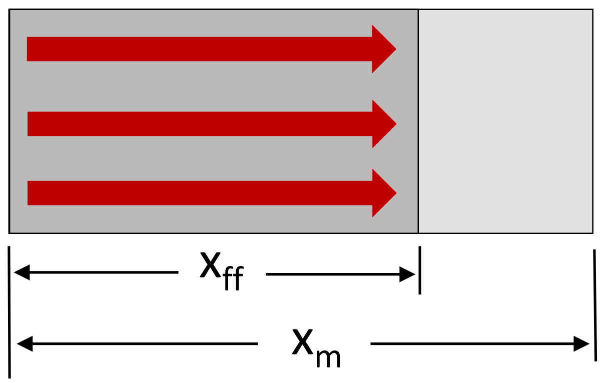


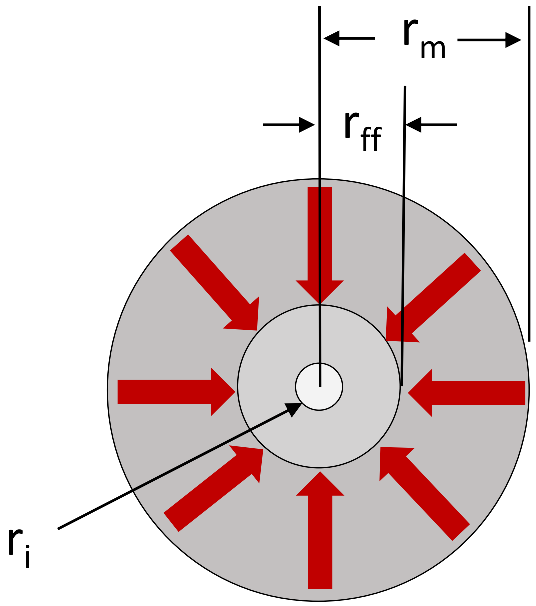
FLOW THEORY

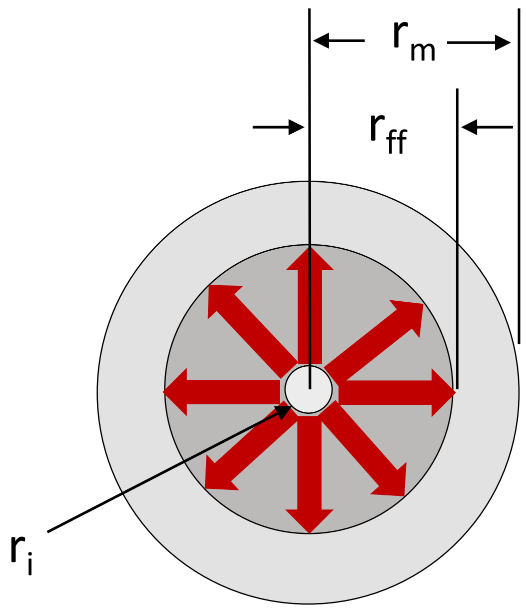
- There are three main types of flow:
  - Linear (which we just derived)
  - Radial convergent (radial flow towards a point)
  - Radial divergent (radial flow away from a point)

- There are two types of resin boundary conditions:
  - Constant injection pressure (vacuum, pressure pot)
  - Constant injection flow rate (injection pump)

FLOW THEORY: TYPES OF FLOW







FLOW THEORY

Constant pressure boundary conditions

	Pressure	Flow Rate	Filling Times
Radial Convergent	$P_0 \frac{\ln(\frac{r}{r_{ff}})}{\ln\left(\frac{r_m}{r_{ff}}\right)}$	$\frac{2\pi hK}{\mu} \frac{P_0}{\ln\left(\frac{r_m}{r_{ff}}\right)}$	$\frac{\varphi\mu}{2KP_0}(r_i^2 \ln\left(\frac{r_i}{r_m}\right) + \frac{r_m^2 - r_i^2}{2})$
Unidirectional	$P_0(1 - \frac{x}{x_{ff}})$	$\frac{\mathrm{x}_m hK}{\mu} \frac{P_0}{x_{ff}}$	$\frac{\varphi\mu}{2KP_0} x_m^2$
Radial Divergent	$P_0 \frac{\ln(\frac{r}{r_{ff}})}{\ln\left(\frac{r_i}{r_{ff}}\right)}$	$\frac{2\pi hK}{\mu} \frac{P_0}{\ln\left(\frac{r_{ff}}{r_i}\right)}$	$\frac{\varphi\mu}{2KP_0}(r_m^2 \ln\left(\frac{r_m}{r_i}\right) + \frac{r_i^2 - r_m^2}{2})$

Where *r* is the location of interest, measured from the outer radius in the case of convergent and measured from the center in the case of divergent flow, and *h* is laminate thickness

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FLOW THEORY

Constant flow rate boundary conditions

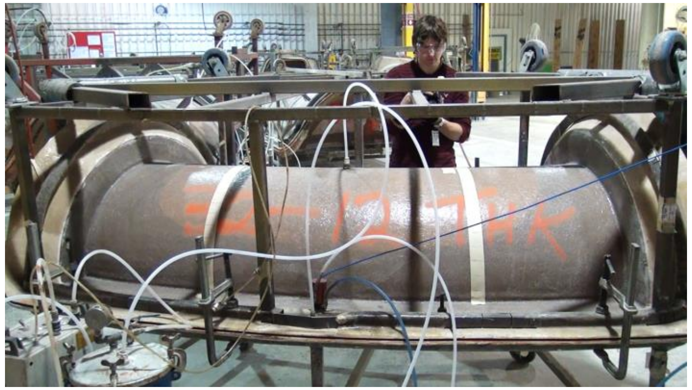
	Pressure	Flow Rate	Filling Times
Radial Convergent	$\frac{\mu Q_0}{2\pi h K}\ln(\frac{r}{r_{ff}})$	Q_0	$\frac{\varphi\pi h\left(r_m^2 - r_i^2\right)}{Q_0}$
Unidirectional	$\frac{\mu Q_0}{\mathrm{x}_m h K}(x_{ff} - x)$	Q_0	$\frac{\varphi h x_m \mathrm{x}_m}{Q_0}$
Radial Divergent	$\frac{\mu Q_0}{2\pi h K}\ln(\frac{r_{ff}}{r})$	Q_0	$\frac{\varphi\pi h\left(r_m^2 - r_i^2\right)}{Q_0}$

Where *r* is the location of interest, measured from the outer radius in the case of convergent and measured from the center in the case of divergent flow, and *h* is laminate thickness

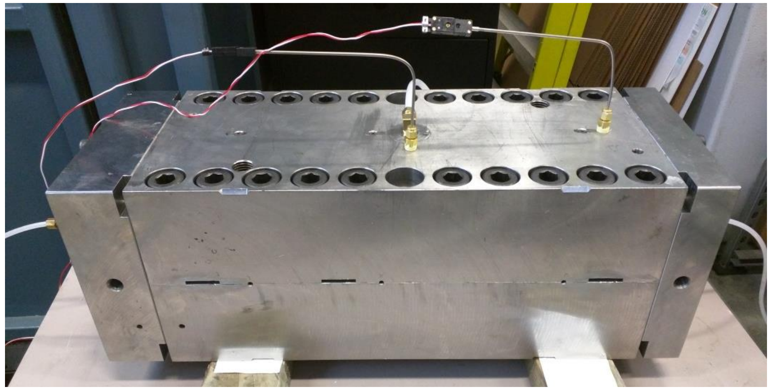
LIQUID COMPOSITE MOULDING PROCESSES

- There are three main sub-processes:
  - Vacuum infusion process (VIP), aka VARTM
  - Resin transfer moulding process (RTM)
  - Light resin transfer moulding process (LRTM)
- These are typically categorized by the type of mould and injection method (boundary conditions)

Vacuum infusion (VIP, VARTM)



Light resin transfer moulding (LRTM)

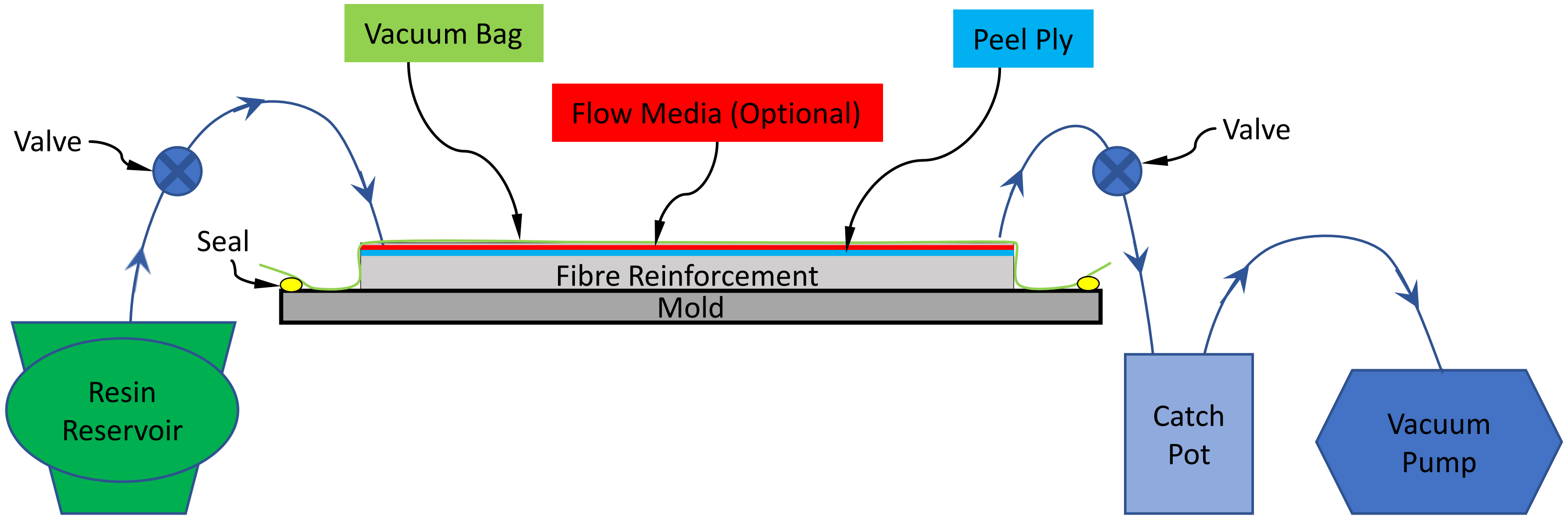


Resin transfer moulding (RTM)

https://www.releaseboatworks.com/the-infusion-process/

VACUUM INFUSION PROCESS (VIP)

- VIP involves placing a preform on a one-sided tool, sealing a vacuum bag on top of it, and drawing resin through the preform with vacuum
- Well suited to medium to large parts



Schematic of vacuum infusion process

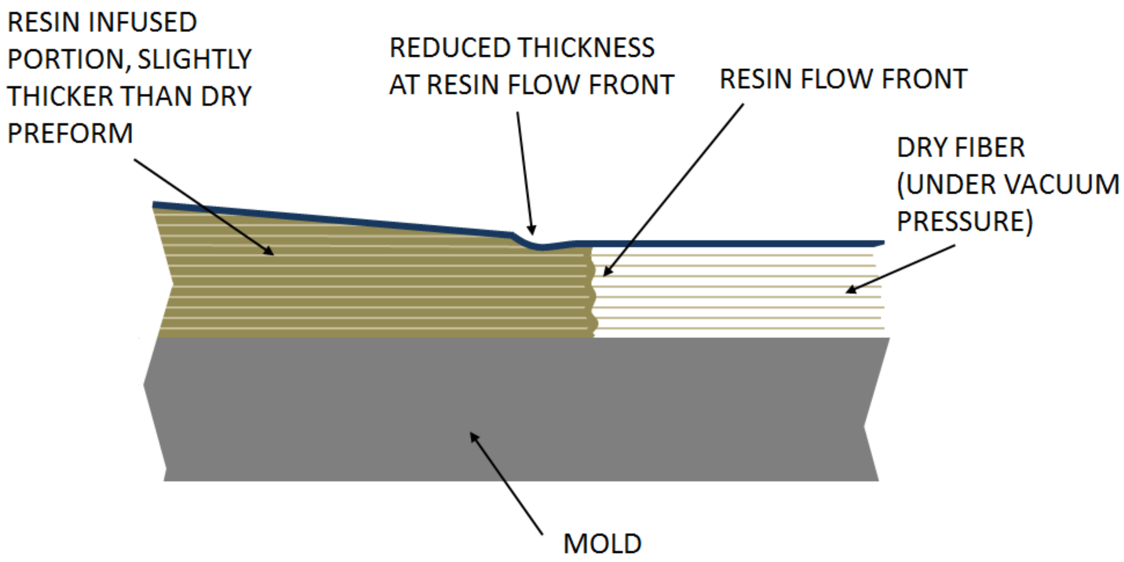
VACUUM INFUSION PROCESS (VIP)

- Advantages:
  - Lower priced process (lower priced tooling, constituent materials, ancillary equipment)
  - High V_f (~65%) possible
  - Low void content possible

- Disadvantages:
  - Slow process
  - Part has only one good side
  - Constituent material limited (low viscosity resin with long working time, acceptable permeability preform)
  - One surface not controlled

VACUUM INFUSION PROCESS (VIP): ISSUES

- Part thickness variation
  - Initially preform compressed under (full) vacuum
  - As resin begins to saturate, it allows the preform to relax because resin is at greater pressure than vacuum (linear pressure distribution from vacuum at flow front to atmospheric at inlet)



Schematic of resin flowing into preform

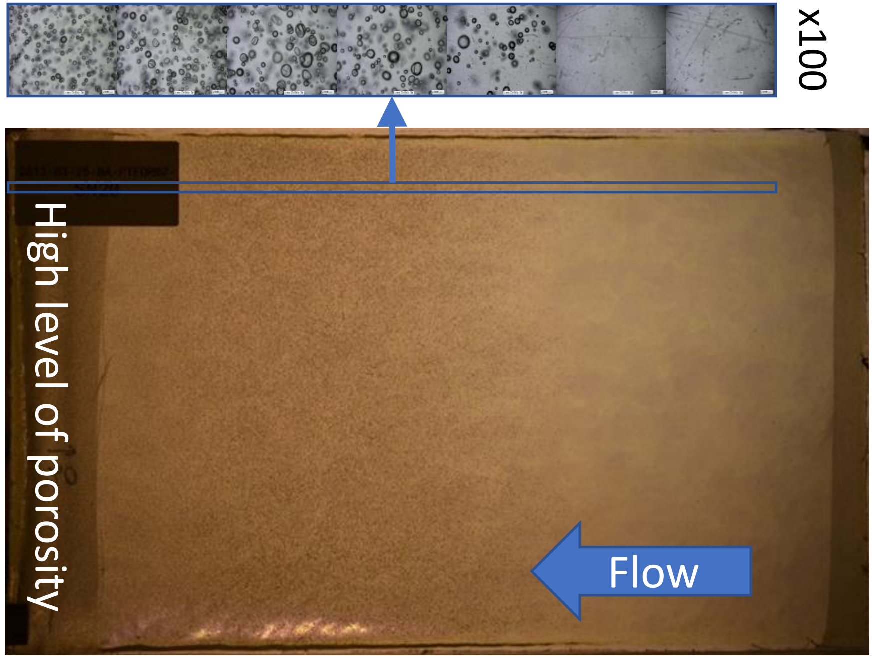
VACUUM INFUSION PROCESS (VIP): ISSUES

- Vacuum bag leaks
  - Vacuum bag/seal leaks can cause air to be drawn into/through the composite resulting in porosity
  - A ‘perfectly’ sealed process is critical
  - A leak test is typically performed before a VIP where the vacuum pump is disconnected and the vacuum level under the bag is monitored (various rules of thumb, <1 in-Hg in 30 min.)

Porosity caused by pin-hole in vacuum bag

VACUUM INFUSION PROCESS (VIP): ISSUES

- Porosity due to entrapped volatiles (inadequate degassing)
  - Resin at the flow front is under vacuum pressure, volatiles in the resin (moisture, air, styrene, etc.) boil off and become trapped in resin
  - Degassing is typically the solution



Porosity caused by non-degassed resin

VACUUM INFUSION PROCESS (VIP): APPLICATIONS

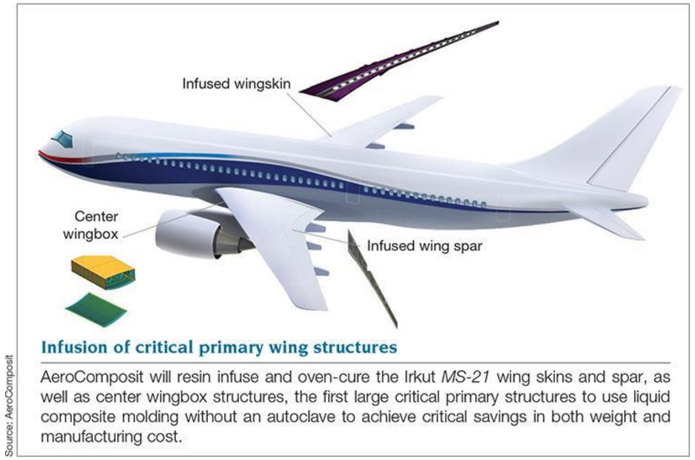
- Marine applications (boat hulls)
  - VIP was initially developed by the marine industry
- Turbine blades
  - a number of large turbine blade companies were/still marine companies
- Aerospace applications
  - Boeing 787 uses VIP'd (variation) leading edges
  - 'Home built' aircraft
- High end tooling (capable of autoclave processing)

VACUUM INFUSION PROCESS (VIP): APPLICATIONS

Turbine blades

Boat hulls

Aftermarket car parts



Aircraft parts

VACUUM INFUSION PROCESS (VIP): CASE STUDY

- Backing structure for 12 m diameter radio telescope built at Profile Composites Inc., Sidney (Victoria), B.C.
  - 5 m long beams, 8 in total
  - Foam cored, carbon/glass with epoxy resin
  - Eight in total, rate: 1/day

Dougherty, S., Composite Antennas for Radio Composite Antennas for Radio Telescopes, National Research Council, Penticton, BC
https://www.casca.ca/ecass/issues/2008-ae/features/ska/ska.htm

VACUUM INFUSION PROCESS (VIP): CASE STUDY

- 15 m diameter disk
- Materials: aluminum surface, glass/carbon with vinyl ester
- 1 hour infusion time


5 piece tool


Loading preform on tool


Installing inlet lines

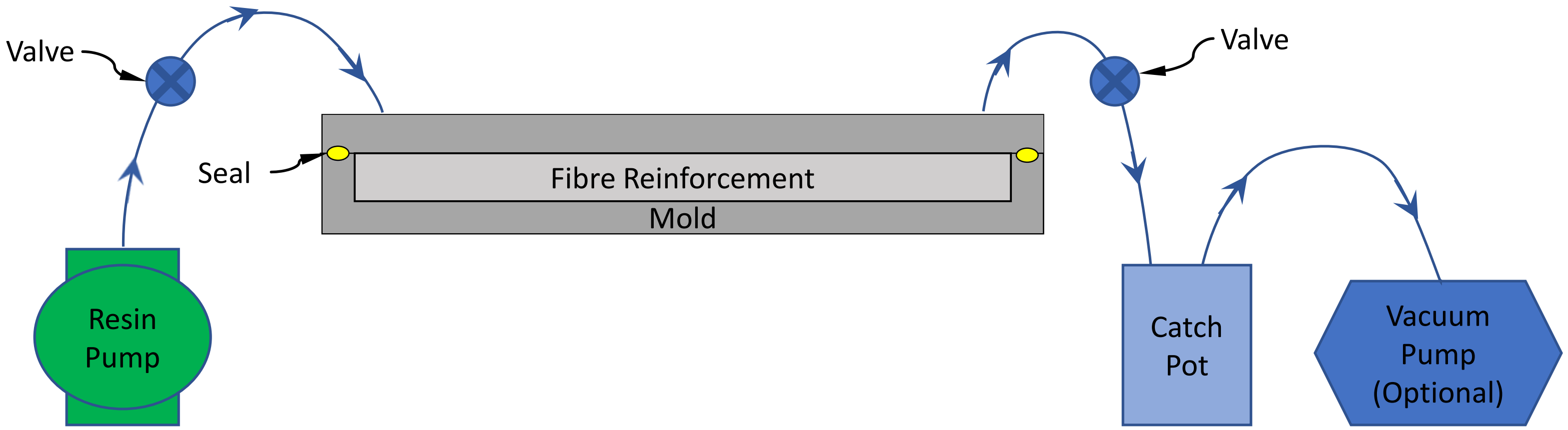

Leak testing vacuum bag


Transporting disk


Installing disk on base

RESIN TRANSFER MOULDING (RTM)

- Resin transfer moulding (RTM) involves loading a preform into a two (or more) piece, matched tool, closing it, and injecting resin under pressure (~15-100 psi)
- Well suited to small to medium sized parts, limited to large sizes due to injection pressure loads and tool cost



Schematic of resin transfer moulding (RTM) process

RESIN TRANSFER MOULDING (RTM)

- Advantages:
  - Parts have two good surfaces
  - Complex, 3D parts possible
  - Moderate to high V_f possible
  - Lower process time
  - Process can be automated
  - Constituent material is less limited vs. VIP and LRTM
- Disadvantages:
  - Tooling is expensive
  - Equipment is expensive
  - Tool design can be challenging (flow prediction and material handling)

RESIN TRANSFER MOULDING: ISSUES

- Racetracking is a common issue with RTM
  - The injection strategy is either designed to avoid it or the process is designed to be robust enough to cope with it
- Why is porosity typically less of an issue?
  - Because RTM is a pressurized process, vapor is compressed back into solution
- Why are mould leaks typically less of an issue?
  - Because RTM is a pressurized process, resin would leak out of the mould rather than air being drawn in

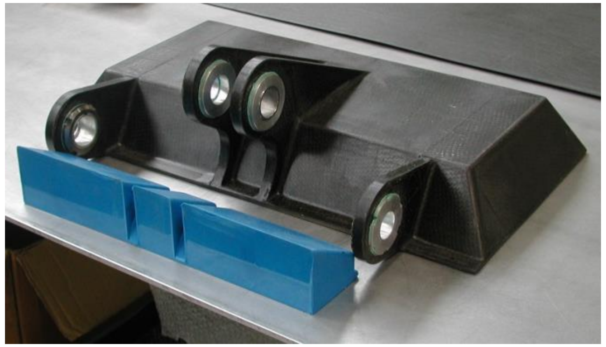
RESIN TRANSFER MOULDING (RTM): APPLICATIONS

- Automotive components:
  - Body panels
  - Leaf springs
  - Tubs
  - Wheels
- Aerospace components:
  - Ribs
  - Spars
  - Hinges
- Pressure vessels
- Sports and recreation:
  - Bike parts
  - Surfboard fins

BMW i3 body

Supercar tub

Wheel



Aircraft flap hinge

Leaf spring

Surf fin

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RESIN TRANSFER MOULDING (RTM): APPLICATIONS

- RTM'd pressure vessel

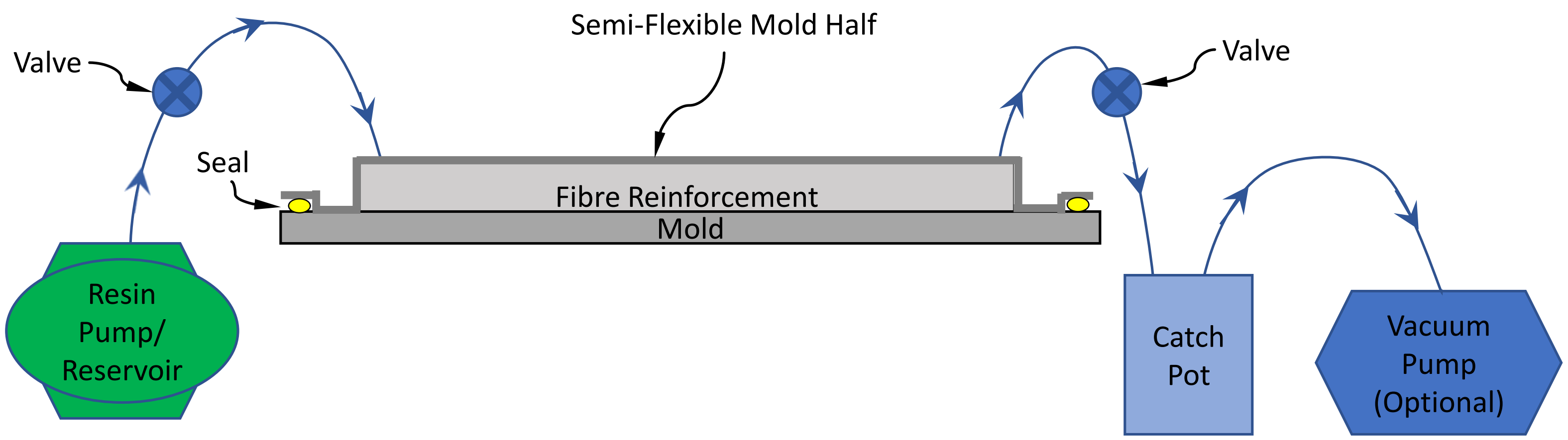
Pressure vessel

Tooling

https://www.compositesworld.com/articles/composites-fuel-growth-of-fuel-cell-technology

LIGHT RESIN TRANSFER MOULDING (LRTM)

- LRTM uses a semi-rigid tool half (A-side) that is similar to those used in VIP and a semi-flexible tool half (B-side) (typically made of thin fibreglass)
- Injection pressure is typically from vacuum to 1 atmosphere (14.7 psi) plus up to full vacuum on outlet (~2 ATM pressure differential)
- Light Resin Transfer Moulding (LRTM) falls between VIP and RTM



Schematic of light resin transfer moulding (LRTM) process

LIGHT RESIN TRANSFER MOULDING (LRTM)

- Advantages:
  - Low cost compared to RTM
  - Similar tooling fabrication to open moulding/VIP
  - Parts have two good surfaces
  - Complex, 3D parts possible
- Disadvantages:
  - Low injection pressure and non-rigid tooling limit preform options and increase process time
  - Preform is essentially limited to CSM/CFM or material with internal flow medium
  - Use of semi-flexible mould half reduces compaction, which in tern reduces V_f
  - Typical V_f ~10-30%

LIGHT RESIN TRANSFER MOULDING (LRTM): ISSUES

- Mould deflection resulting in non-uniform thickness
  - Due to the flexibility of the mould (B-side especially) and the fact that resin is injected under pressure the tool tends to deflect
- Tool leaks
  - It is not uncommon for fibre to get trapped across the seal allowing air to be drawn into the composite
- Porosity due to entrapped volatiles (inadequate degassing)
  - Resin at the flow front is under vacuum pressure, volatiles in the resin (moisture, air, styrene, etc.) boil off and become trapped in resin resulting in porosity

LIGHT RESIN TRANSFER MOULDING (LRTM): APPLICATIONS

- Marine (hatches, panels, etc.)
- Tubs and sinks
- Water slides
- Automotive body panels (transport trucks)
- Industrial covers and enclosures
- Fascia and signage

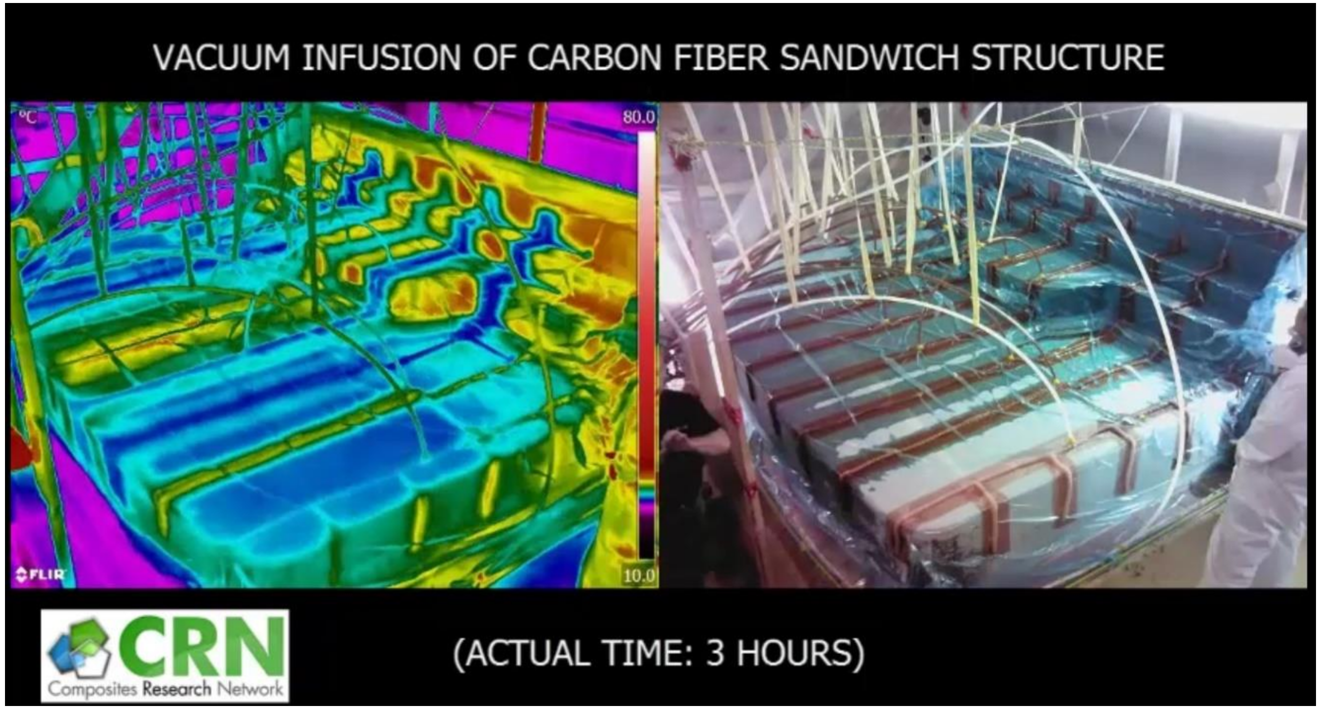
Gas station fascia

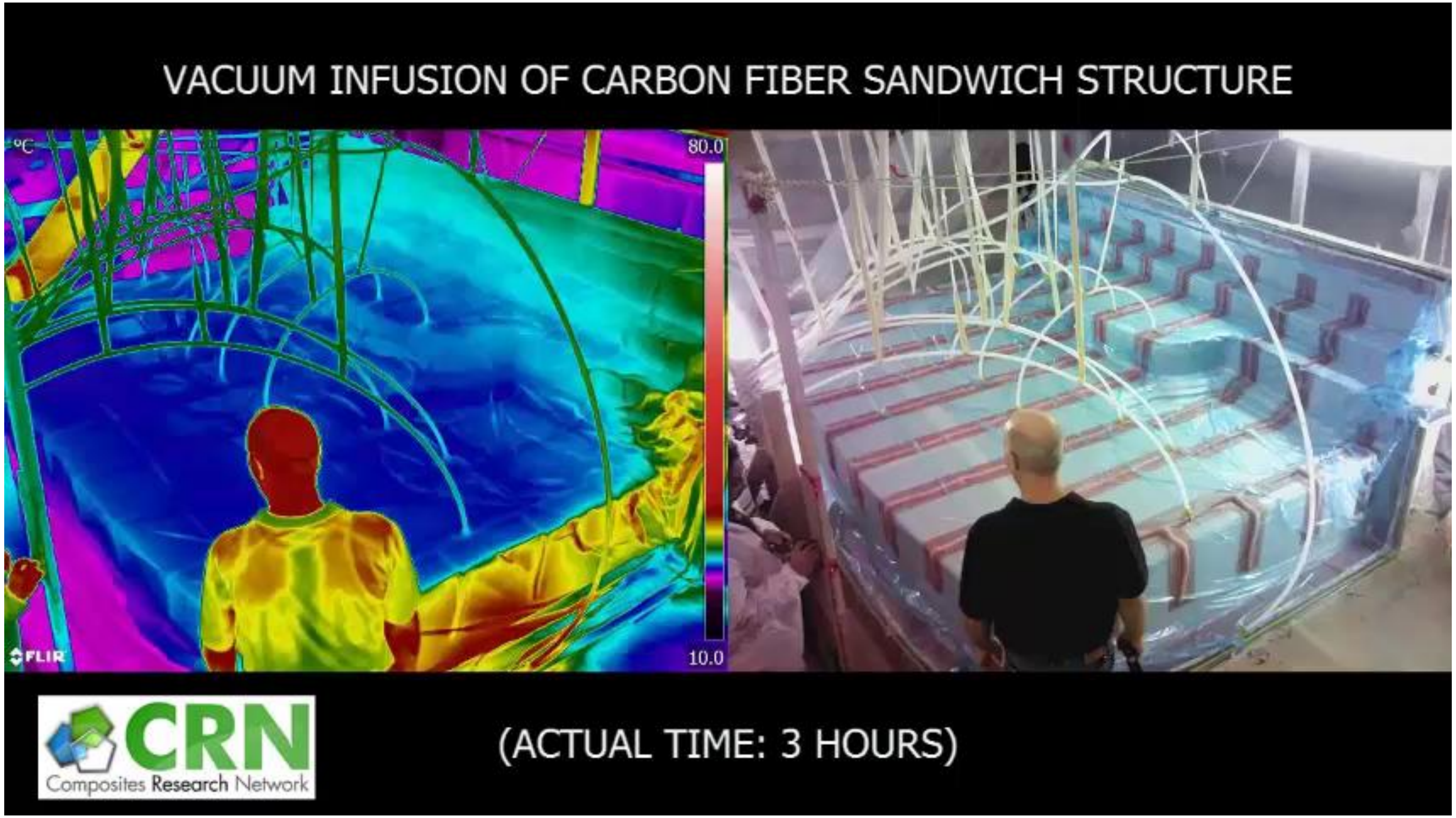

Sink


Waterslide section

VIP THERMAL MANAGEMENT CASE STUDY

- Infusion of stairs/deck for 145’ luxury yacht




VACUUM INFUSION OF CARBON FIBER SANDWICH STRUCTURE
°C
80.0
10.0
FLIR
CRN
Composites Research Network
(ACTUAL TIME: 3 HOURS)

Thank you for joining us!

The next session is:

Session 8: Mechanics of Compoisites Part 1: Lamina Level

September 2, 2020 @ 9:00 am PT

Questions?

For more information on future dates and times visit:

compositeskn.org