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LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Elements of Fabrication I

Lamination and Bagging/Tool Design

Autoclave Cure

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Outline

- Tools and Machines
- The Layup Process
  - Layup
  - Bagging
- Materials
- Layup Step by Step Procedures
- Autoclave Curing
- Plybooks

We are not addressing here automated processed such as filament winding, fiber placement, etc.

Generalized Part Fabrication Cycle

Composite parts are generally made from several plies, stacked together with specific fiber orientation and ply shapes.

They require a rigid tooling surface, to give the part form, which must be capable of withstanding compaction forces and cure process without distortion (usually temp, possibly chemical attack)

To generate specific properties, these ply stacks must be compacted together removing voids (air bubbles) and excess resin in a controlled manner, which must be maintained through part cure

Part cure can occur at Room Temperature (RT) or elevated temperature depending on the chemistry of the resin system

After part cure, the part must be released from the tool, and can subsequently be machined to shape—tool surface integrity is key

Most composite parts are bonded (occasionally bolted) to other components, metal or composite. Preparation involves careful cleaning to remove mold release, and increase surface wettability

Autoclave (5' X 10')

5' Diameter, 10' Long

- Capable of150psi internal pressure
- only using shop air now—set up for aux source if needed
- 450F Max, Nominal use for 350F max cure

Fully Computer controlled

- Controls PART Temp—ramps air faster to achieve part temp ramp
- Internal Pressure and Vacuum bag probes controlled by program

All sensor data recorded to disk for QA

Qualified for unattended running

- Can run system overnight or over weekend

Cycle cost ~2man hours, and ~$150 for power

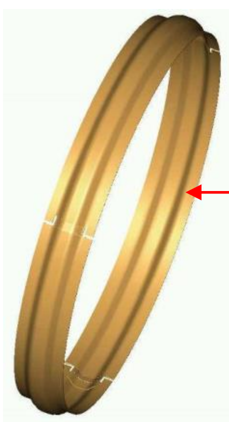
Automated Ply Cutter

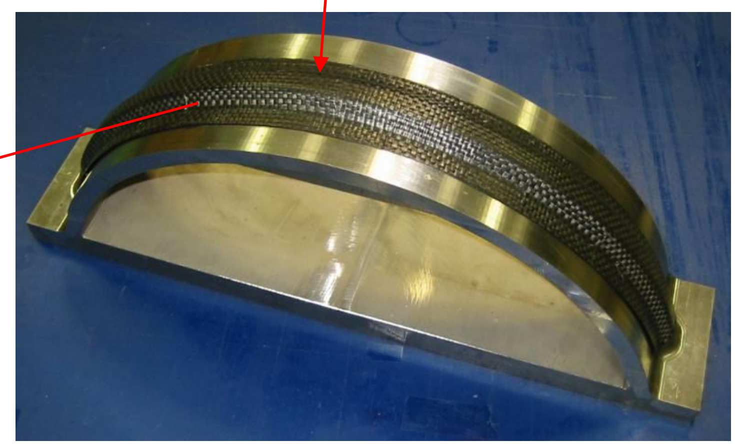
Using CAD models to design parts, we can generate 'flat patterns' to be cut on the ply cutter

- Manually generated requiring iterations
- Additional software would be helpful

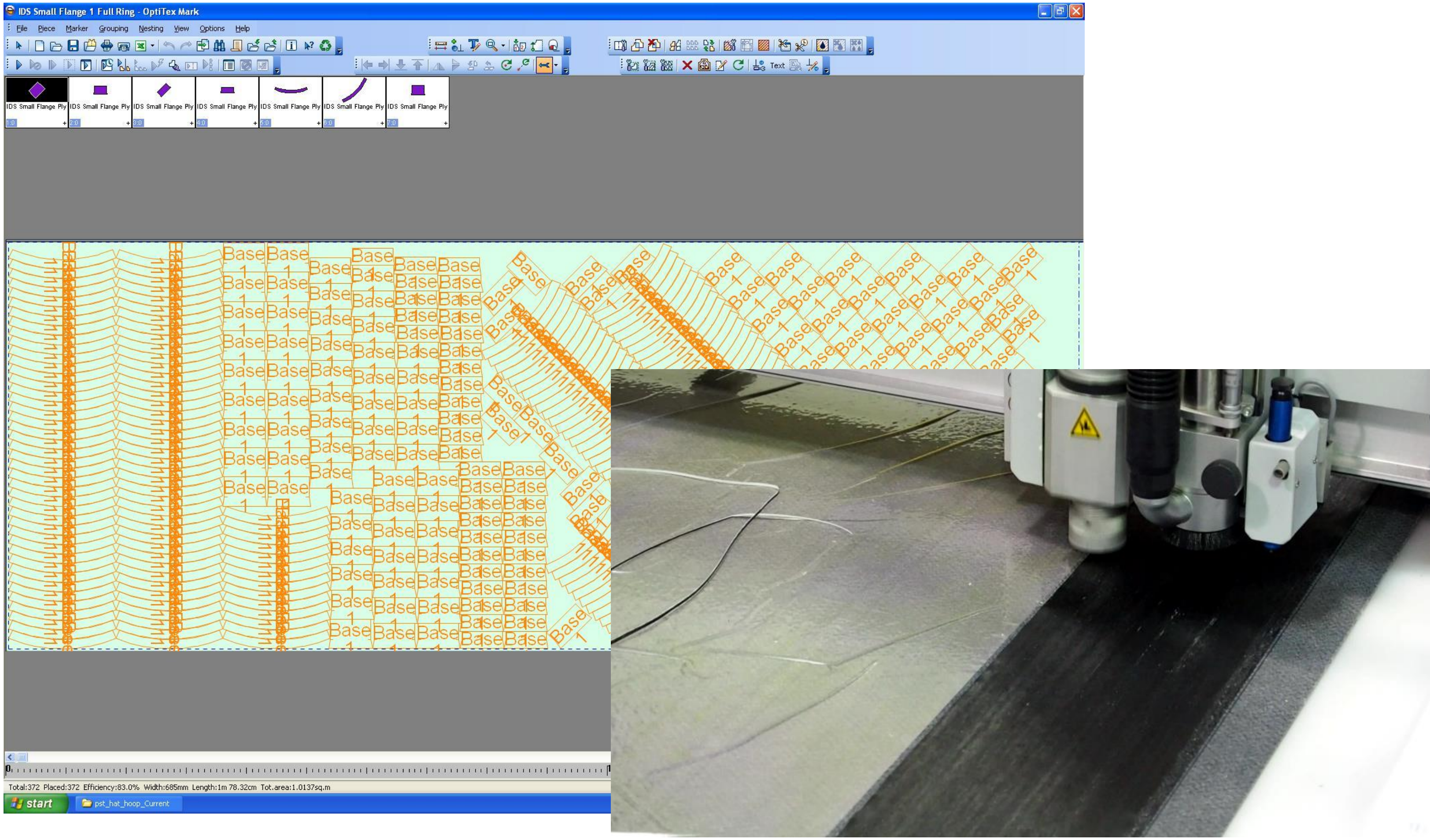
Ply cutter saves enormous amounts of labor

- Cutting plies by hand for Hat stiffener took ~4hrs each by hand
- Cut half production run (35) on Ply Cutter in 4 hours with sorting, bagging, and freezing





Automatic Ply Cutting



Freezer at -40

Typical 'Spec' life of Prepreg material at 0F is 6months

- Colder extends this, but doesnt change spec
- Real lifetime is longer, but generally shouldnt be used for production parts

'Out Time' of materials must be tracked

- Allowed out time (warm time) of materials is limited (7 to 21 days depending on resin)
- Out time is more critical than storage time, though 'out time spec' is very conservative
- Need to track all times that a given roll or individual ply of material is warm to guarantee that it maintains 'spec'
- Also need to track storage time

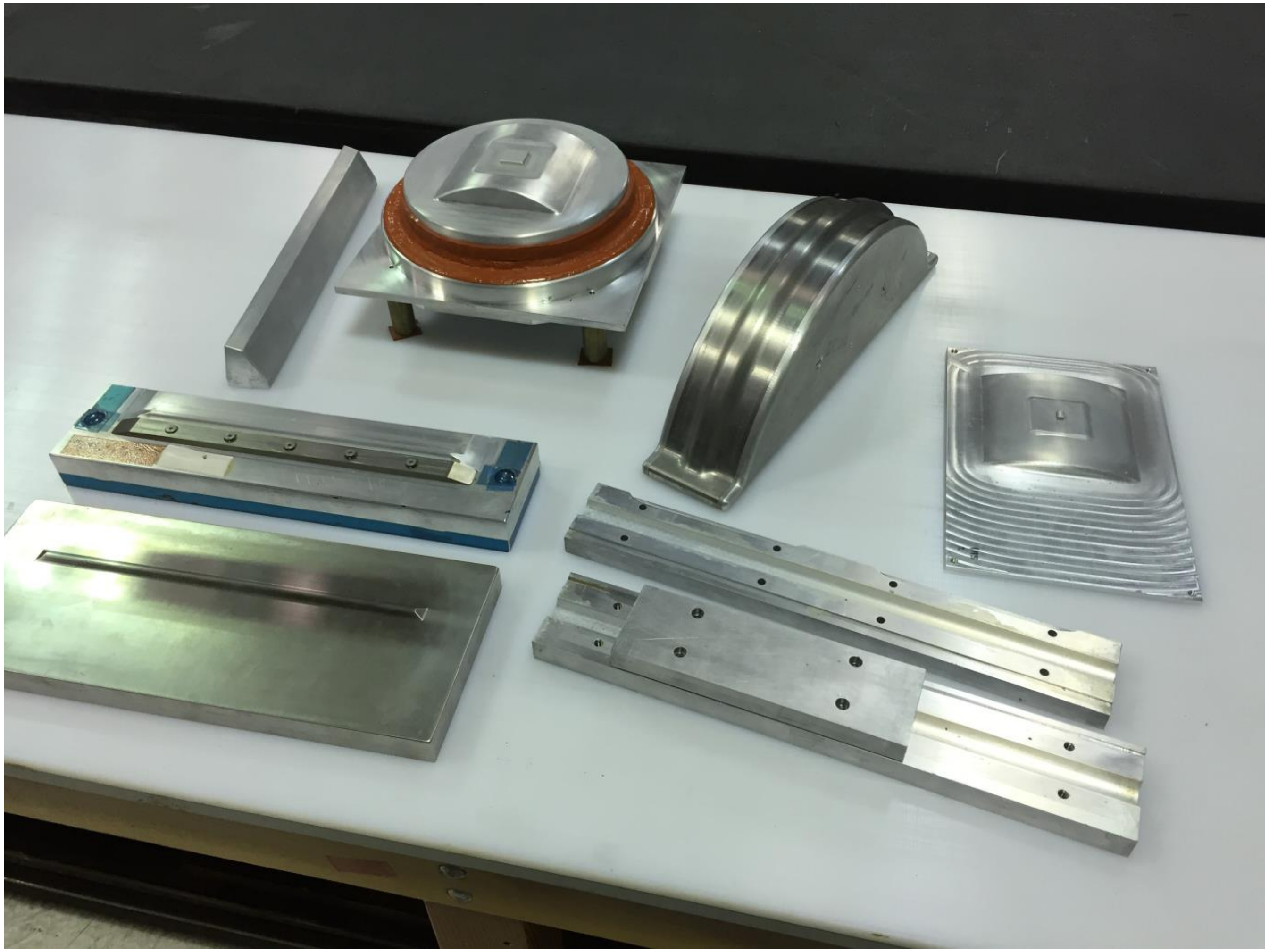
Acquired -40F/C Walk-in Freezer installed behind 77 Assembly shop for Deep Storage of production lots

- On EMCS for notification of out of temp extremes
- On facilities maintenance schedules

-20C Chest freezer for staging assembly lots in Fabrication Area

Generally only need to be wary when high value lots are present

The Tool (or Mold)



Common Tooling Materials

- 6061 Al Alloy—light weight, low thermal mass, easiest to machine
  - High CTE (23.6ppm/C), less tool longevity than Steels
- Steel—moderate CTE, available in more form factors (pipe)
  - Needs Nickel or Chrome plating to maintain surface integrity
- Stainless Steel (300)—stable surface, easy to machine
  - More expensive than Steel or Aluminum
- INVAR—near 0 CTE—good match to Carbon Composites
  - Extremely expensive, hard to machine, but industry standard for challenging laminates with long production runs
- Monolithic Graphite—good CTE match to Carbon Composites
  - Easy to machine, but requires special equipment
  - Low tool integrity—short production runs or several tool re-works
  - Moderately expensive
- Composite Tooling—best thermal performance, good CTE match
  - Complicated manufacturing process—requires ‘Master’ to create mold
- ‘Tooling Board’ (foam, cast plastics)—good for quick turn around large tools
  - Limited temperature performance, CTE 1.5-4X as high as Aluminum

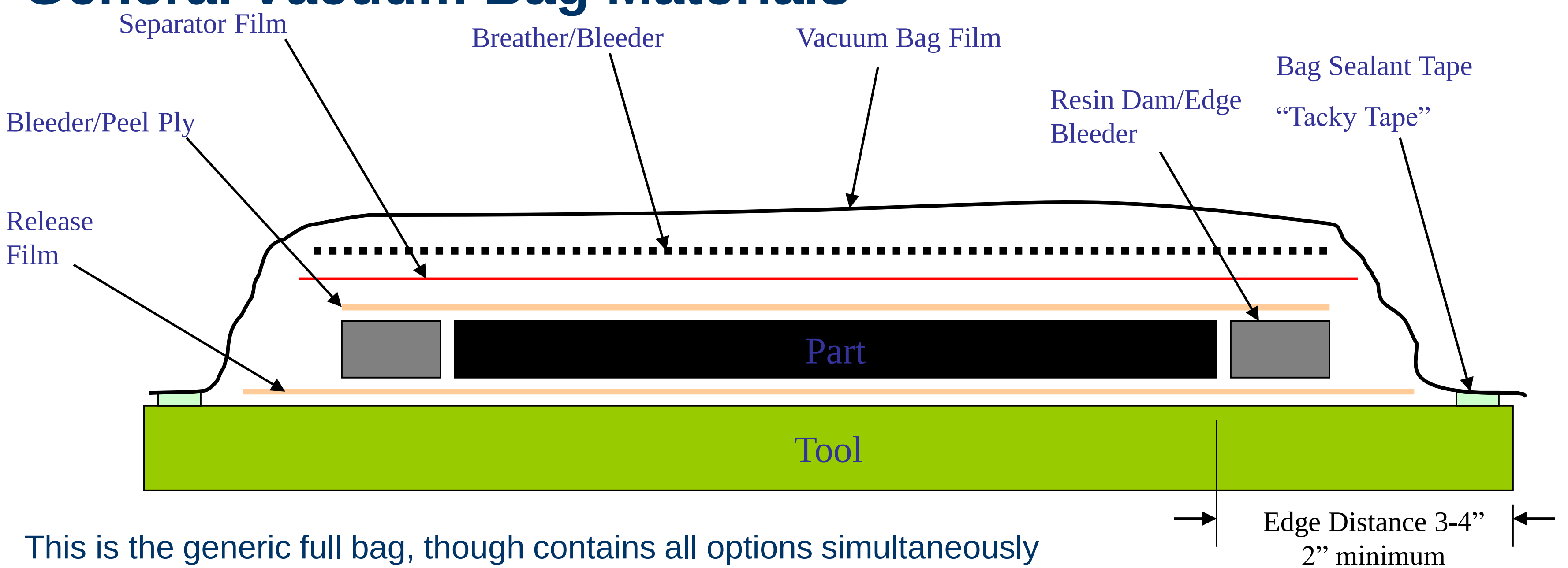
Layup Process Goals

- Vacuum bagging has two equal goals
  - Compaction
  - Resin Control
- Getting good compaction is easy
- Getting good resin control is an artform
- Pre-preg is specified by mass
  - FAW GSM per ply (Fiber Areal Weight in grams/m^2)
  - Approximate resin % by Volume
- During the layup process, we must manipulate the resin % through bleeding via bagging materials to achieve desired Fiber Volume fraction (Modulus)

Elements of the Curing Process

- Distribute vacuum and autoclave pressure
  - Breather
- Control resin movement
  - Resin dam, flashbreaker tape
- Remove excess resin
  - Bleeder, peel-ply
- Allow part removal from tool
  - Release ply, release agent (wax)
- Allow bag removal from part
  - Release film, separator ply
- Create useable part surfaces
  - Peel ply

General Vacuum Bag Materials



This is the generic full bag, though contains all options simultaneously

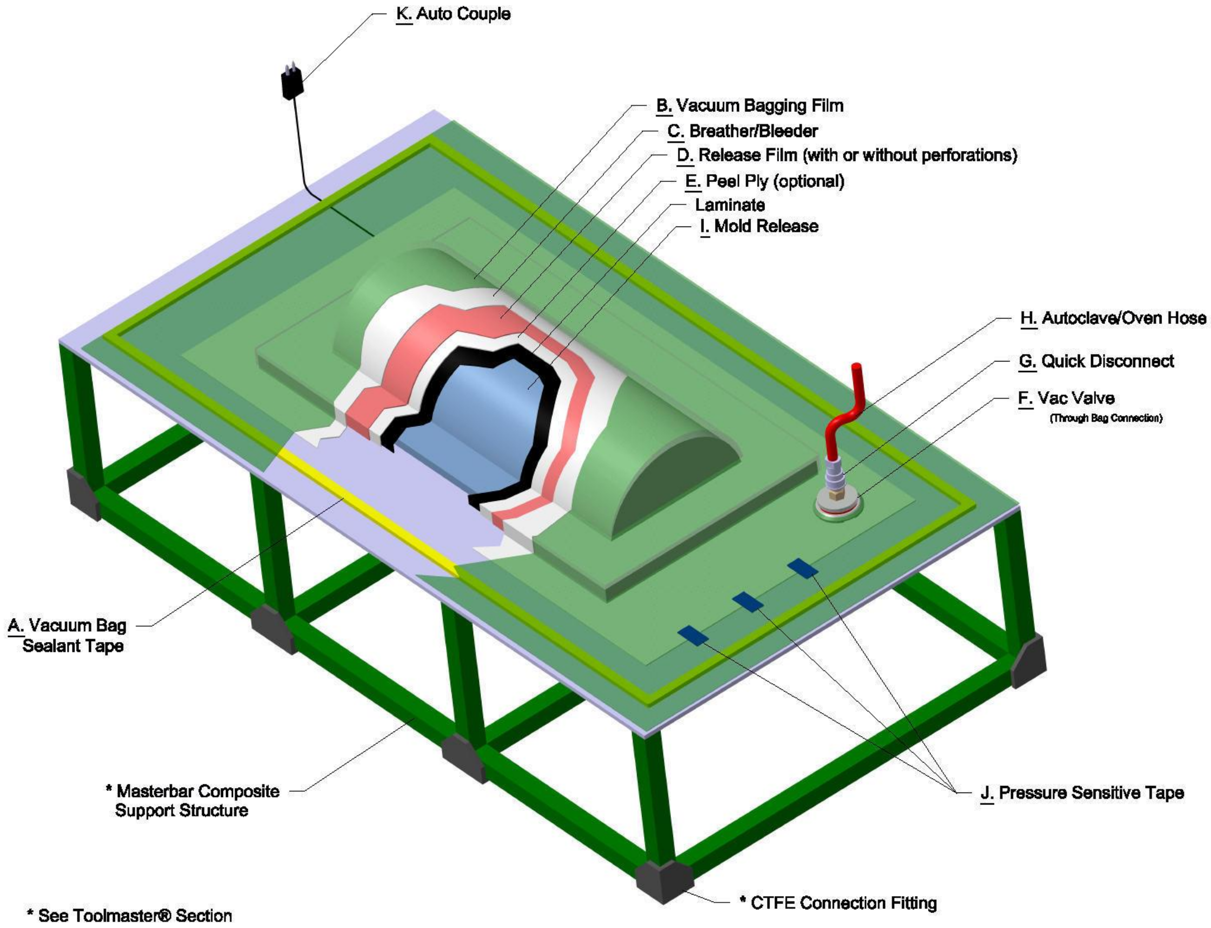
- Minimum bag includes only separator film (perforated) and breather which then becomes the bleeder
- Controlled bleed bag uses Bleeder/Peel Ply and separator film (impermeable) in addition
- Need for Resin Dam/Edge Bleeder depends on part edge thickness

Relative Overhangs are important—Separator Film protects Breather/Bleeder from getting stuck to part/tool by excess resin

Release film could be permanently attached to tool or as wipe on film (mold release)

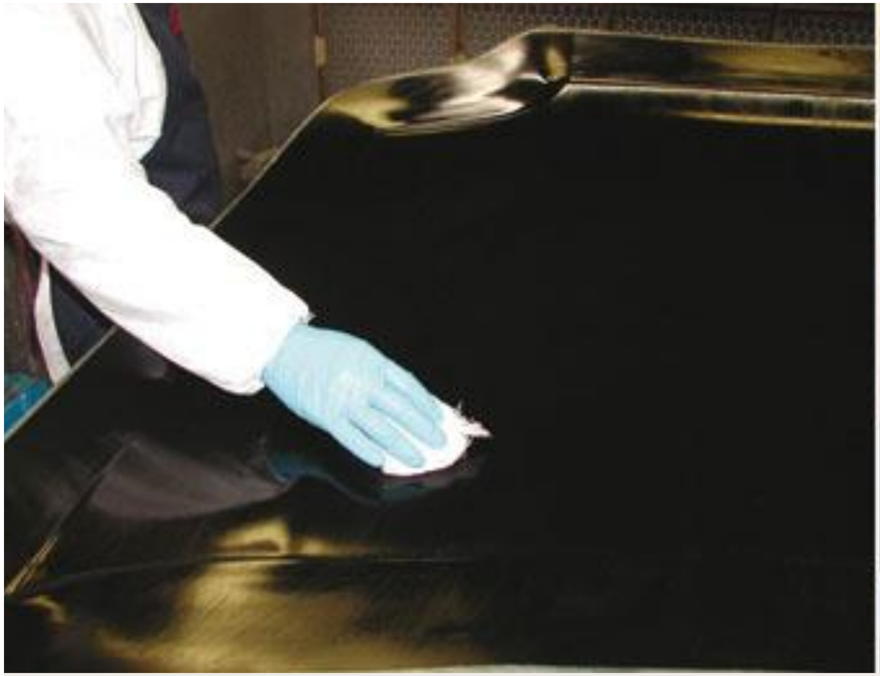
Two side Bleeding would place another Bleeder/Peel Ply between part and release film (presents certain complications, but sometimes required)

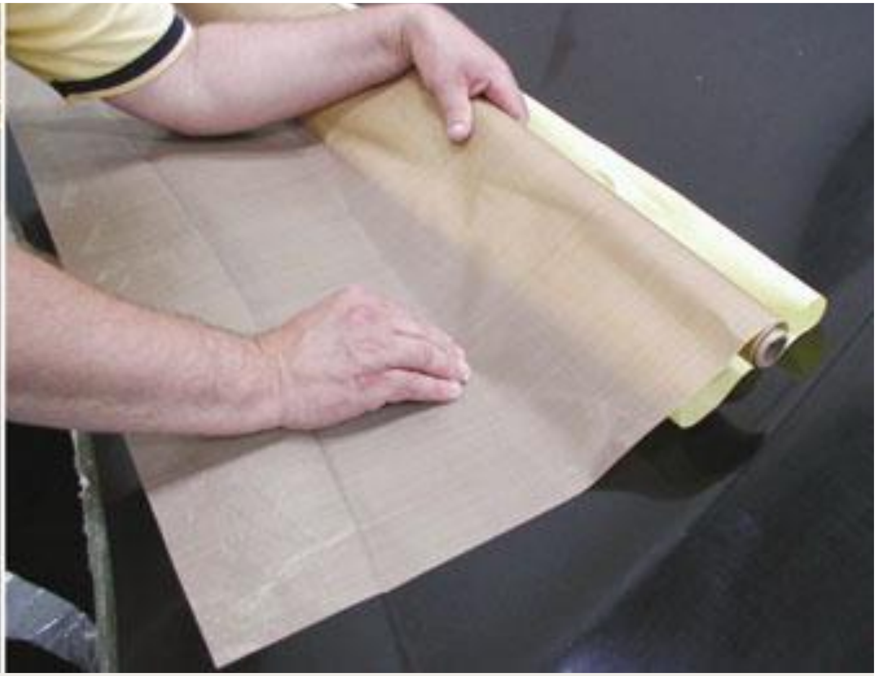
Generic Vacuum Bagging Setup



Preparing for Mold Release

Allows your part to be removed from the tool.





Release Agent (Wax): Good for any shape, but requires reapplication for every cure cycle. Must be applied properly, depends on tool material.

Release Cloth (Tooltec™): Robust, multi cycle, but must be replaced when overly used (labor intensive). Only works on flat or near flat surfaces.

The Layup Happens
(more in later section at CERN)
Then the bag is applied

Application of Release Ply

After lamination, prevents bagging materials from bonding to laminate.

Peel Ply or Release Ply: Protects laminate from bagging material, ensures clean release, provides even surface finish. Must be applied *flat* on all surfaces, but *can be joined or overlapped*.
This is also the Bleed system to extract appropriate amount of resin.

Release Film and Breather/Bleeder

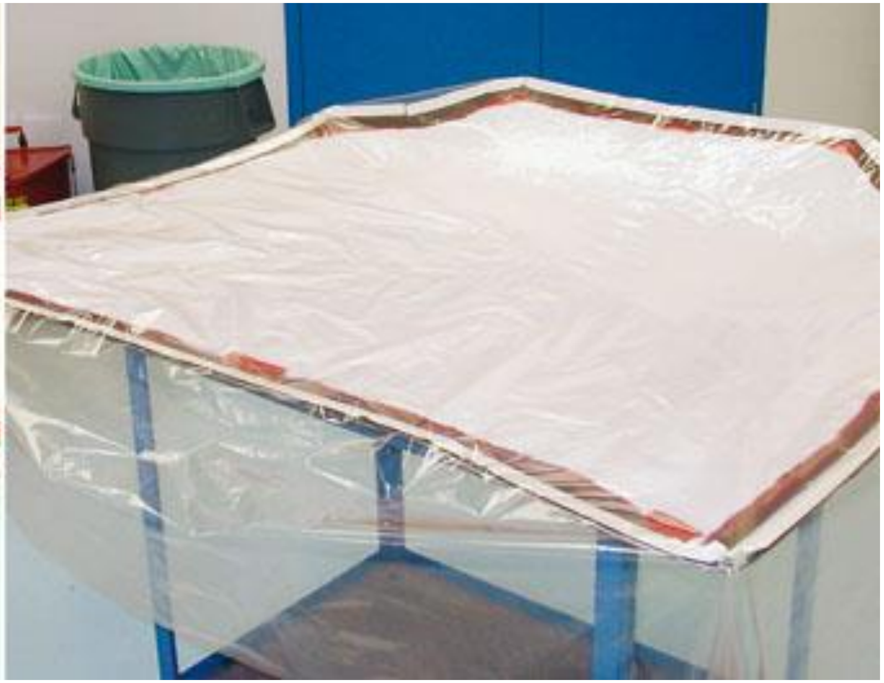
Distributes vacuum/pressure evenly over the laminate.

Release Film (Plastic Sheet): Can be loosely applied over peel ply, but must not bridge. Can be perforated or not. Prevents breather from becoming saturated with resin, starving laminate, and cutting off vacuum. Perforations allow for greater resin flow/loss. Need to experiment for rich or high-volatile systems.

Breather/Bleeder: Non-woven textile, 'distributes' vacuum and bleeds laminate to differing degrees depending on release film perforation and breather thickness. Can be applied in multiple layers, but bridging should be avoided. Also used as 'insulator' to even heat input to tool to ameliorate thermal gradients.

Fitting the Vacuum Bag

Provides compaction, degassing, and application of autoclave pressure.



Bag Sealant (« Tacky ») Tape: Applied continuously to tool all the way around the part. Must be rolled onto tool for good seal. Can be doubled, but care should be taken to avoid penetrating leaks.

Vacuum Bag: Must be cut 30-40% larger than tool surface. In most cases, the material does not stretch appreciably, so bridging must be avoided (especially for autoclave cure). Care should be taken on curved surfaces and corners.

Bag Sealing Techniques

Create well sealed, bridgeless bags.

Sealing on long flat surfaces: Remove tape backing and smooth bag slowly and progressively, in order to avoid creating leak channels, which can be corrected, but are time consuming. Seal bag by pressing down flat, do NOT stretch bag during sealing, or bridges and excess will be created in corners.

Creating Pleats: Pleats will be necessary near corners, curves, and wherever excess bag is bunched up. They are also critcial for avoiding bridging on complex shapes. It is preferable to include pleats regularly on the long edges of irregular bag shapes.

Sealing Pleats: Make sure vacuum tape is sealed completely at the root and end of the pleat. These are locations where leaks typically occur. It may help to stretch the pleat while pinching at top and bottom to create the seal.

Installing the Vacuum Fitting

One fitting will be used for vacuum, and one for the pressure probe line.

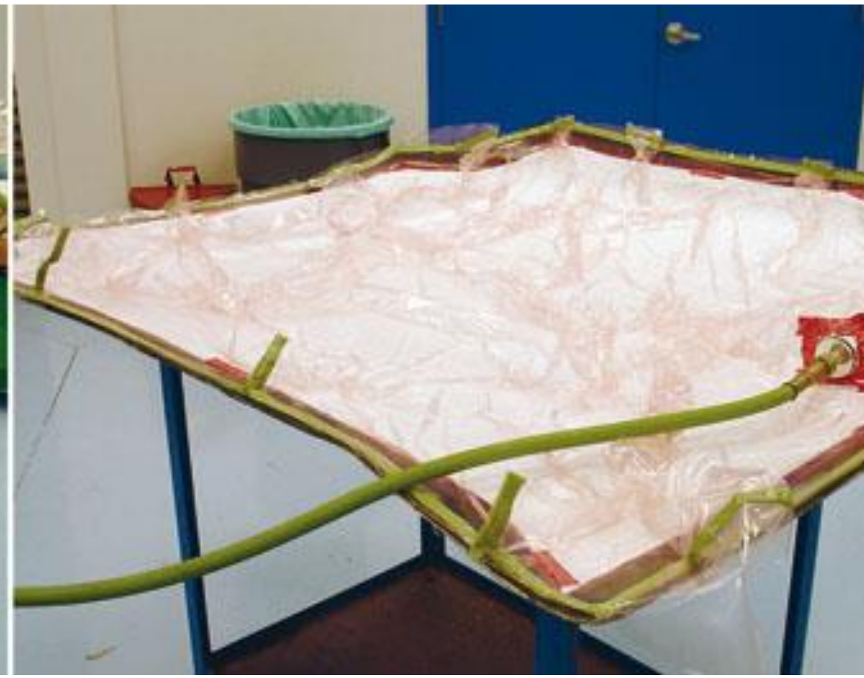
Foot of vacuum fitting must be inserted into bag: Remember to do this before completely sealing the bag. Cut a small X where the fitting will penetrate. Find a position on the mold where the fitting will not sit on the part itself. Make sure there is adequate breather for conduction.

Close vacuum Fitting: There are ¼ twist and threaded varieties of vacuum fitting. In both cases, make sure elastomer seal is outside the bag and against bag material. Stretch bag to ensure that there are no wrinkles against the foot of the vacuum fitting.

Vacuum Fitting Placement

Fitting can be applied either against the mold surface or on a pleat.

Against the mold surface is most secure: However, sometimes there is no space for the fitting, or applying to the mold (for example a curved mold) would cause bridging and potential bag failure.



In a pleat: Allows placement on any mold, anywhere. However, the pleat must have adequate breather to ensure conduction to the bulk of the tool surface, and it should be strain relieved so as to aviod bridging of the pleat where it contacts the tool.

Part Compaction *is* Resin Control

- Resin Control assures that
  - the resin is evenly distributed, and that
  - the appropriate volume fraction is achieved in the part
- Compaction forces accomplish two things
  - Force plies together and press out or reduce void fraction
  - Provides driving forces for Resin Control
- Improper bag design can impact compaction
  - Sharp edges, or bridging across pockets or tight radii can lead to bag rupture or reduced compaction forces
  - Some areas cannot be reached without caul plates or pressure amplifiers
- Significant amount of labor is spent bagging a part—frequently as much as laminating
- Material can be ordered ‘Net-Resin’ or ‘Resin-Rich’ affecting Resin Control Requirements
  - Ramifications for lamination (differing resin content in pre-pregs affect drape and tack)
- Wet lay-ups by their nature are extremely resin rich requiring different bag materials for resin control

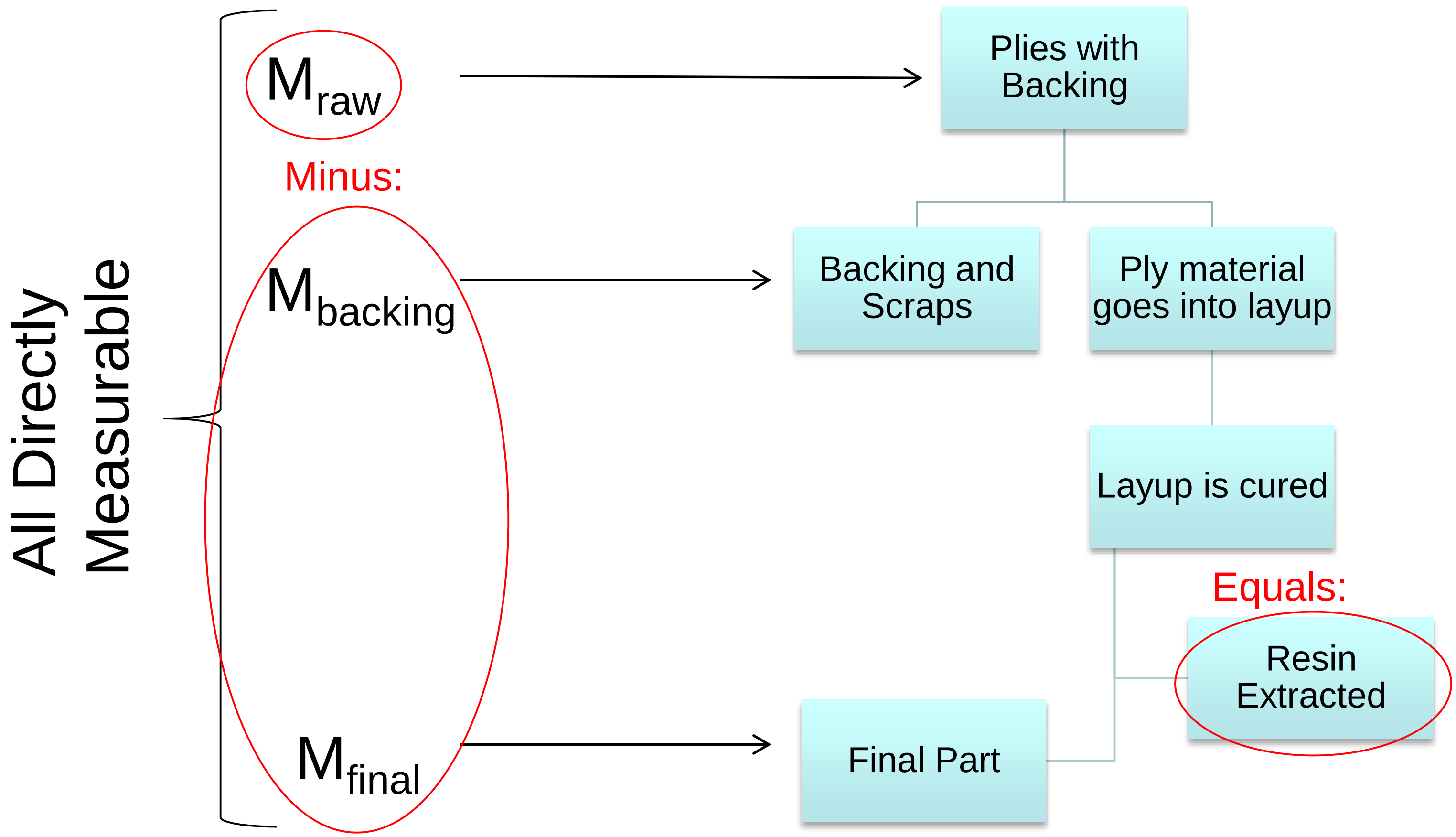
Resin Control Method Depends on Amount of Resin

- Removing liquid spilled on a carpet is an excellent analog for this process
  - Think of Resin Content Control as a controlled blotting process
- Resin Content is controlled by extraction of a specific volume of Resin—usually over the area, sometimes by edge bleeding
- Blotter materials are called ‘Bleeder Plies’ and come in various thicknesses and properties
  - They extract a re-producible volume per unit area
  - Because they come in a finite number of thicknesses, accuracy for thin parts, where only 1 ply of the thinnest bleeder material can be used, can become an issue…
- Target Volume fraction depends on accuracy of bleed process
  - Thin parts have very small volumes to extract, so accuracy usually dictates Net Resin System and minimal extraction.
  - Thicker laminates have larger volumes and a Bleed system can be more accurate way to achieve desired resin content
- In ordering a pre-preg, you specify the volume/mass fraction of resin
  - This is always a little ‘rich’ as some resin is always lost during lamination from transfer or bleeding
  - ‘Net Resin’ which is ~2-5% rich (~55% volume fraction)
  - Resin Rich (50% or higher) is usually specified for ‘Appearance Parts’ or thicker laminates where volumetric flow is larger or a resin rich finish is desirable
- Net Resin system is only option if no bleeding is possible or desired (some tool designs)

Determining Resin Content

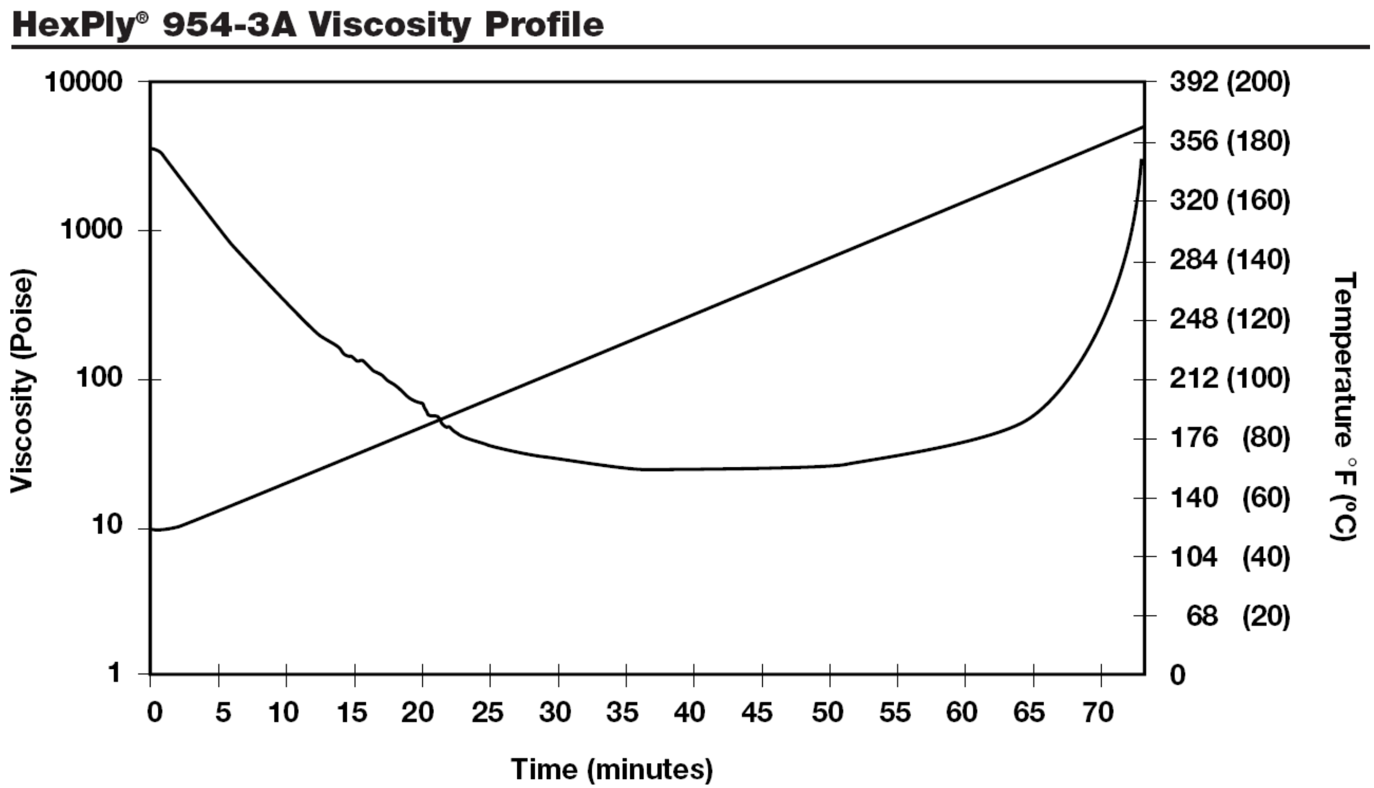
- Resin content can be measured during QA, but feedback is **slow**
  - Acid digestion
  - Micrograph analysis
- Immediate feedback can be had by careful weighing during the layup process
- This requires diligence, but is an integral part of the construction
- The arithmetic will be covered tomorrow, but it is important to weigh properly as a first step

Weighing Procedure



Curing Process
and
Tool/Part interaction

Resin Viscosity & Gel Temperature



This is a typical viscosity profile—μ drops first from increased temp then increases from onset of cure and cross-linking—in this case a 350F cure Cyanate Ester system is shown

Tells you that the Gel Temp is likely below the Cure Temp

Best time/temp for compaction is @ 175F

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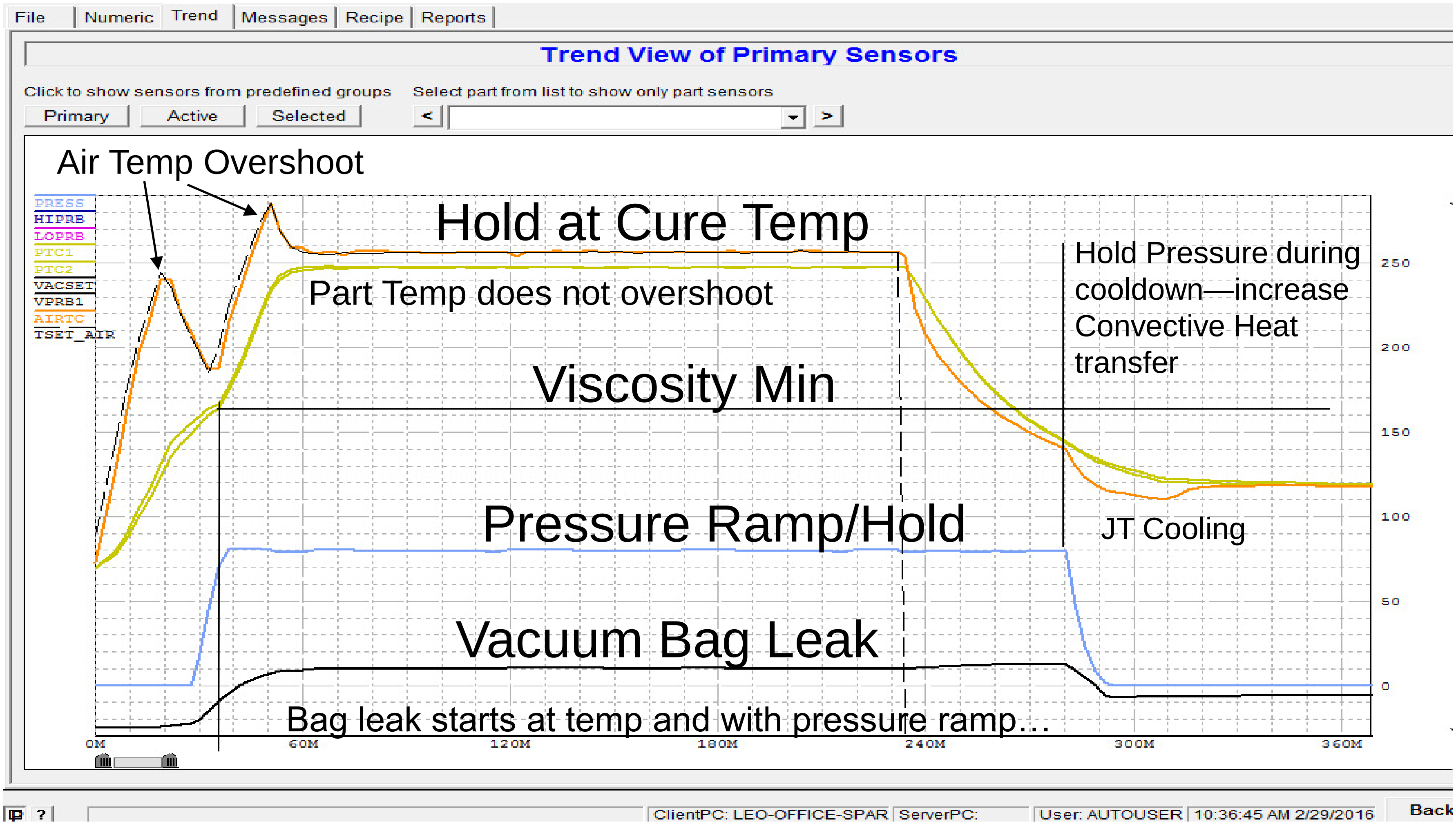
Autoclave Cure Cycle (Thin Flat Plate)

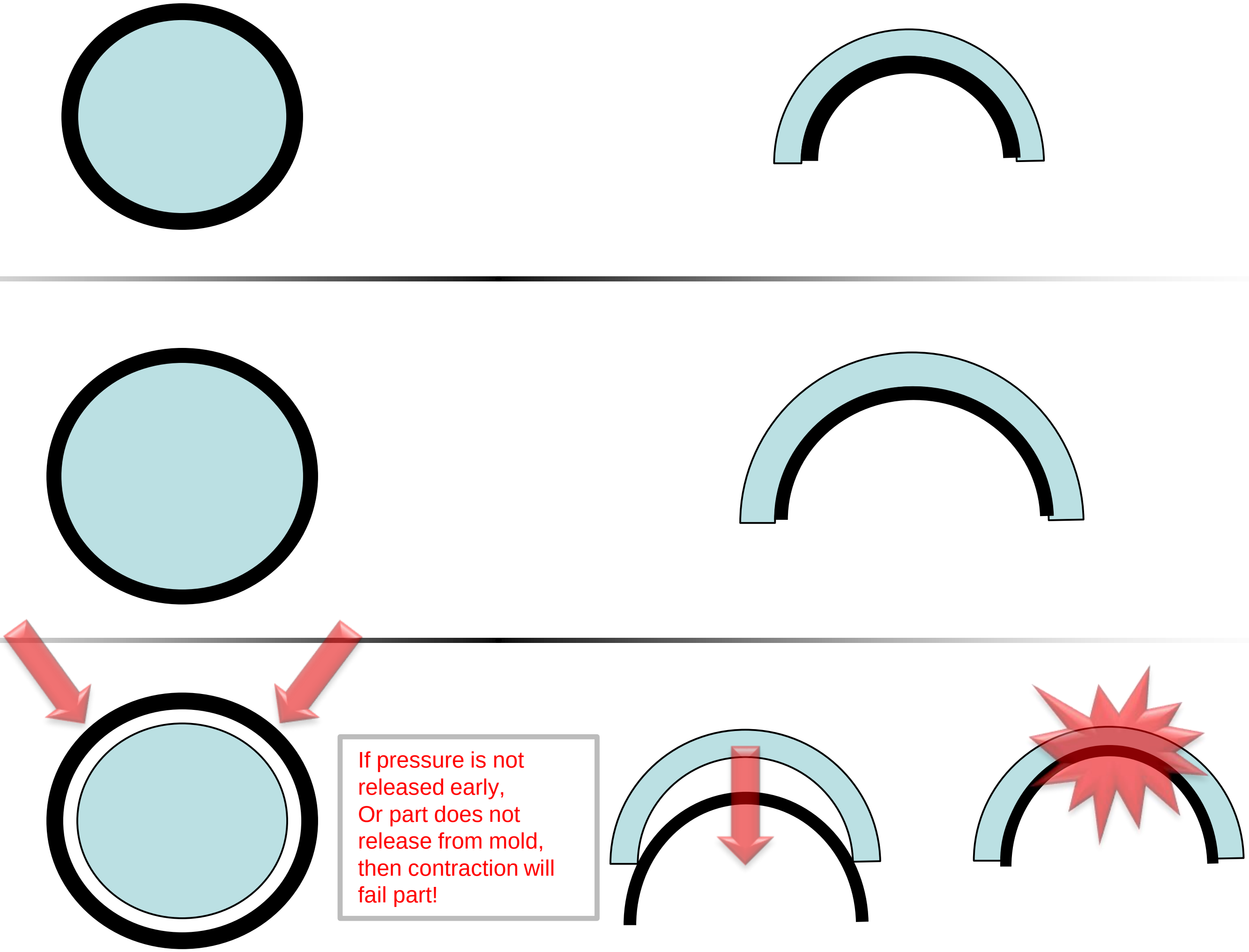


Part Size And Mold Expansion During Cure

Part at RT
on Mold

Part at Gel
Temp on Mold

Part final
size



Cure ‘Recipe’ (phasing of temp/pressure are part shape dependent!

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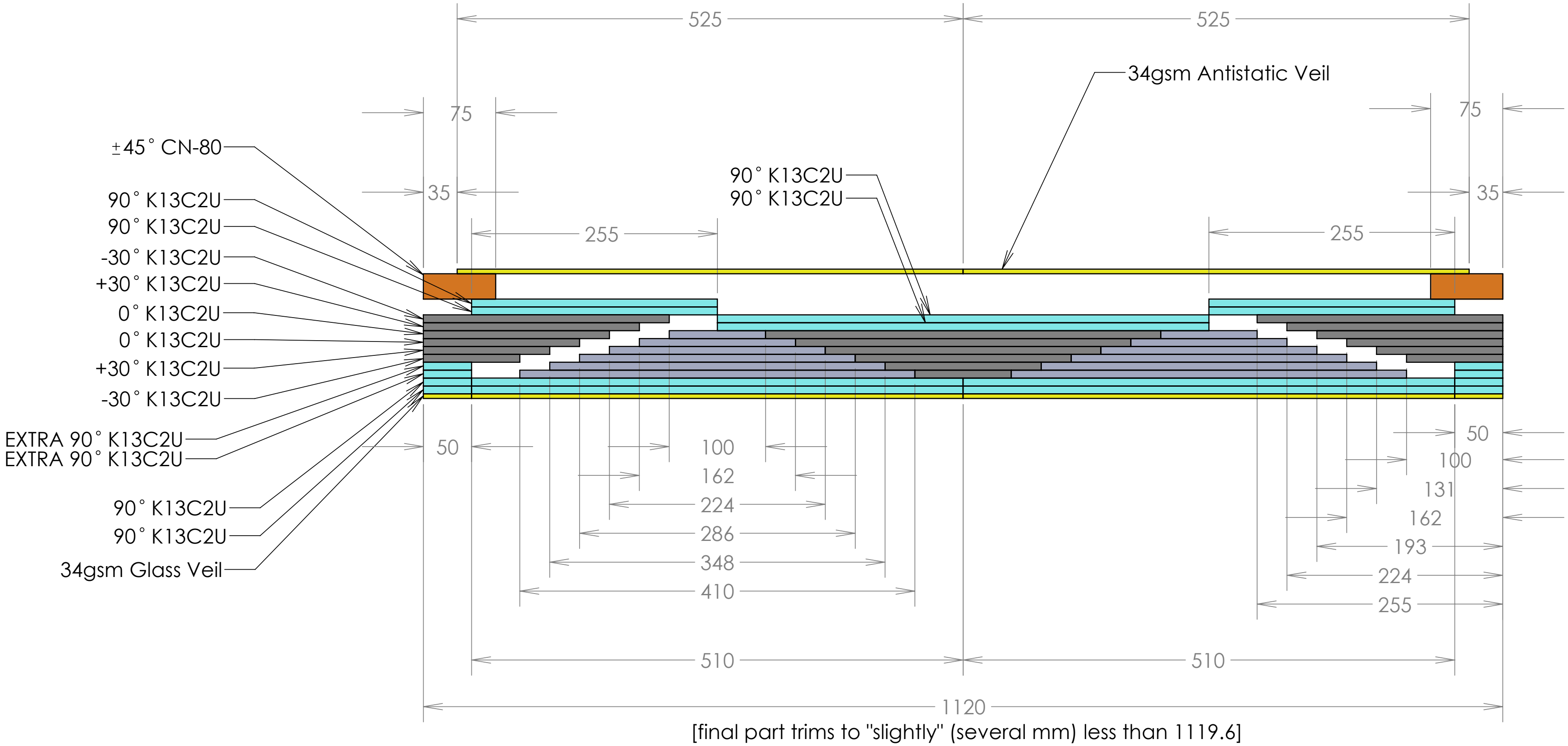
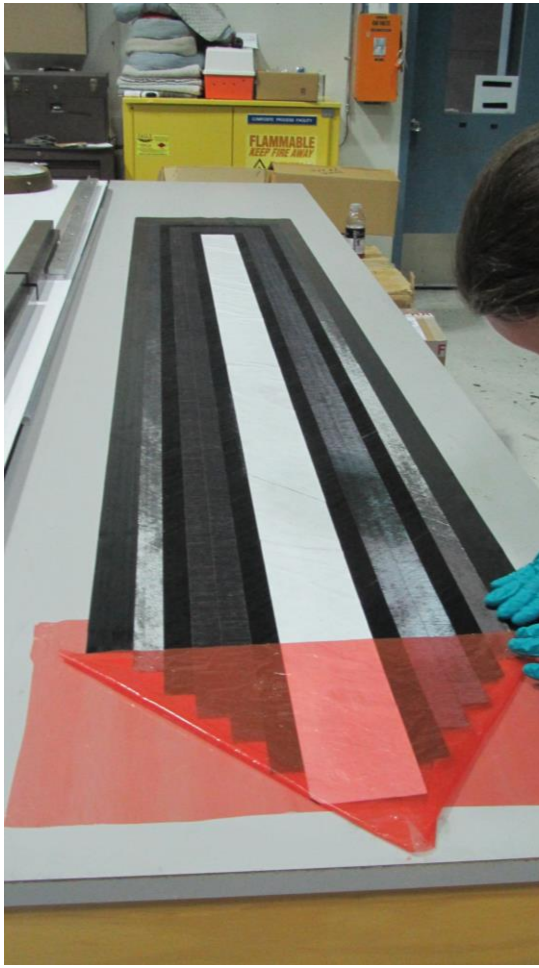
Ply Stacks—useful for thin-walled cylinders



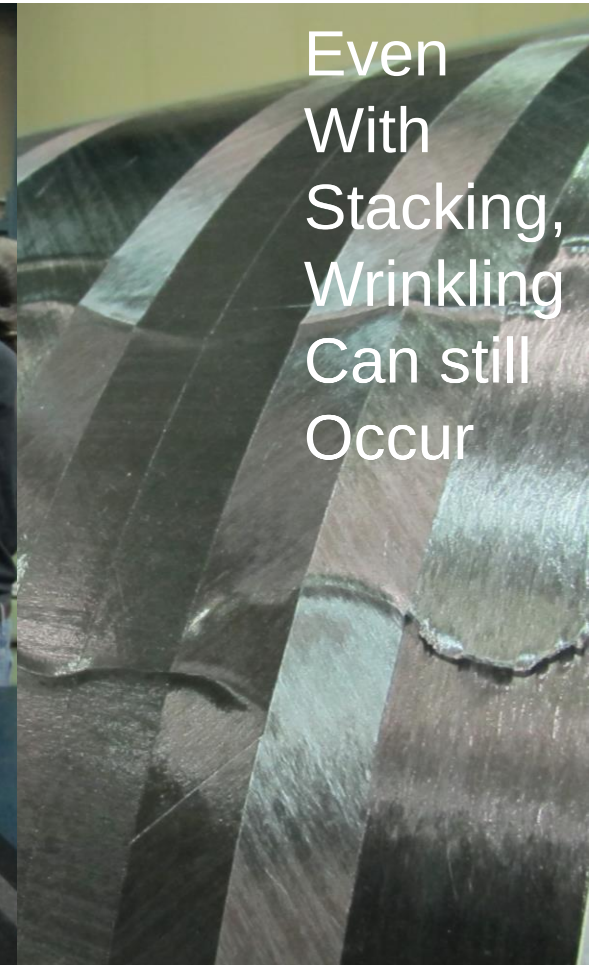
Pre-orients fibers, makes thin (30-50μm) lamina easier to handle and apply to tool

Ply Stack on a Cylinder



Pre-Assemble

Apply with Tension

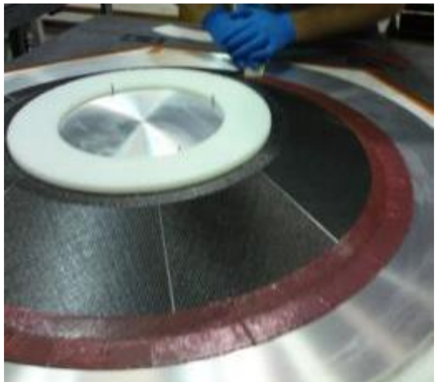


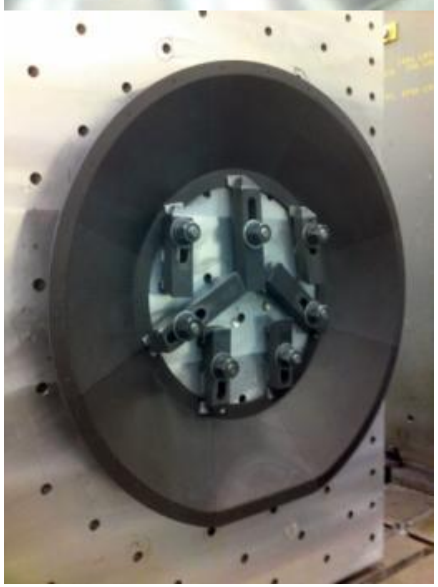
External Pressure…

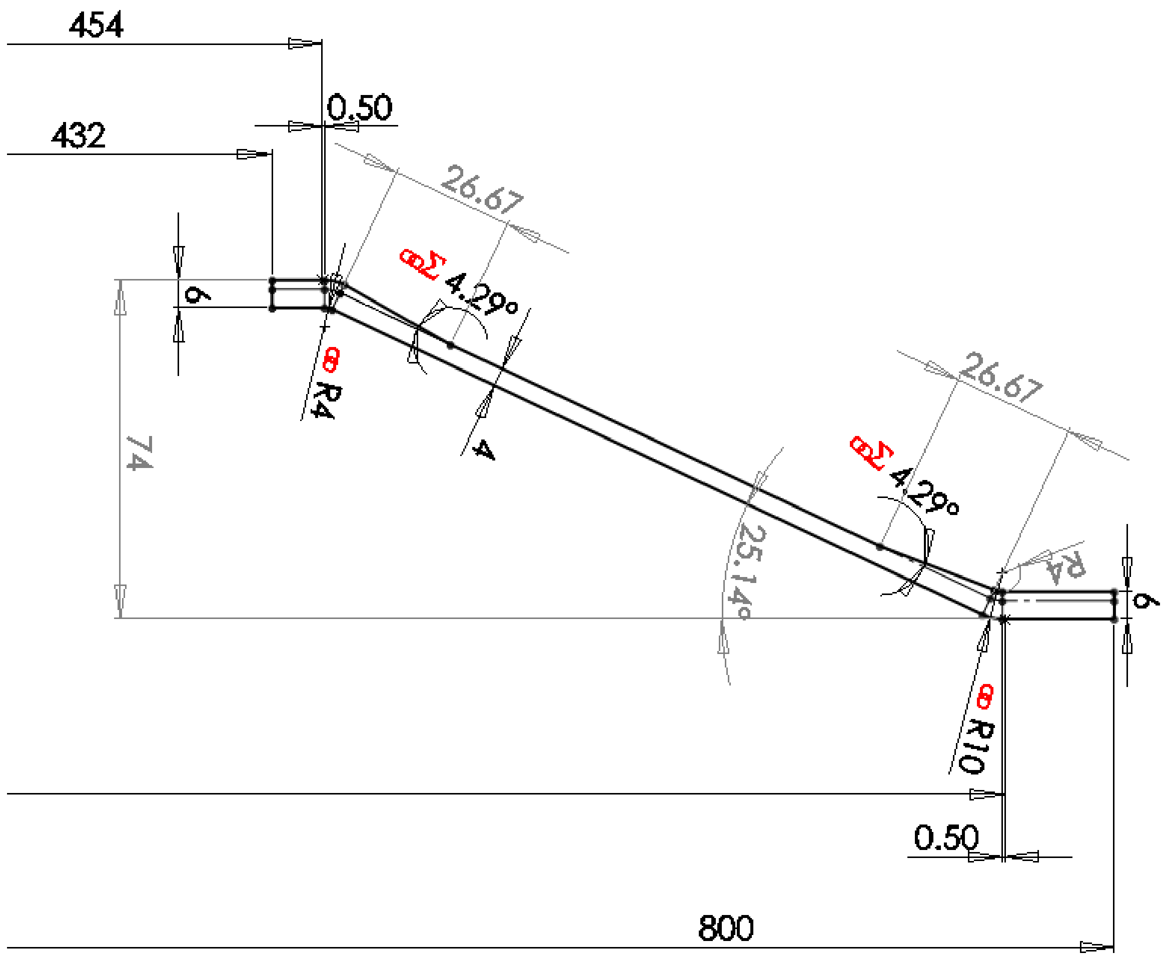
IDS Flange

Sample Layup Ply Book

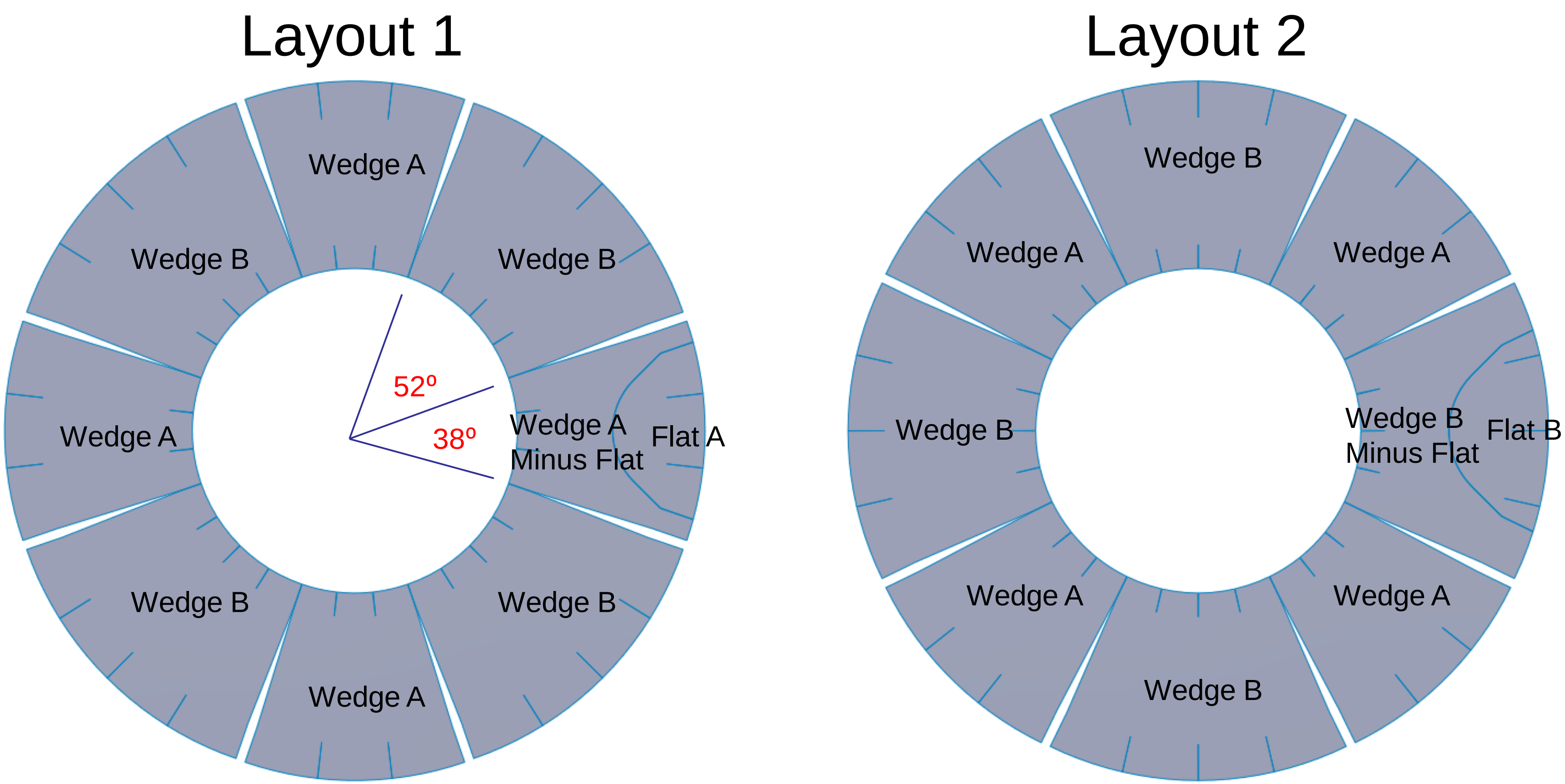
Nominal Cross-Section of Part





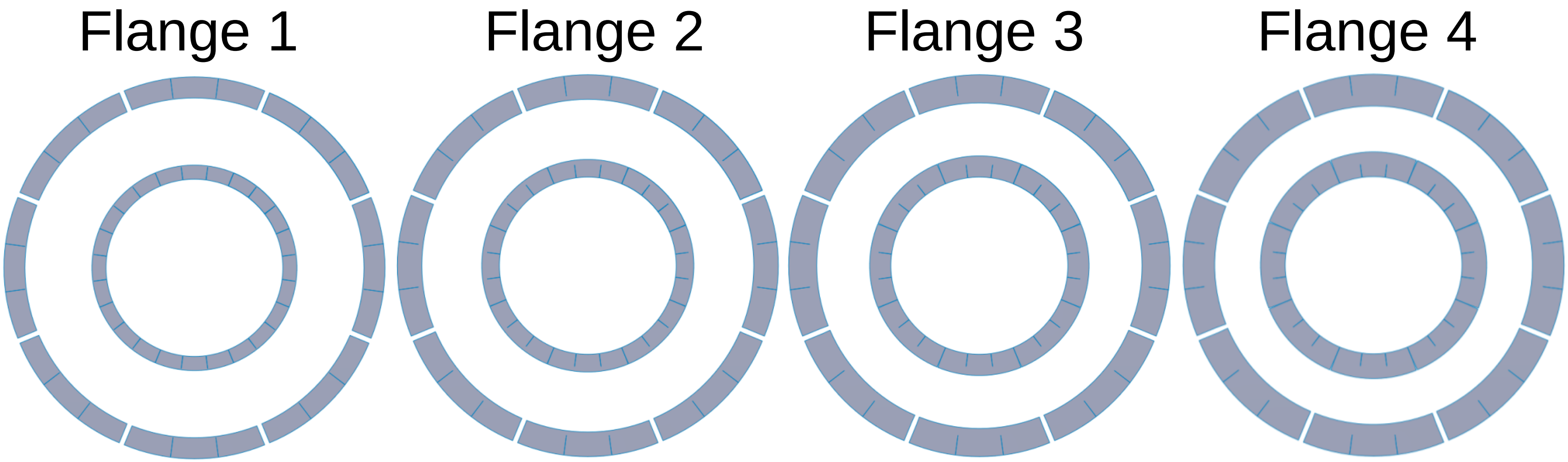


Ply Layouts



The staggered angle variation (38º to 52º) allows good overlap from ply to ply.
Half the plies must be cut at 0/90, and half at ±45.
0.5mm gaps are provided between plies.

Extra Flange Buildup



Flanges are thickened by interleaving extra ring plies at the inner and outer radii.
The extra thickness tapers into the cone in 4 steps.
Half the plies must be cut at 0/90, and half at ±45.
Clock successive flange layers by approx 3.5° to ensure overlaps of darts/breaks
(3.5° is equivalent to about 1/2" on inside radius, 1" on outside)

Stackup and Plies To Cut Out

STACKUP				PLIES TO CUT OUT									
Ply Number	Layout / Ply Shape	Fiber Angle (As Cut)	Flange Ply Clocking	A			B			inner and outer radius pieces all flanges			
				Wedge	*WedgeMinusFlat*	*Flat*	*Wedge*	*WedgeMinusFlat*	*Flat*	*Flange 1*	*Flange 2*	*Flange 3*	*Flange 4*
0 ?	Glass+Resin?												
1	Layout 1	±45		3	1	1	4						
2	Flange 4	±45	~0.0°							8			
3	Layout 1	0/90		3	1	1	4						
4	Layout 2	±45		4			3	1	1				
5	Flange 4	0/90	~0.0°							8			
6	Layout 2	0/90		4			3	1	1				
7	Layout 1	±45		3	1	1	4						
8	Flange 3	±45	~3.5°								8		
9	Layout 1	0/90		3	1	1	4						
10	Layout 2	±45		4			3	1	1				
11	Flange 3	0/90	~3.5°								8		
12	Layout 2	0/90		4			3	1	1				
13	Layout 1	0/90		3	1	1	4						
14	Flange 2	0/90	~7.0°									8	
15	Layout 1	±45		3	1	1	4						
16	Layout 2	0/90		4			3	1	1				
17	Flange 2	±45	~7.0°									8	
18	Layout 2	±45		4			3	1	1				
19	Layout 1	0/90		3	1	1	4						
20	Flange 1	0/90	~10.5°										8
21	Layout 1	±45		3	1	1	4						
22	Layout 2	0/90		4			3	1	1				
23	Flange 1	±45	~10.5°										8
24	Layout 2	±45		4			3	1	1				
25	Antistatic												

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Ply 1

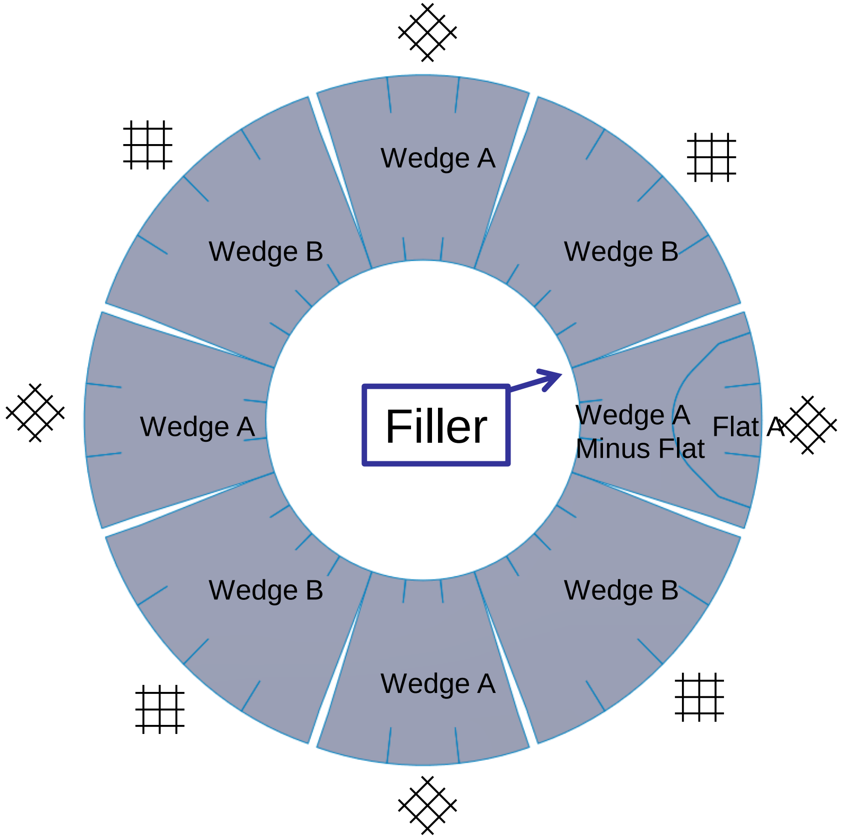
Layout 1

Angle ±45

Mass:

fiber+backing: ________ g

backing only: ________ g



SIGN OFFS:

Layup by ________

Layup check ________

Backing check________

Ply 2

Flange 4

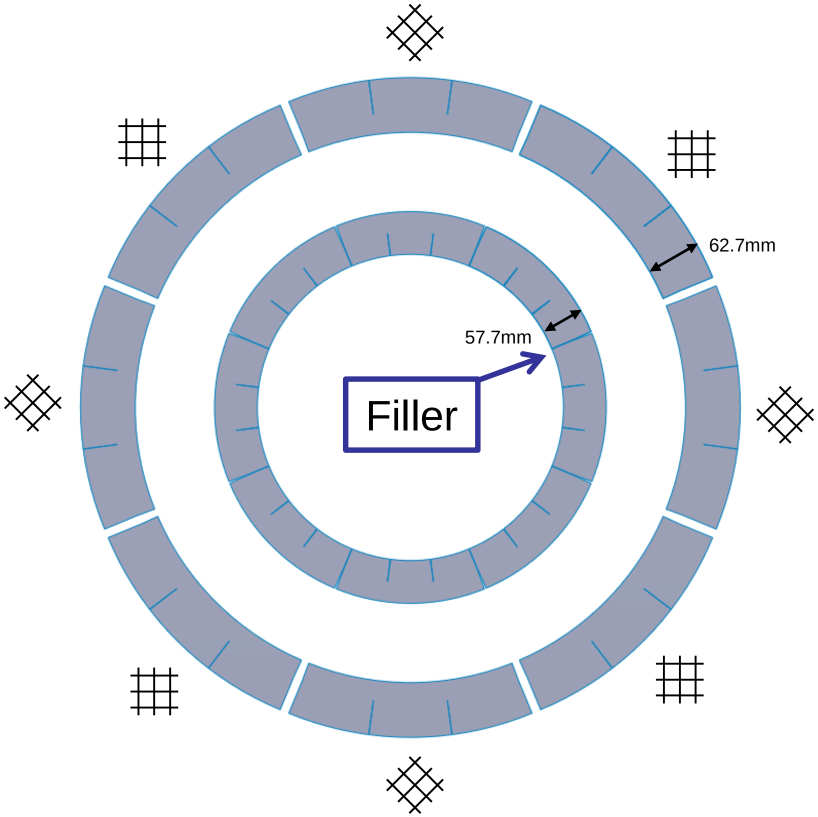
Angle ±45

Clock 0°

Mass:

fiber+backing: ________ g

backing only: ________ g



SIGN OFFS:

Layup by ________

Layup check ________

Backing check________

Final Thoughts

- With composites, fabrication is an empirical process
  - The final procedure will never be known until it's been tried at least once
- Documentation and record keeping are instrumental to part quality
  - In both process determination and final part QA
- Attention to detail and manual accuity are critical to successful fabrication