2010 DOE Hydrogen Program

Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels

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Project ID # ST083

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BOEING
Pacific Northwest NATIONAL LABORATORY
Lawrence Livermore National Laboratory

Overview

Timeline

- Project start date 09/2008
- Project end date: 03/2012
- Percent complete: 33%

Budget

- **Total Budget: $5,486,848**
- DOE Share: $2,566,451
- QT/Boeing Share: $1,920,397
- FFRDC Share: $1,000,000
- FY08 Funding: $475,845
- Funding for FY09: $350,000
- Funding for FY10: $800,000

Barriers

- Material system costs
- Manufacturing processes

Partners

- Quantum Technologies, Inc.
- The Boeing Company (Boeing)
- Pacific Northwest National Laboratory (PNNL)
- Lawrence Livermore National Laboratory (LLNL)

Project Objectives- Relevance

To manufacture Type IV H_2 storage pressure vessels, utilizing a new hybrid process with the following features:

- Optimal elements of advanced fiber placement (AFP) & commercial filament winding (FW).
- Reduced production cycle times by adaptations of high-speed “dry winding” methodology.
- Improve understanding of polymer liner H_2 degradation.

With the aim of achieving:

A manufacturing process with lower composite material usage, lower cost, and higher efficiency.

Milestones

Time	Milestone
09/08-04/09	Program Kick-off Material development investigation; 100% complete Composite design literature review & optimum liner dome profile; 100% complete Fiber placement delivery head modification; 100% complete Initial cost model; input/output & approach; 100% complete
05/09	Merit Review
05/09-12/09	Manufacture & test best effort tank using hybrid process: build & test two tanks Baseline cost model complete Go/NoGo decision→ data shows AFP & FW processes can manufacture a tank → GO Decision
11/09-04/10	Dry tape technology evaluation
06/10	Merit Review
03/10-01/11	Manufacturing process development; manufacture & test best effort tank Revised cost model Go/NoGo decision→ demonstrate process can reduce material usage and cost
03/11-06/11	Hybrid manufacturing technology refinement
05/11	Merit Review
06/11-01/12	Produce hybrid manufacturing technology tanks; test per EIHP Final cost model

Approaches

- Material study to address material compatibility, cure profile, AFP process requirements.

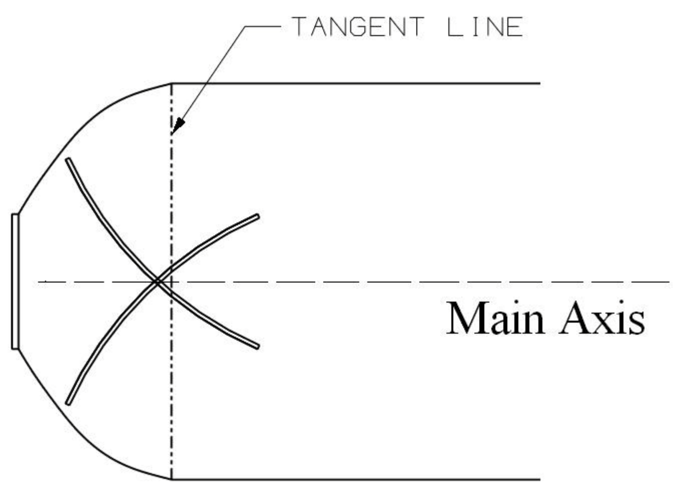
- Composite design & stress analysis

Governing Equilibrium Equation

$$\frac{N_\alpha}{R_m} + \frac{N_\beta}{R_P} = p$$

Assumed dome profile in parametric form

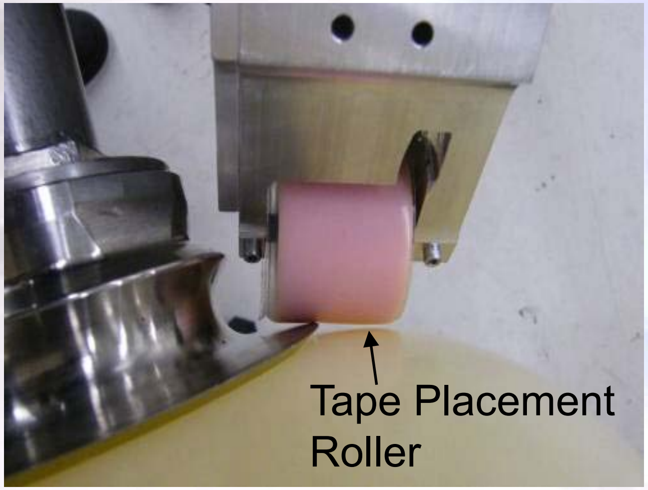
$$S(r, \beta) = \{r\cos\beta, r\sin\beta, z(r)\}$$

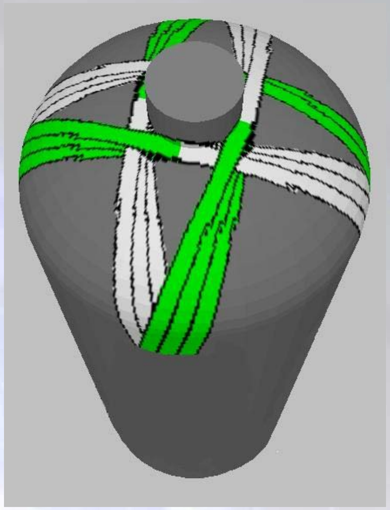


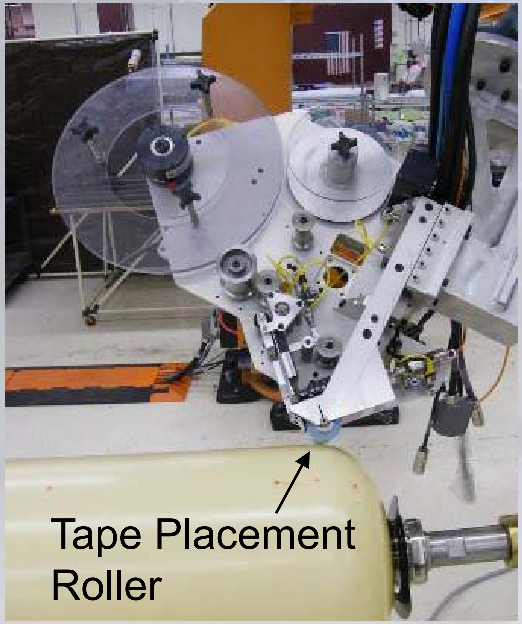
➡ **Optimum liner dome profile, composite lay-up**

Approach: Advanced Fiber Placement- Boeing

- **Advanced Fiber Placement:** A CNC process that adds multiple strips of composite material on demand.
  - Maximum weight efficiency - places material where needed
  - Fiber steering allows greater design flexibility
  - Process is scalable to hydrogen storage tanks
  - Optimize plies on the dome sections with minimal limitation on fiber angle
  - Reinforce dome without adding weight to cylinder







Approach: Advanced Fiber Placement- Boeing

- Integration of Filament Winding and Advanced Fiber Placement
  - In the same cell
  - In parallel cells
  - Off line fiber placement of reinforcement details

Technical Progress: Advanced Fiber Placement - Boeing

- Boeing Advanced Fiber Placement (AFP) Process

  Boeing has successively modified their AFP head

  - Smaller polar openings, more optimal structural design
    - 2.5-inch aft dome, and a 3.7-inch forward dome
  - Local heating and cooling of the towpreg.
    - Control of "tackiness" and "boardiness"
    - Enhances feeding and lay-down, reduces wrinkling

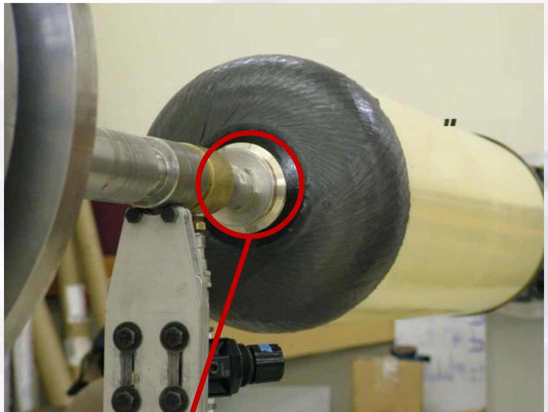
Technical Progress: Advanced Fiber Placement - Boeing

Developed an alternative build approach (Off-line AFP process)

- Stand-alone mandrel for the AFP operations
  - Sub-laminate is released and then re-mounted onto the liner
  - Same shape and dimensions as the liner
  - Cantilevered full head access to the end regions
  - Eliminates head interference problems
  - No polar-opening issues
  - Versatile build options

Approaches

- Tank preparation and validation test



Representative smallest polar opening that the AFP process can currently make

The localized reinforcement protected the dome regions very well

- Static Burst Result: 23420 PSI > 22804 PSI, EN standard (New European Standard superseding EIHP)
- 64.9 kg composite usage in the 1st hybrid vessel vs. 76 kg in the baseline tank (FW alone)

11.1 kg (14.6%) Savings!

Approach: Tank Cost Analysis

- Quantum and Boeing's manufacturing experience was used to estimate the $/kg of Filament Wound (FW) and Advanced Fiber Placed (AFP) Composites.
- Hybrid composite design provided the mass of Filament Wound and Advanced Fiber Placed Composites.
- Cost model included materials, labor, overhead, balance of system, manufacturing equipment and factory space costs.

Approach: Tank Cost Analysis

Baseline and two bounding manufacturing scenarios were investigated:

1. Baseline = Quantum Filament Wound 129 Liter, Type IV Tank.
2. <u>Fully Integrated FW and AFP</u> – Composite layup optimized for high strength, but inefficient machine usage.
3. <u>Fully Separate FW and AFP</u> - 100% machine usage, but composite strength may be slightly reduce.

Technical Progress: Tank Cost Analysis
500,000/yr, $11/lb Carbon Fiber

Summary Table		Type IV Tank Baseline 129L Filament Wound	Hybrid FW + AFP Reinforced: Fully Integrated FW and AFP	Hybrid FW + AFP Reinforced: Separate FW and AFP
Composite Mass, kg	FW	76	63.4	63.4
	AFP		1.5	1.5
Total Composite Mass, kg		76	64.9	64.9
Comp. Placement Speed, kg/hr	FW	13.2	13.2	13.2
	AFP		0.9	0.9
Comp. Placement Time, hr/tank	FW	5.75	4.80	4.80
	AFP		2.48	1.65
Total Comp. Place Time, hr/tank		5.75	7.27	4.80
# Manuf. Cells for 500K/yr	FW	191	242	159
	AFP		484	165
Tank Costs				
FW Composite		$2,290	$1,910	$1,910
AFP Composite			$90	$90
End Boss		$250	$250	$250
Manufacturing Equipment		$36	$66	$41
Factory Space		$7	$10	$7
Total Tank Cost		$2,583	$2,326	$2,299
% Tank Cost Savings		0%	10%	11%
DOE Measures				
Specific Energy, kWh/kg [1]		1.50	1.67	1.67
Cost Efficiency, $/kWh [2]		$23.45	$21.91	$21.75

[1] 5 kg H2 * 33.31 kWh/kgH2 / (Tank+OtherComponents+H2 mass, kg) OtherCompMass=30kg

[2] (Tank+OtherComponents $$) / (5 kg H2 * 33.31 kWh/kgH2)

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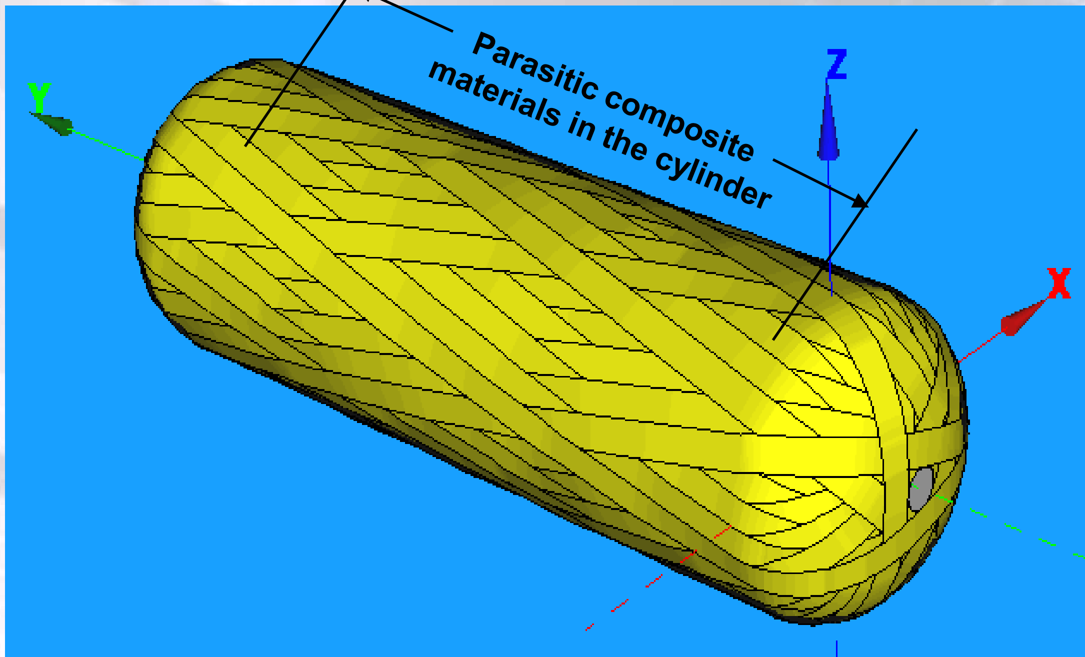
Accomplishment: Material & Cost Saving



64.9 kg composite usage in the 1st hybrid vessel vs. 76.0 kg in the baseline tank (FW alone)

- The end-user H_2 storage system weight efficiency = 1.67 kWh/kg vs. 1.50 kWh/kg in the system with the baseline tank
- The end-user H_2 storage system cost efficiency:
  - $11/lb CF   Baseline $23.45   Fully Integrated $21.91   Fully Separate $21.75
  - $6/lb CF   Baseline $18.74   Fully Integrated $17.79   Fully Separate $17.63

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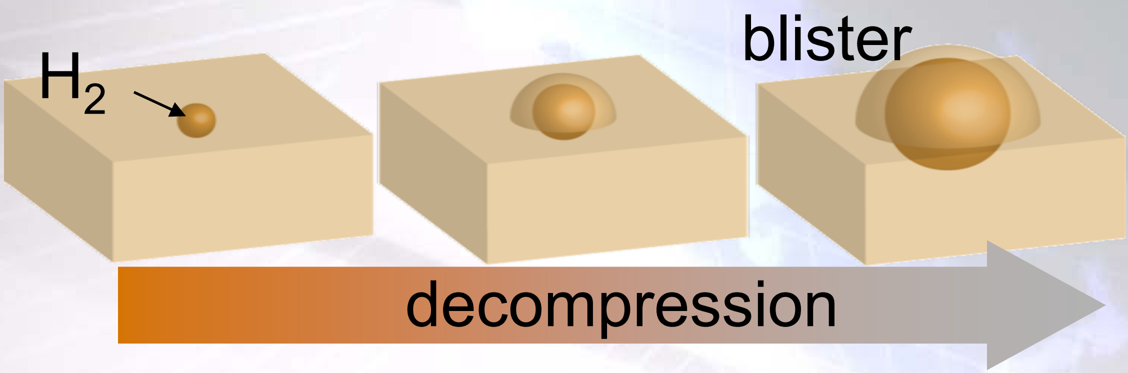
Approach: Hydrogen Liner Compatibility

Relevance:
- Polymer liner prevents H_2 diffusion
- Exposed to high pressure H_2, decompression
- H_2 embrittles, blisters metals, ceramics
- Little is known about H_2 effect on Polymers

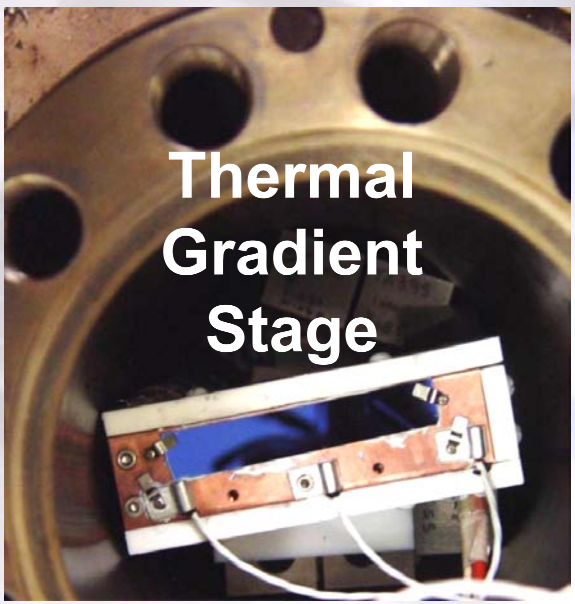
Approach:
- Charge Polymers in high pressure H2
- Investigate degradation: blistering
  - Function of temperature, decompression
  - Function of crystallinity
- Bulk Modulus tests planned to look for changes

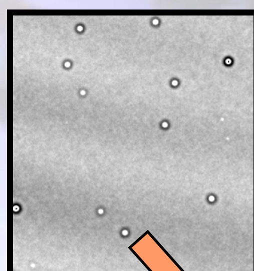


PNNL High Pressure H_2 Setup
- 100% H_2 or D_2 atmosphere
- up to 5,000 psi
- RT to 200C temperature
- large samples possible

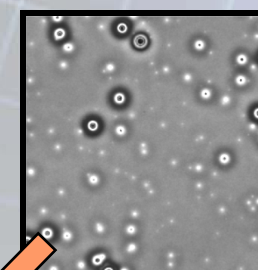
Technical Progress: Hydrogen Liner Compatibility

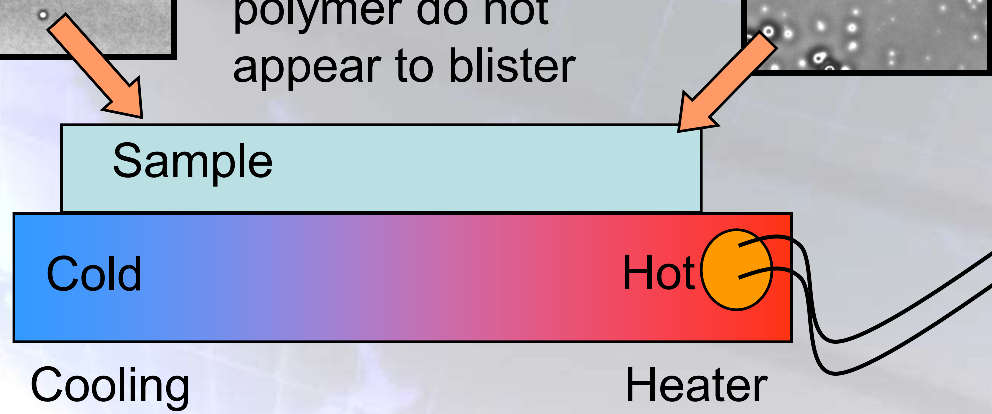
- Developed Thermal Gradient Stage for ***<u>in-situ</u>*** Combinatorial testing
- Preliminary testing of amorphous polymers with temperature
- Preliminary testing of 100% crystalline polymers with temperature
- Observed blistering dependent of temperature, crystallinity





- Blister size/density increase with Temp.
- 100% crystalline polymer do not appear to blister



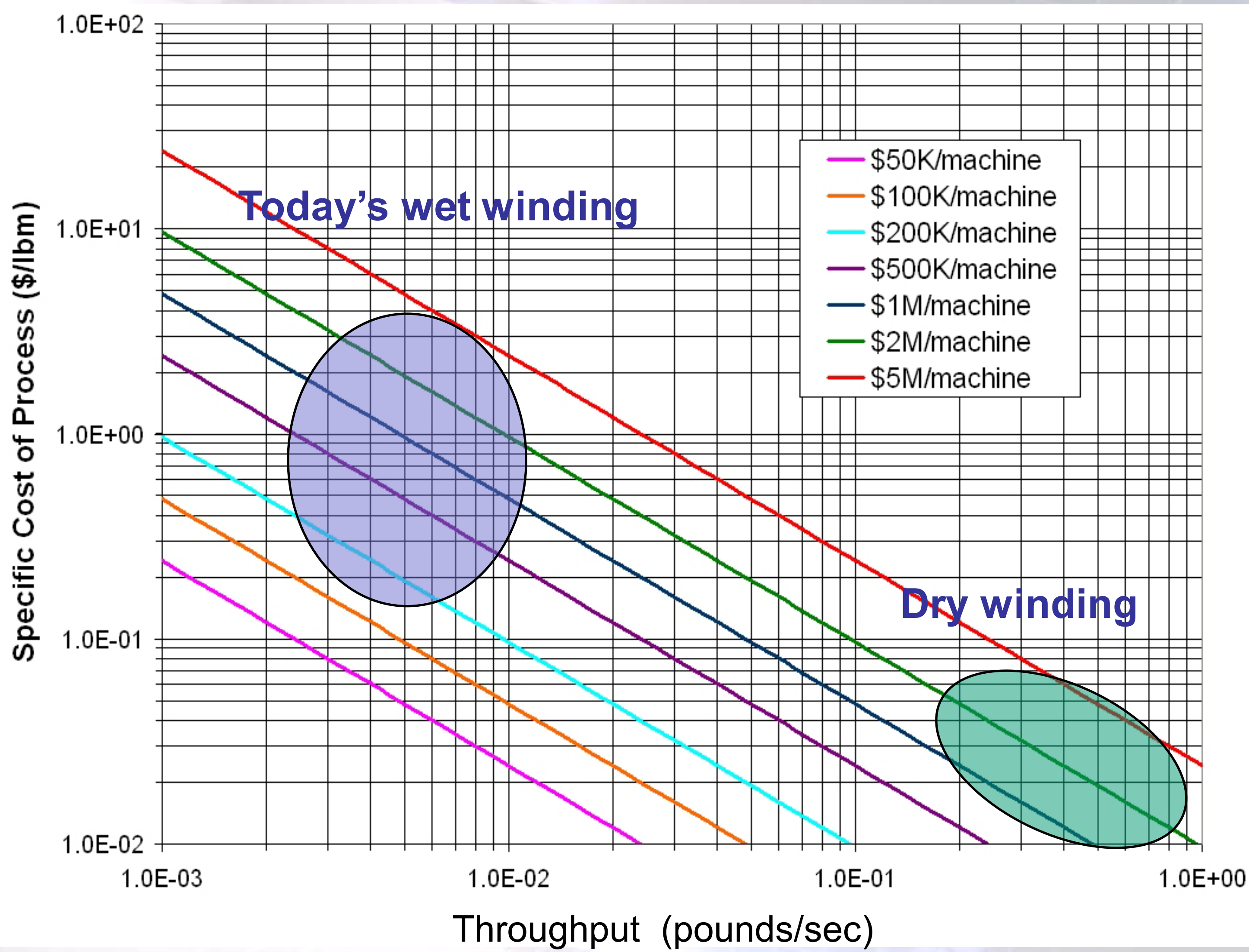


Hydrogen Liner Compatibility: Future Work

- Further H_2 blistering studies semi-crystalline Polymers
  - HDPE, PVDF, other standard materials
  - Function of crystallinity (LDPE, HDPE, UHMWPE)
  - XRD measurements to confirm crystallinity
  - Function of temperature (aging)
- Tests on Quantum Polymers
- Bulk Modulus testing (bulk rods)
  - HDPE, other materials
  - Function of H2 exposure
  - Recovery time

PNNL mechanical testing lab

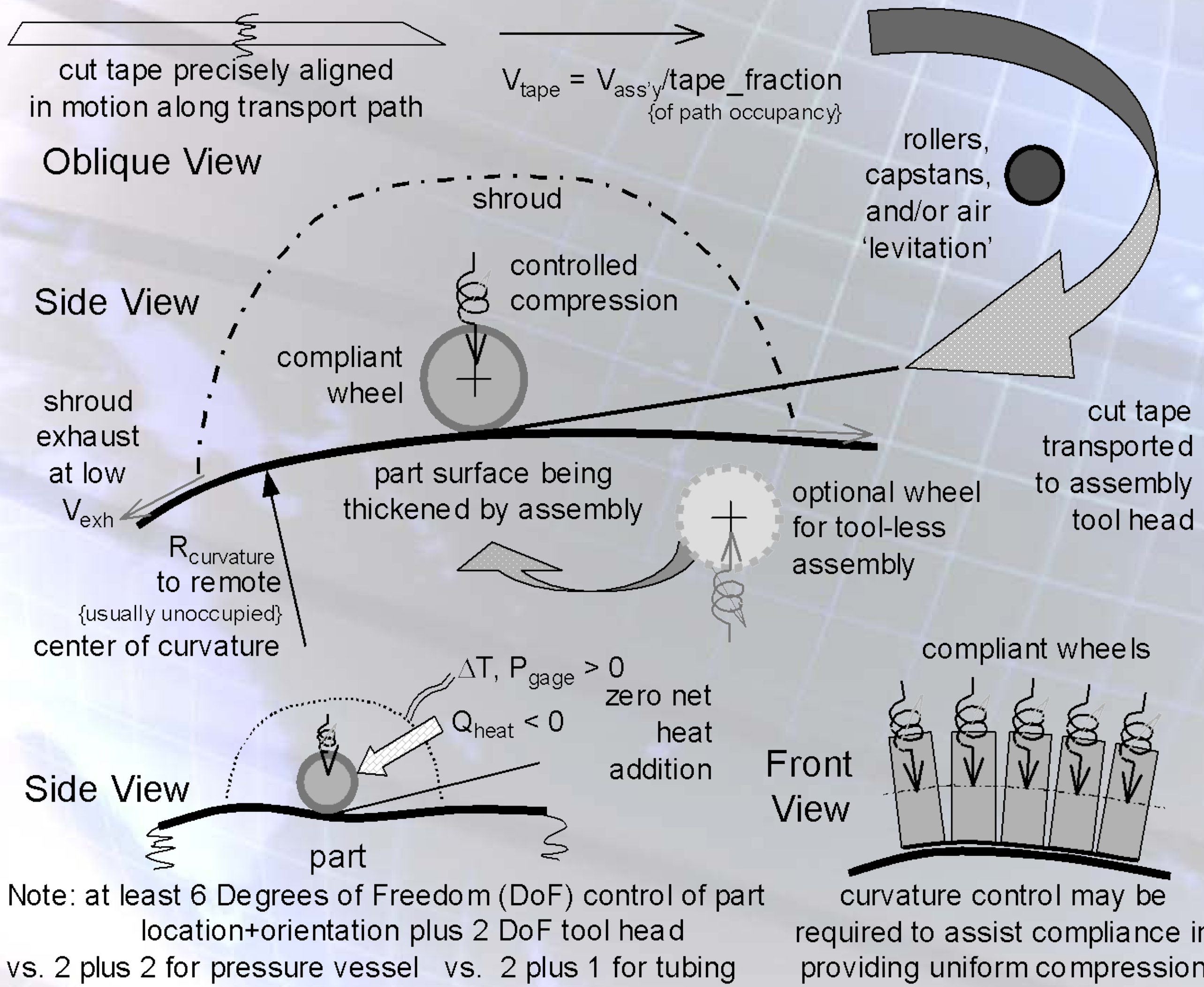
Approach: Dry Tape Winding



Manufacturing cost is inversely proportional to Throughput → *Significant* cost reductions require *fast* winding

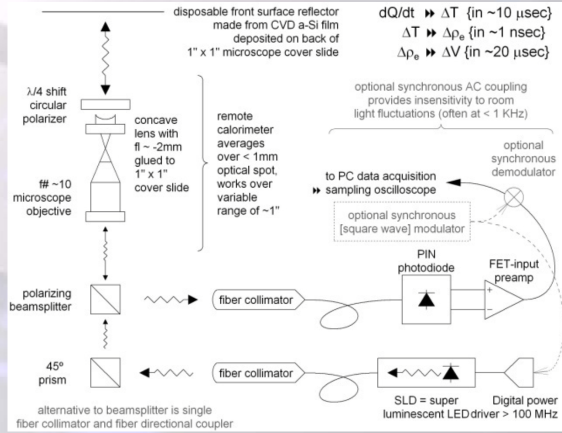
Approach: Dry Tape Winding

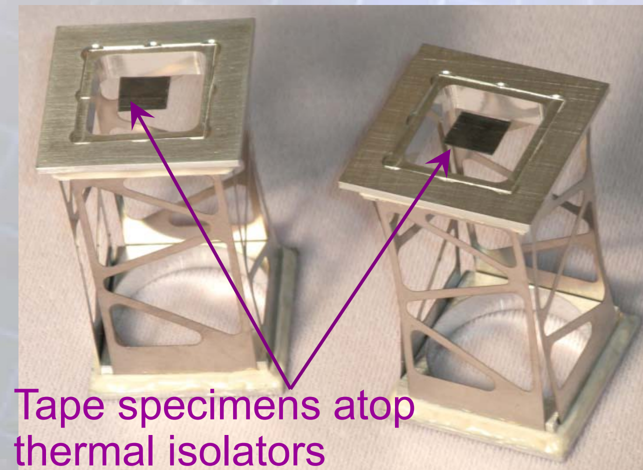
How to implement ultra fast bonding? Our approach retains full fiber strength, improves tensile strength, and produces precise parts (like tires, instead of like baskets)



Approach: Dry Tape Winding

We are measuring tape-to-tape bonding process speed with calorimeters (exothermic plastic + endothermic solder bonds)

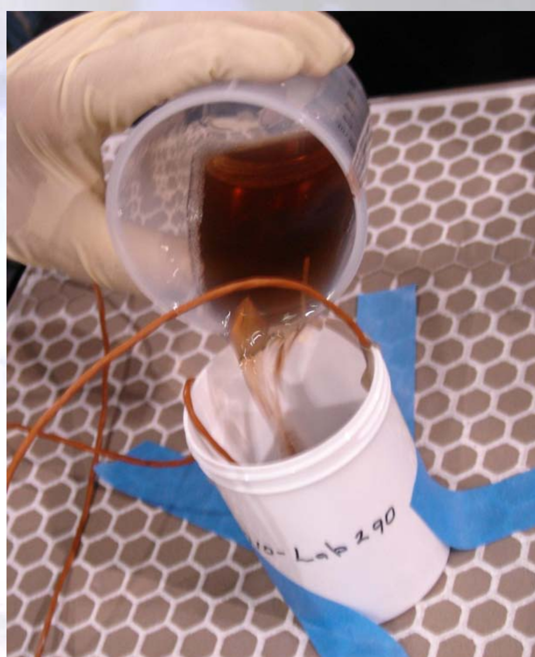




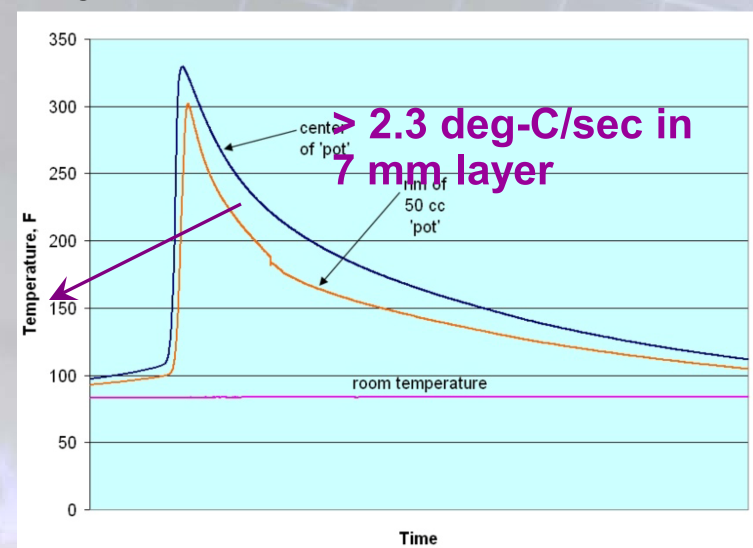
Tape specimens atop thermal isolators

Design for 1st generation RTD remote infrared calorimeter measures heat emissions from >> T's (found in Go-No-Go trial)

Scaled by heat diffusion (from 280 to 1 mil thick bond layers) gains 10 x viscosity in ~0.14 msec



Thermocouple-instrumented hot pot experiment Achieved Go-No-Go Milestone in August 2009



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Future Work: Strategies for Program Goals

- Continued improvement on advanced fiber placement (AFP) processes and structural design
  - Flexibility in AFP to cover more regions
  - Off-line AFP process for automation platforms
- More testing to validate the AFP/FW hybrid process
  - Ambient temperature cycle fatigue
  - Extreme temperature cycle fatigue
  - Accelerated stress rupture
- Cost model update including consideration of textile performing approaches as compared to our hybrid AFP/FW process.
- Continuous evaluation of polymer liner candidate material resistance to H_2 environment
- Improve tape processes speed and test performance
  - Measure strength: bond shear stress and strain, tensile stress
- Evaluation of alternative materials: S-Glass, Basalt fibers

Project Summary

- A Boeing/Quantum Composite Tank Has Been Produced Using a Hybrid AFP/FW Process:
  - Significant step towards DOE's efficiency goals
  - The first hybrid tank exceeded the required burst pressure and saved 11.1kg of the 76 kg baseline (14.6% !!)
  - Composite cost is high compared to factory equipment and space costs. The composite layup can be optimized without significant cost from machine inefficiencies.
  - Reduced tank mass improves:
    - Specific energy increased from 1.5 to 1.67 kWh/kg.
    - Cost efficiency reduced from $23.45 to $21.75/kWh (7.2% reduction) for $11/lb carbon fiber.

Project Summary (Con't)

- PNNL Hybrid Process Cost Model Development and Polymer Liner Hydrogen Compatibility:
  - Initial cost model shows additional costs of equipment required for hybrid process is insignificant compared to cost saving achieved from fiber usage reduction.
  - Polymer liner compatibility testing in hydrogen indicates crystalline density and temperatures have direct effect on formation of blisters in liner material.

- LLNL Dry Tape Winding Development:
  - Dry tape initial feasibility showed positive results. Development of process still in early stages.