

# TOUCHSTONE

RESEARCH LABORATORY, LTD.

## ***PRODUCTION OF AL MMC CASES FOR IM TESTING***

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Touchstone Research Laboratory***

*NDIA Insensitive Munitions and Energetic Materials Technology Symposium  
May 11 – 14, 2009*



# *Outline*

## ■ **Technology Overview**

- Touchstone Research Laboratory
- Metal Prepreg Technology
- Materials
- AI MMC Lamina Properties
- AI MMC Process Background

## ■ **AI MMC Cylinder Production**

- MMC Design Tool Calibration and Validation
- Validation Testing
- IM and Static Firing Test Cylinders

## ■ **Conclusions and Future Work**

**Material Testing**



**Industrial Problem Solving**



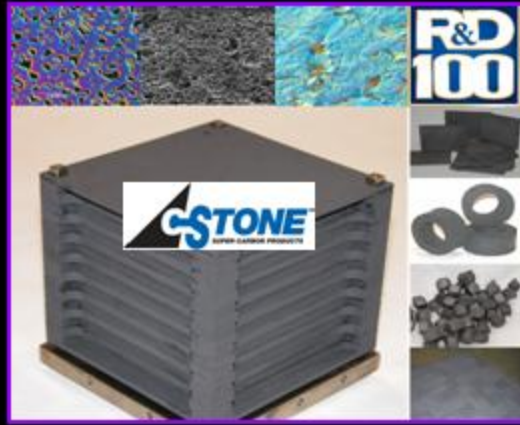
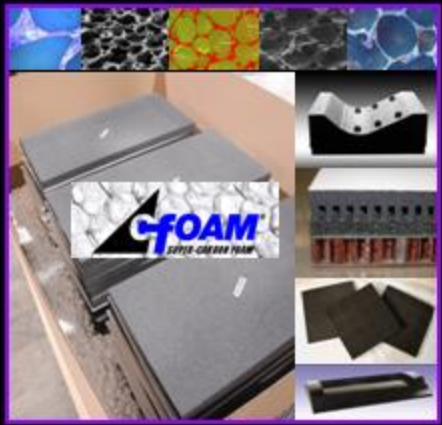
**Advanced Composites**



**Outsourced R&D**



**Products**



# *Metal Prepreg Technology*



Tape Width – 0.25 to 1.50"  
Tape Thickness – 0.007 to 0.020"  
Tubing – 0.25" OD, 0.015" wall  
Angle – 0.375" per leg, 90° angle  
Other sizes and shapes possible



# *Fiber and Matrix Typical Properties*

Property	Units	Fiber	Matrix
Chemical Composition	wt. %	>99 Al <sub>2</sub> O <sub>3</sub>	99.99 Al
Melting Point	°C	2000	660
	°F	3632	1220
Filament Diameter	μm	10-12	-
	in (10 <sup>-4</sup> )	4-5	
Crystal Phase		α- Al <sub>2</sub> O <sub>3</sub>	-
Density	g/cm <sup>3</sup>	3.9	2.7
	lb/in <sup>3</sup>	0.141	0.098
Tensile Strength	MPa	3100	40-50
	ksi	450	6-7
Tensile Modulus	GPa	380	62
	Msi	55	9
Elongation	%	0.7-0.8	50-70
Thermal Expansion (100-1100°C)	ppm/°C	8.0	25
	ppm/°F	4.4	14

# Metal Prepreg Tape Properties

	$V_f$	Density (lb/in <sup>3</sup> )	Width (in)	Thickness (in)	$F_1^{tu}$ (ksi)	$E_1^t$ (Msi)	$\epsilon_1^{tu}$ (%)
Mean	0.50	0.119	0.377	0.0134	210	33	0.63

Material = Al<sub>2</sub>O<sub>3</sub> fibers in pure Al

Temperature = RT

Environment = Air

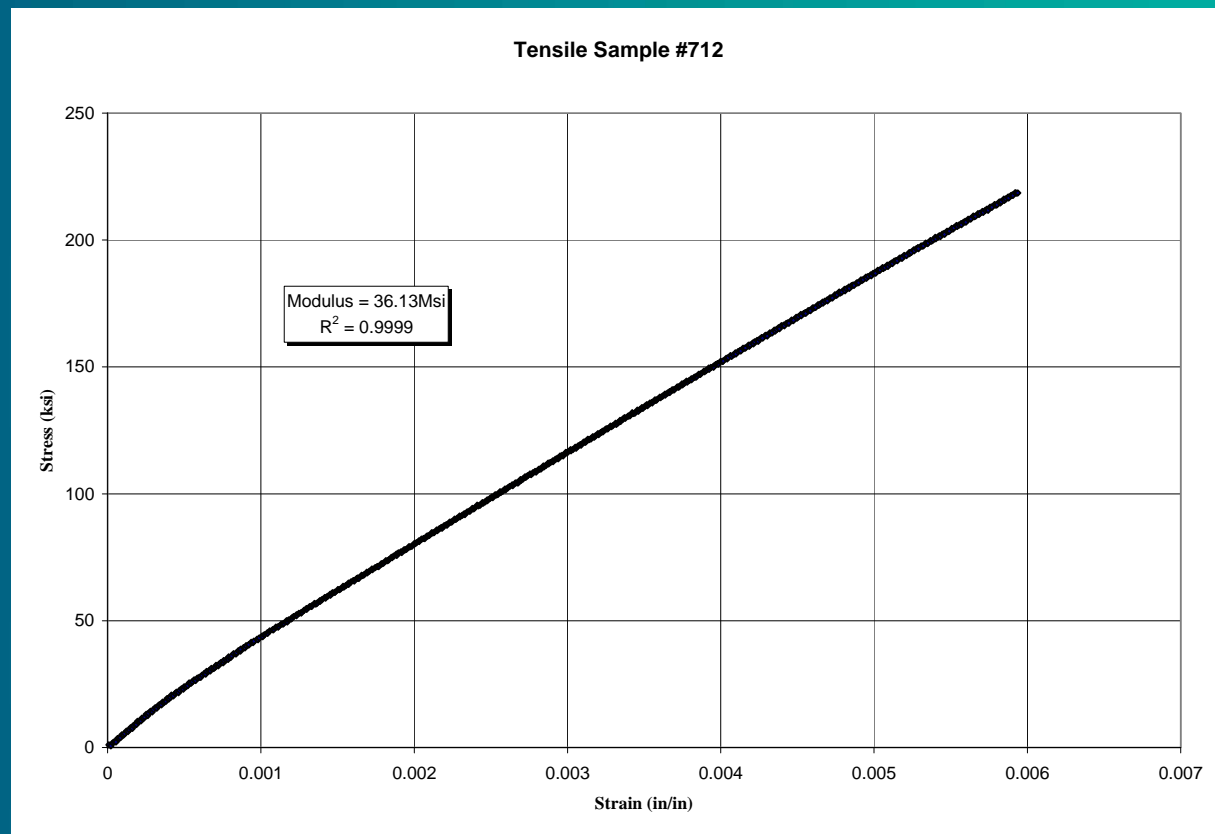
Direction = [0]

**Standard Tape:**

**Fiber volume of 50%**

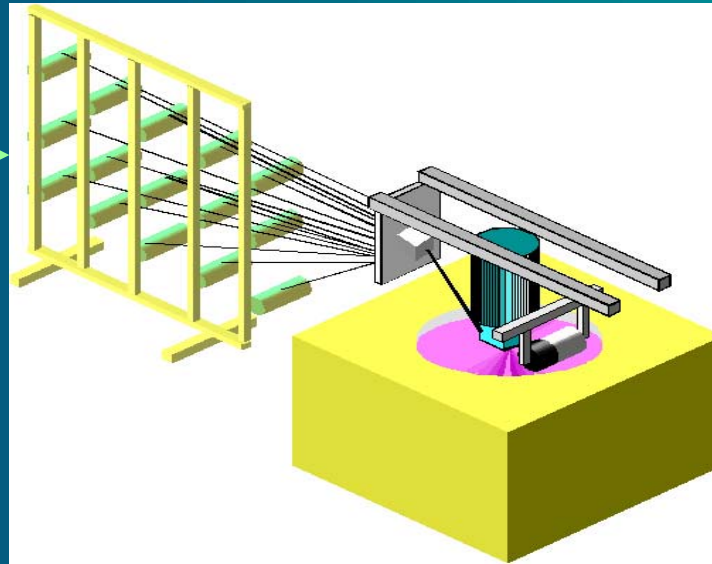
**Width of 0.5 inch**

**Thickness of 0.015 inch**



**Properties similar to steel but with the weight of aluminum**

# *Metal Prepreg Filament Winding*

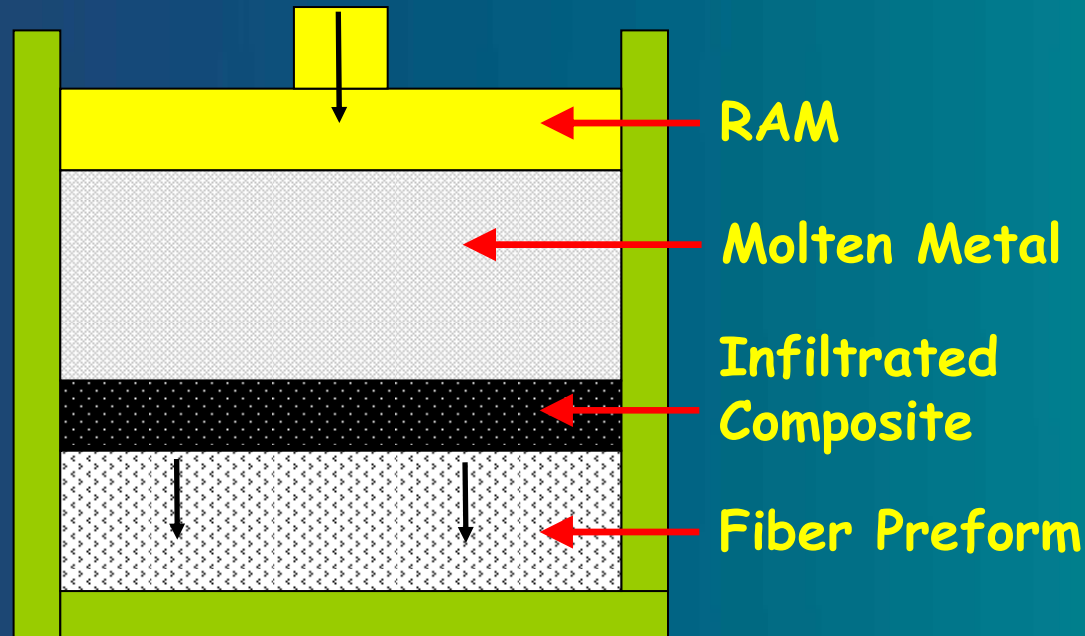


## ■ Analogous to PMC wet winding

- Based on MetPreg metal prepreg technology
- Spools of fiber are put on creel
- Tension is built into each tow
- Fiber bundle is dipped into the liquid matrix (molten aluminum) to impregnate
- Impregnated fiber bundle is laid onto the mandrel

*Low-cost, flexible processing for MMCs*

# Casting vs. Filament Winding for MMCs

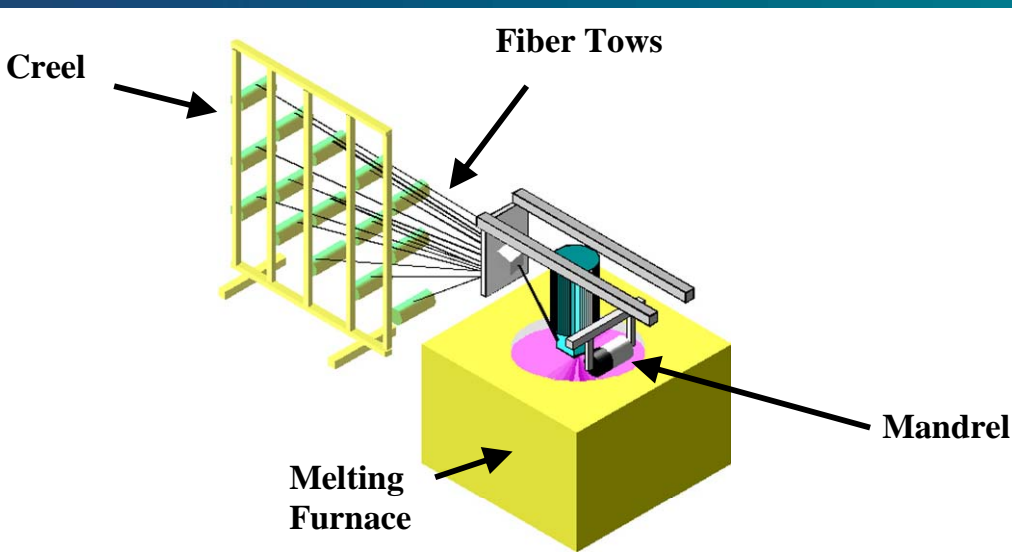


- **Pressure or squeeze casting is a multi-step process**

- Wind preform
- Load mold
- Melt metal
- Infiltrate preform

- **MMC filament winding is one step**

- Aluminum is kept molten in furnace
- Fibers are infiltrated and wound in a continuous process
- Mandrel is removed from finished part after winding





*MMC Design Tool Model  
Calibration and Validation*

# Virginia Tech/Aerojet MMC Design Tool

MMC Design Tool

File Tools Help

Current Units System: English Graphics Mode: Full Graphics

Materials Composite Point Stress Tabular Results Fastener Buckling

**Define Lamina**

Matrix: Aluminum 7075 T62 (149 C)

Reinforcement: Nextel 610 300ksi

Reinforcement Volume Fraction: 0.42 (0<vol. frac.<1)

Lamina Thickness: 0.0125 inches

Defined Lamina:  
Aluminum 7075 T62 (149 C) Reinforced with 42. vol% Nextel 610 300ksi;

**Lamina Properties**

View Lamina Properties:  Parallel to Fiber Axis (Direction 1)  
 Perpendicular to Fiber Axis (Dir. 2)  Shear (Dir. 1,2)

$\sigma$ , ksi Composite Tensile, Fiber Dir.

Composite Properties Summary:

E1: 28 Msi  $\alpha$ 1: 6.28 ppm/°F  $\nu$ 12: 0.29

Comp.  $\epsilon$  at Mtx. Yld: 0.005 Comp.  $\sigma$  at Mtx. Yld: 76.1d ksi

Comp.  $\epsilon$  at Rnf. Fail: 0.0055 Comp.  $\sigma$  at Rnf. Fail: 156 ksi

**Define Laminate**

Load Laminate From Database  
none

Laminate Name: private

Lamina Properties  
Number of Lamina: 18

Variable Lamina Thickness and Vol. Frac.

**Lamina Definition Table:**

Lamina	Orientation, °	Vol. Frac.	Thickness, in.	Mid. Point, in.
1	89	0.46	0.011	-0.1005
2	-22	0.35	0.013	-0.0885
3	-89	0.46	0.011	-0.0765
4	89	0.46	0.011	-0.0651
5	22	0.35	0.013	-0.0531
6	-89	0.46	0.011	-0.0411
7	89	0.46	0.011	-0.0297
8	-22	0.35	0.013	-0.0177
9	-89	0.46	0.011	-0.0057
10	-89	0.46	0.011	0.0057

Return or equivalent required to change orientation value.  
Lamina orientation range is  $\pm 90^\circ$ . At  $0^\circ$ , the lamina fiber direction is parallel to the global x-direction.

Lock and Check Laminate (Required for Analysis)  
If the Lock and Check Laminate button does not stay illuminated when selected, there is an orientation range error in one or more of the orientation values.

Load Composite From Database

300 Int 300F

Composite Name: 300 Int 300F

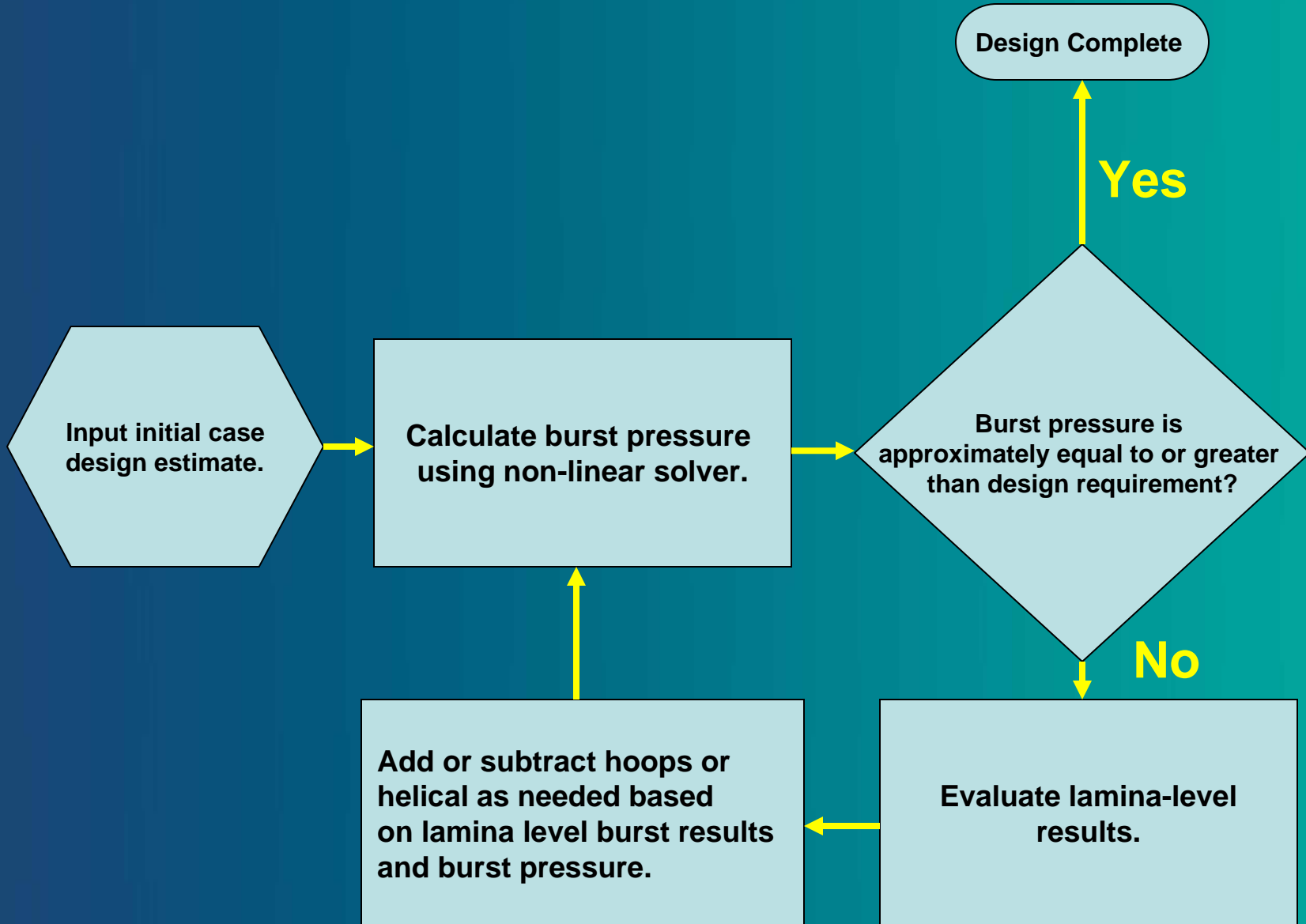
# *Calibrate to Experimental Values*

- Calculated mean  $N_y$  was 7030 lb/in for 4-inch diameter hoop-only cylinders  $N_y = P \times r$
- Model uses a non-linear point-stress analysis to determine lamina stresses
- Stress in the fiber direction for this load is 249 ksi
- This value was put back into the model and used to predict burst pressure for a 6-ply  $\pm 45/90/90/\pm 45$  lay-up
- Prediction was within 4% of experimental value

Cylinder Laminate	Assumed Fiber Strength (ksi)	Predicted Burst Pressure (psi)	Actual Burst Pressure (psi)	% Diff
[90] <sub>4</sub>	249	2813	2812	0
$\pm 45/90/90/\pm 45$	249	3250	3393	-4

*Production of Validation  
Test Cylinders*

# Case Design Using the MMC Design Tool

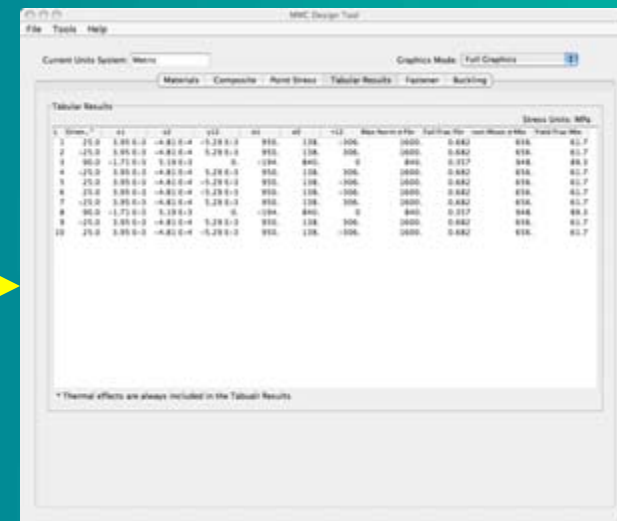
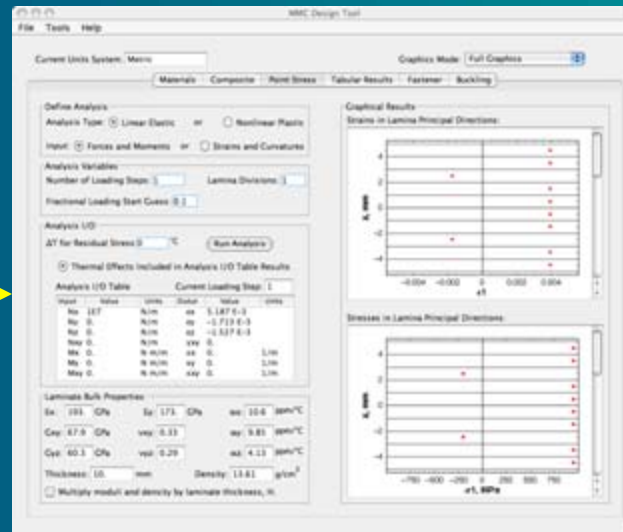
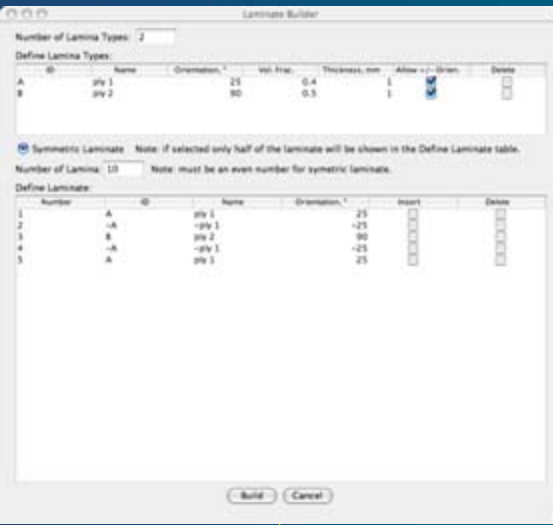


# Iterative Case Design Decision Loop

Laminate Builder -  
Modify Lay-up

Nonlinear Solver -  
Calculate Burst Pressure

Lamina-level Results -  
Determine Modifications



# Step #1 - Laminate Builder

Laminate Builder

Number of Lamina Types:

Define Lamina Types:

ID	Name	Orientation, °	Vol. Frac.	Thickness, mm	Allow +/- Orien.	Delete
A	ply 1	25	0.4	1	<input checked="" type="checkbox"/>	<input type="checkbox"/>
B	ply 2	90	0.5	1	<input checked="" type="checkbox"/>	<input type="checkbox"/>

Symmetric Laminate Note: if selected only half of the laminate will be shown in the Define Laminate table.

Number of Lamina:  Note: must be an even number for symmetric laminate.

Define Laminate:

Number	ID	Name	Orientation, °	Insert	Delete
1	A	ply 1	25	<input type="checkbox"/>	<input type="checkbox"/>
2	-A	-ply 1	-25	<input type="checkbox"/>	<input type="checkbox"/>
3	B	ply 2	90	<input type="checkbox"/>	<input type="checkbox"/>
4	-A	-ply 1	-25	<input type="checkbox"/>	<input type="checkbox"/>
5	A	ply 1	25	<input type="checkbox"/>	<input type="checkbox"/>

# Step #2 - Calculate Burst Pressure

MMC Design Tool

File Tools Help

Current Units System:  Graphics Mode:

Materials Composite Point Stress Tabular Results Fastener Buckling

**Define Analysis**

Analysis Type:  Linear Elastic or  Nonlinear Plastic

Input:  Forces and Moments or  Strains and Curvatures

**Analysis Variables**

Number of Loading Steps:  Lamina Divisions:

Fractional Loading Start Guess:

**Analysis I/O**

$\Delta T$  for Residual Stress:  °C

Thermal Effects Included in Analysis I/O Table Results

**Analysis I/O Table** Current Loading Step:

Input	Value	Units	Output	Value	Units
Nx	1E7	N/m	ex	5.187 E-3	
Ny	0.	N/m	ey	-1.713 E-3	
Nz	0.	N/m	ez	-1.527 E-3	
Nxy	0.	N/m	xy	0.	
Mx	0.	N m/m	kx	0.	1/m
My	0.	N m/m	ky	0.	1/m
Mxy	0.	N m/m	kxy	0.	1/m

**Laminate Bulk Properties**

Ex:  GPa Ey:  GPa  $\alpha_x$ :  ppm/°C

Gxy:  GPa  $\nu_{xy}$ :   $\alpha_y$ :  ppm/°C

Gyz:  GPa  $\nu_{yz}$ :   $\alpha_z$ :  ppm/°C

Thickness:  mm Density:  g/cm<sup>3</sup>

Multiply moduli and density by laminate thickness, H.

**Graphical Results**

Strains in Lamina Principal Directions:

z, mm	$\epsilon_1$
2	-0.002
0	0.004
-2	-0.002
-4	0.004

Stresses in Lamina Principal Directions:

z, mm	$\sigma_1$ , MPa
2	-250
0	750
-2	-250
-4	750



# Step #3 – Review Lamina Level Results

MMC Design Tool

File Tools Help

Current Units System:  Graphics Mode:

Materials Composite Point Stress **Tabular Results** Fastener Buckling

Tabular Results

Stress Units: MPa

L	Orien., °	$\epsilon_1$	$\epsilon_2$	$\gamma_{12}$	$\sigma_1$	$\sigma_2$	$\tau_{12}$	Max Norm $\sigma$ Fbr	Fail Frac Fbr	von Mises $\sigma$ Mtx	Yield Frac Mtx
1	25.0	3.95 E-3	-4.81 E-4	-5.29 E-3	950.	138.	-306.	1600.	0.682	656.	61.7
2	-25.0	3.95 E-3	-4.81 E-4	5.29 E-3	950.	138.	306.	1600.	0.682	656.	61.7
3	90.0	-1.71 E-3	5.19 E-3	0.	-194.	840.	0	840.	0.357	948.	89.3
4	-25.0	3.95 E-3	-4.81 E-4	5.29 E-3	950.	138.	306.	1600.	0.682	656.	61.7
5	25.0	3.95 E-3	-4.81 E-4	-5.29 E-3	950.	138.	-306.	1600.	0.682	656.	61.7
6	25.0	3.95 E-3	-4.81 E-4	-5.29 E-3	950.	138.	-306.	1600.	0.682	656.	61.7
7	-25.0	3.95 E-3	-4.81 E-4	5.29 E-3	950.	138.	306.	1600.	0.682	656.	61.7
8	90.0	-1.71 E-3	5.19 E-3	0.	-194.	840.	0	840.	0.357	948.	89.3
9	-25.0	3.95 E-3	-4.81 E-4	5.29 E-3	950.	138.	306.	1600.	0.682	656.	61.7
10	25.0	3.95 E-3	-4.81 E-4	-5.29 E-3	950.	138.	-306.	1600.	0.682	656.	61.7

\* Thermal effects are always included in the Tabular Results

# Pattern Development

**Helix Wind -- [Hel19.8]**

Part Parameters:		Wind Parameters:	
Fiber Start Position (Z1)	20.000	Fiber Angle (Deg.)	45.000
Fiber End Position (Z2)	0.200	Fiber Bandwidth	0.500
Mandrel Diameter	4.000	End Dwell (Deg.)	120.000
Turnaround Range	1.000	Path File Threshold (Deg)	2

Metric Units (mm)

**Wind Pattern Selection Menu**

Base Path Statistics:

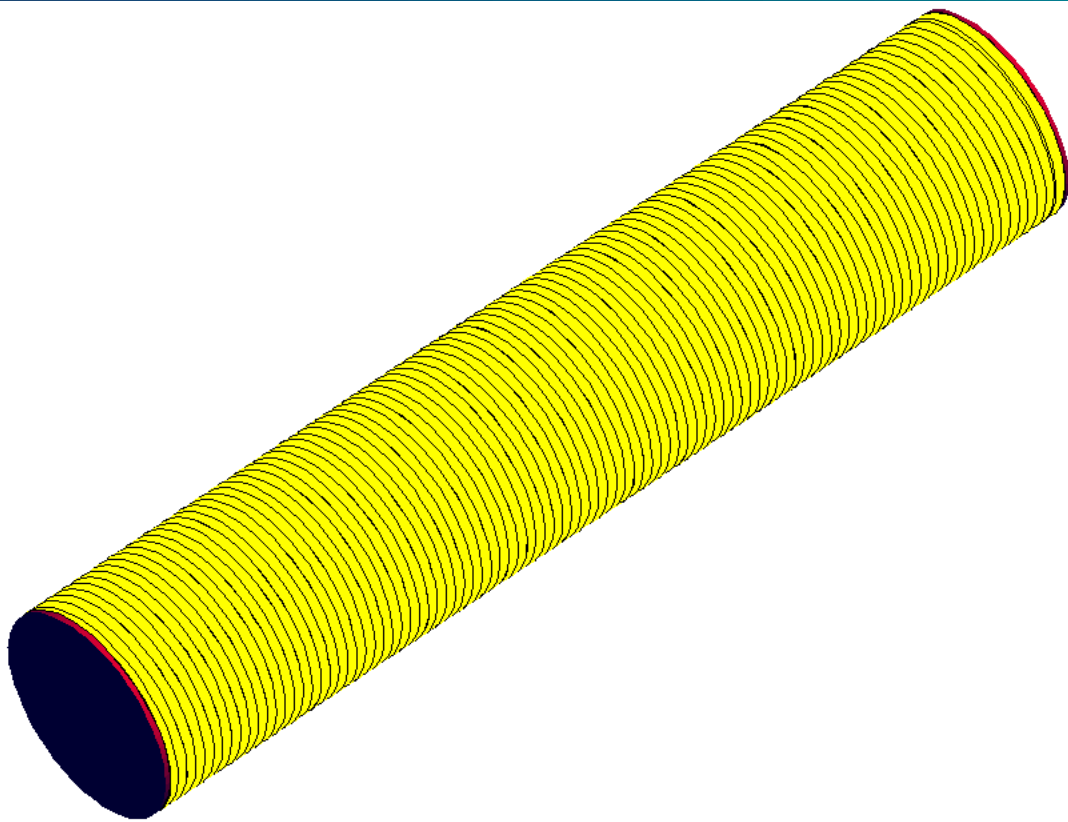
Number of Patterns Generated:	24
Mandrel Rotation in Current Path:	1489.05°
Rotation in Turnaround Range:	234.59°

Circuits / Coverage	Pattern	Pattern Type	Adjusted Angle	Adjusted Width	Turn / Dome Left	Turn / Dome Right	Natural Path Deviation
17	6	Lag	45.28°	0.520	236.9°	236.9°	0.97%
17	4	Lead	45.68°	0.516	240.2°	240.2°	2.39%
18	7	Lead	45.96°	0.485	242.6°	242.6°	3.42%
17	7	Lag	46.07°	0.513	243.5°	243.5°	3.82%
17	3	Lag	46.46°	0.509	246.9°	246.9°	5.24%
18	5	Lead	46.70°	0.479	248.9°	248.9°	6.11%
17	5	Lag	46.85°	0.506	250.2°	250.2°	6.66%
17	2	Lead	47.22°	0.502	253.6°	253.6°	8.08%
17	2	Lag	47.60°	0.498	256.9°	256.9°	9.51%

Start on Right End of Mandrel

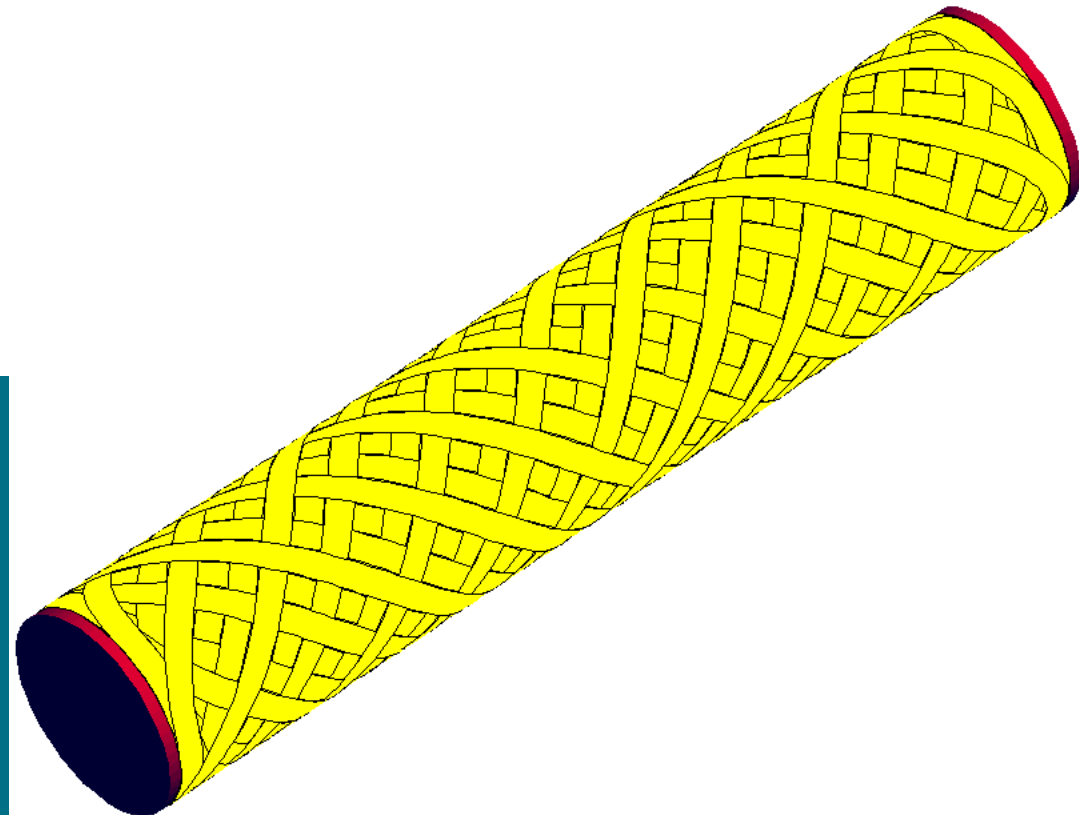
- Pattern files are created for each ply or layer
- Hoop ply patterns require the input of the mandrel diameter, pattern length, and fiber bandwidth
- Helical layer patterns require these same inputs plus the fiber angle, parameters that deal with the reversal of the fiber direction on each end, and choosing the circuits/coverage and circuits/pattern

# *Preview of the Winding Patterns*

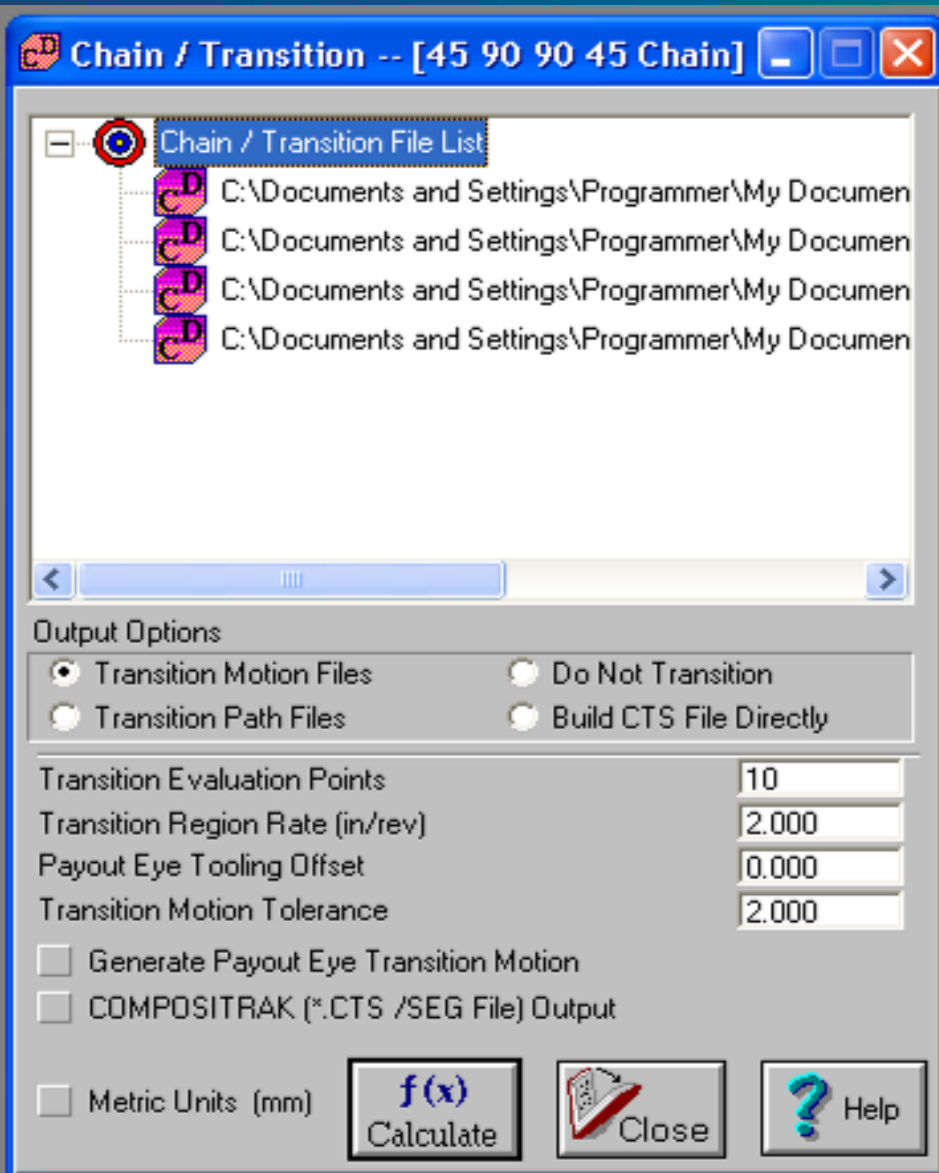


**Check for pattern coverage**

**Check for coverage and smoothness of turns on ends**

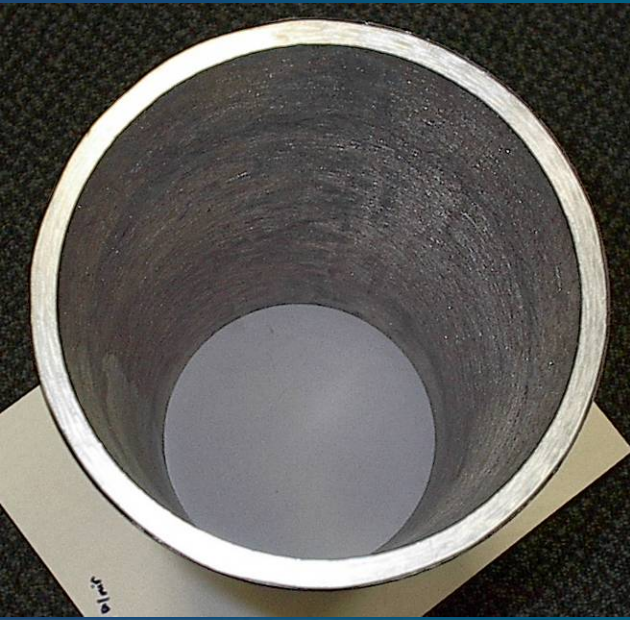


# Combining Individual Patterns Into Chain Pattern



- Individual patterns are linked together in a chain wind to ensure smooth transitions between segments
- The pattern is “filtered” to level out any acceleration spikes in the machine motion

# Validation Test Results



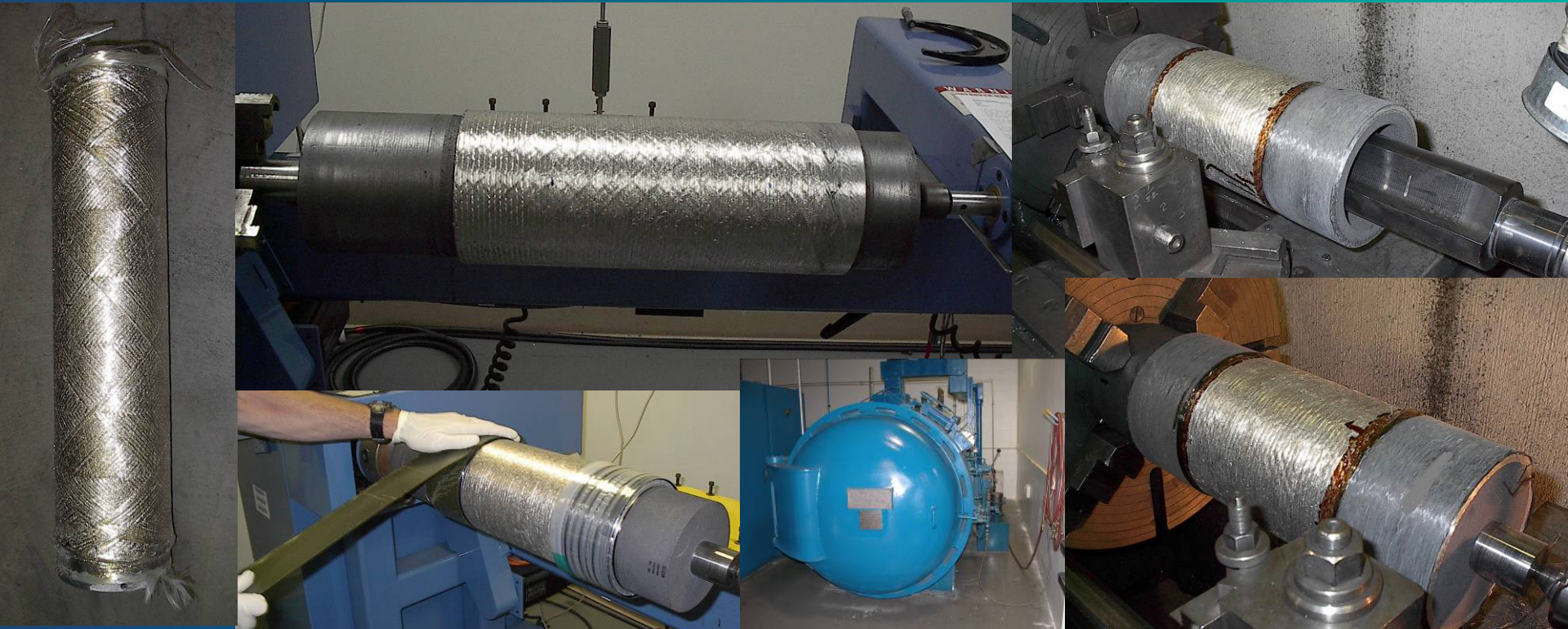
SUMMARY DATA	Cyl 1	Cyl 2
Test Date	28-Feb-08	19-Jan-08
Test Temp., (°F)	~77	~77
Wall Thickness, in	0.220	0.233
Fiber Vol. Fraction	0.404	0.385
Burst Pressure, psi	3331	3277
Ultimate Hoop Stress, ksi	39.8	39.2
Hoop Elastic Modulus, Msi	20.0	5.0
Hoop Strain at Failure, %	0.33	1.14
Ultimate Axial Stress, ksi	19.9	19.6
Axial Elastic Modulus, Msi	30.0	7.0
Axial Strain at Failure, %	0.06	0.26



- Wall thickness of nearly  $\frac{1}{4}$ " with a lay-up of 90/ $\pm$ 45/ $\pm$ 45/90/ $\pm$ 45/ $\pm$ 45/90
- Hoop fiber failure achieved
- Consistent properties with the exception of some strain data anomalies

*Production of IM and Static Fire  
Test Cylinders*

# AI MMC Cylinder Production



# *Conclusions*

- MMC filament winding process has been further demonstrated through the production of nine 6-inch OD x 15-inch long cylinders with ~0.25-inch wall thickness
- MMC Design Tool and burst test results were successfully used to design cylinders for IM and static fire testing
- Tests completed thus far indicate that Al MMC motor cases will be better than steel cases against BI and FI
- Al MMC cases may be better than steel in FCO as well, but the first test was not conclusive and another test is being planned
- The response to SCO should be no worse than current designs, the most difficult threat to mitigate, and there is the potential for incorporating unique closure designs specifically geared towards SCO mitigation



# *Future Work*

- **Currently implementing a 3<sup>rd</sup> axis on the filament winding machine which should allow cylinders with thinner walls to have higher burst pressures**
- **Additional scale-up to make cylinders with lengths up to six feet is being planned**
- **A method for NDI/NDE will need to be developed**
- **End closure processing and attachment point designs will also need to be developed**

# *Questions?*

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***www.metpreg.com***

***E-mail: metpreginfo.com***