Compressed Hydrogen Storage Workshop

Manufacturing Perspective

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Project ID #MF008

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Program Overview

Timeline

- Project start date 09/2008
- Project end date: 09/2011
- Percent complete: 60%

Budget

- **Total Budget: $5,486,848**
- DOE Share: $2,566,451
- QT/Boeing Share: $1,920,397
- FFRDC Share: $1,000,000

Barriers

- Material system costs
- Manufacturing processes

Partners

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

Briefly – Composites at Boeing, 787 Family

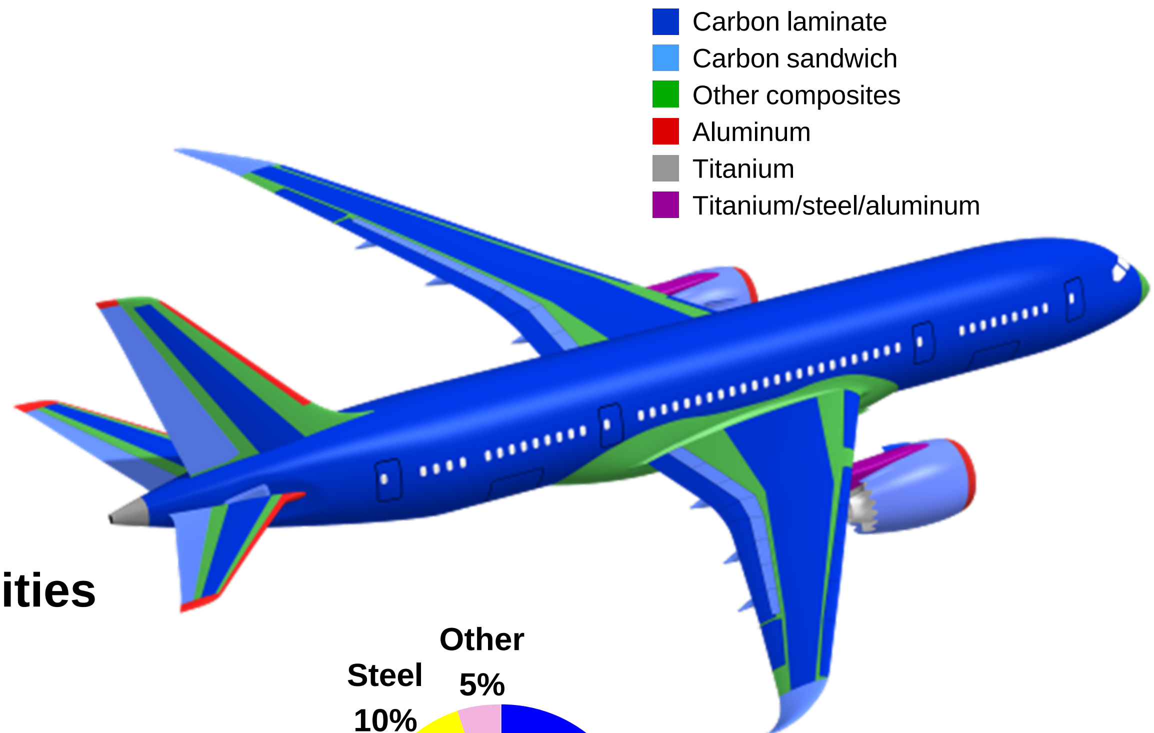
DOE Hydrogen Program

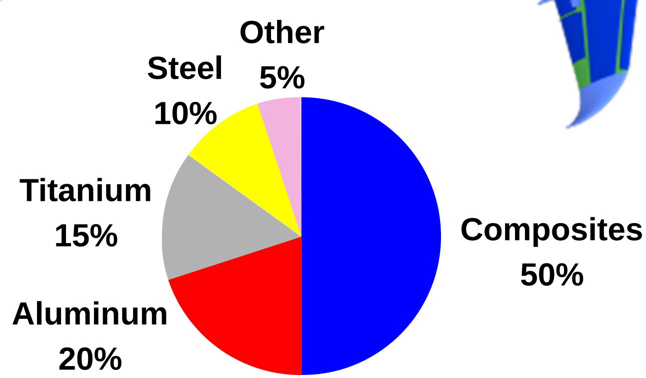
787-8
210-250 passengers
7,650-8,200 nmi
(14,200-15,200 km)

787-9
250-290 passengers
8,000-8,500 nmi
(14,800-15,700 km)

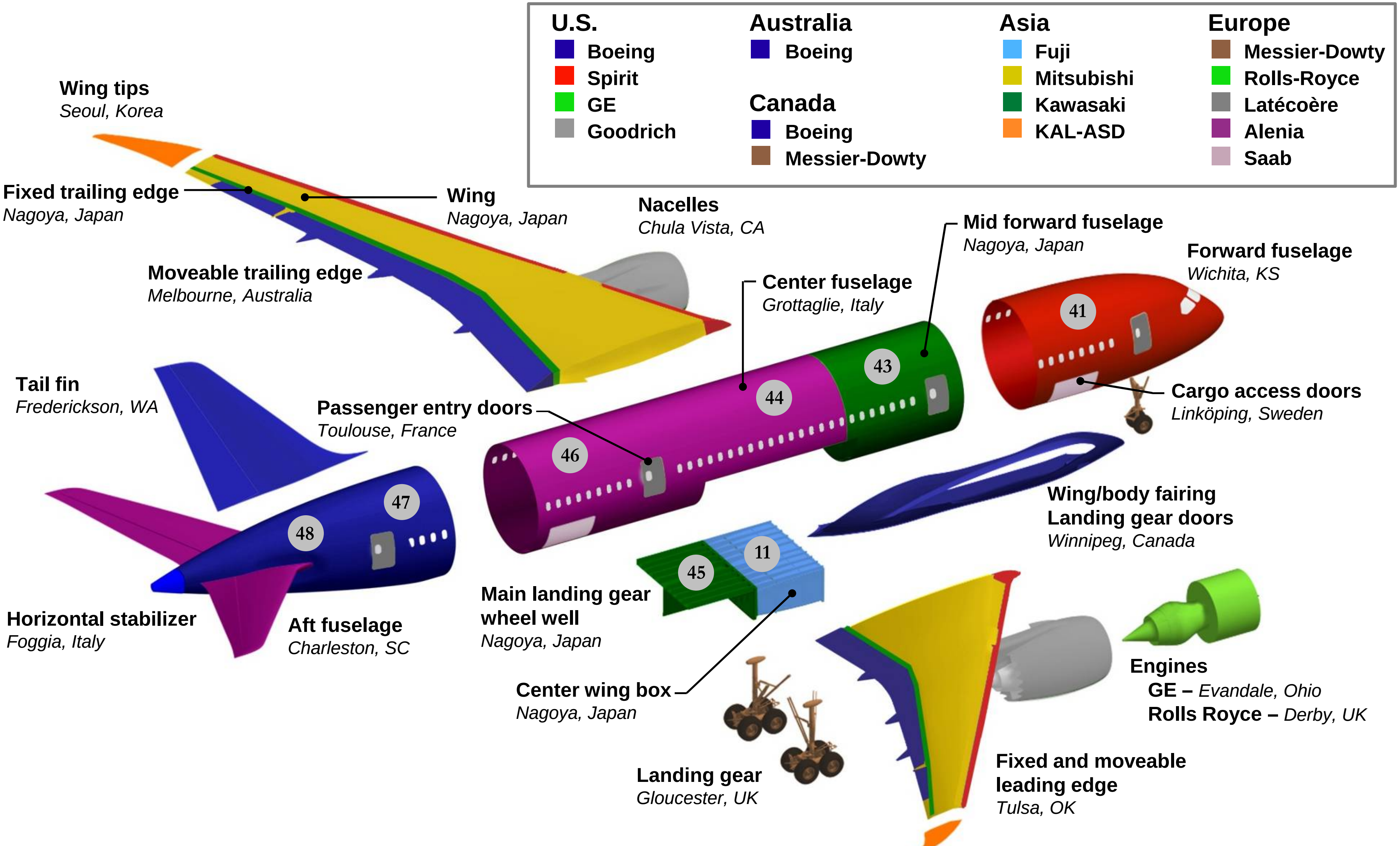
Composite Structure

- **Lighter**
- **More durable**
- **Negligible corrosion and fatigue**
- **Reduced scheduled maintenance**
- **Opens new design possibilities**

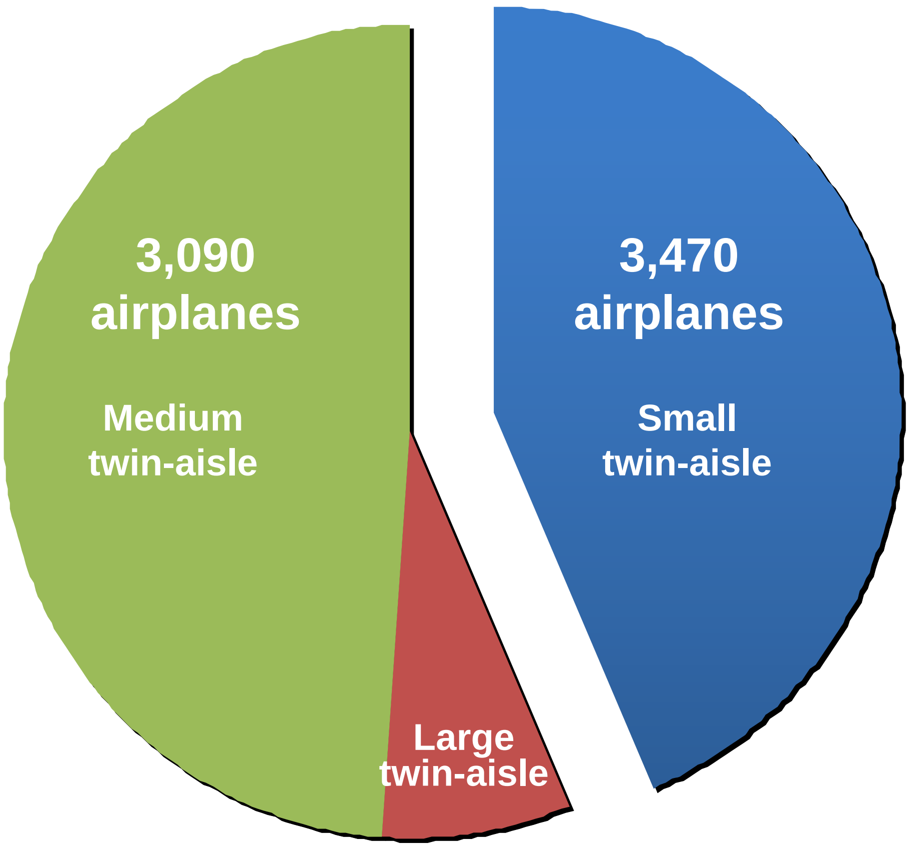




Partners Across the Globe are Bringing the 787 Together



20-Year Market Forecast



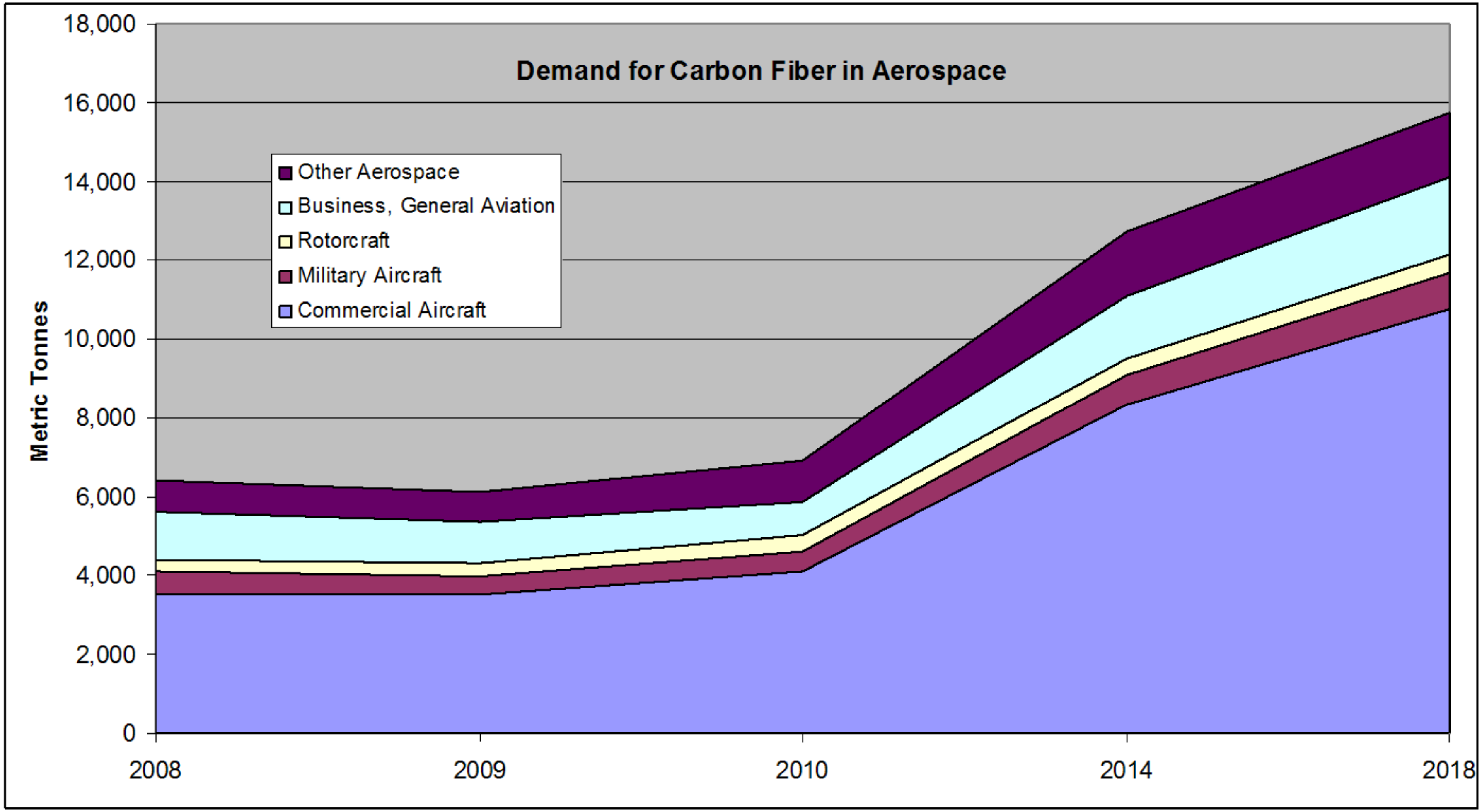
787-8
242 seats

787-9
280 seats

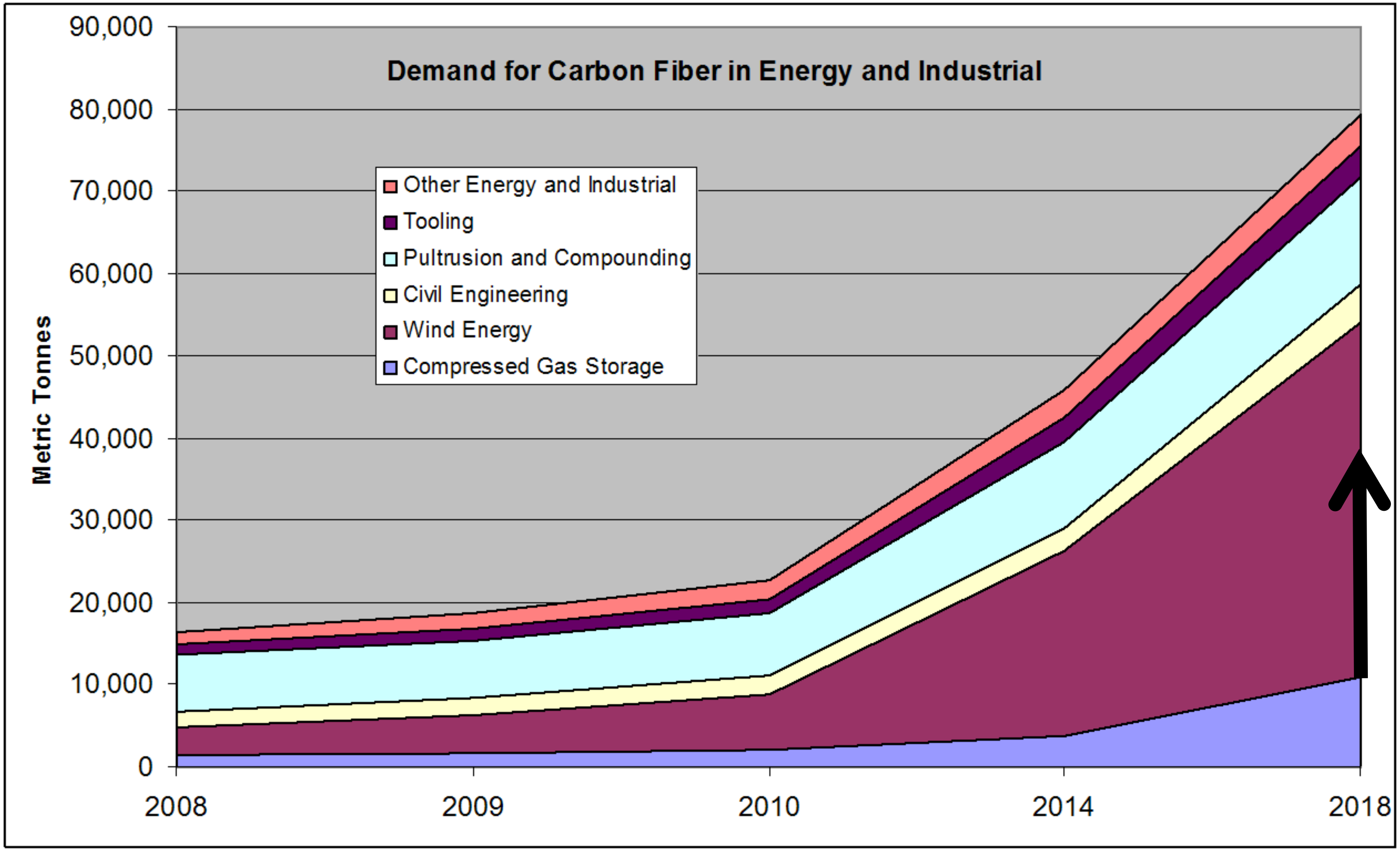
787-size airplanes represent 3,400+ market

Source: Boeing CMO 2010 - 2029

Significant Need for Carbon Fibers in Aerospace

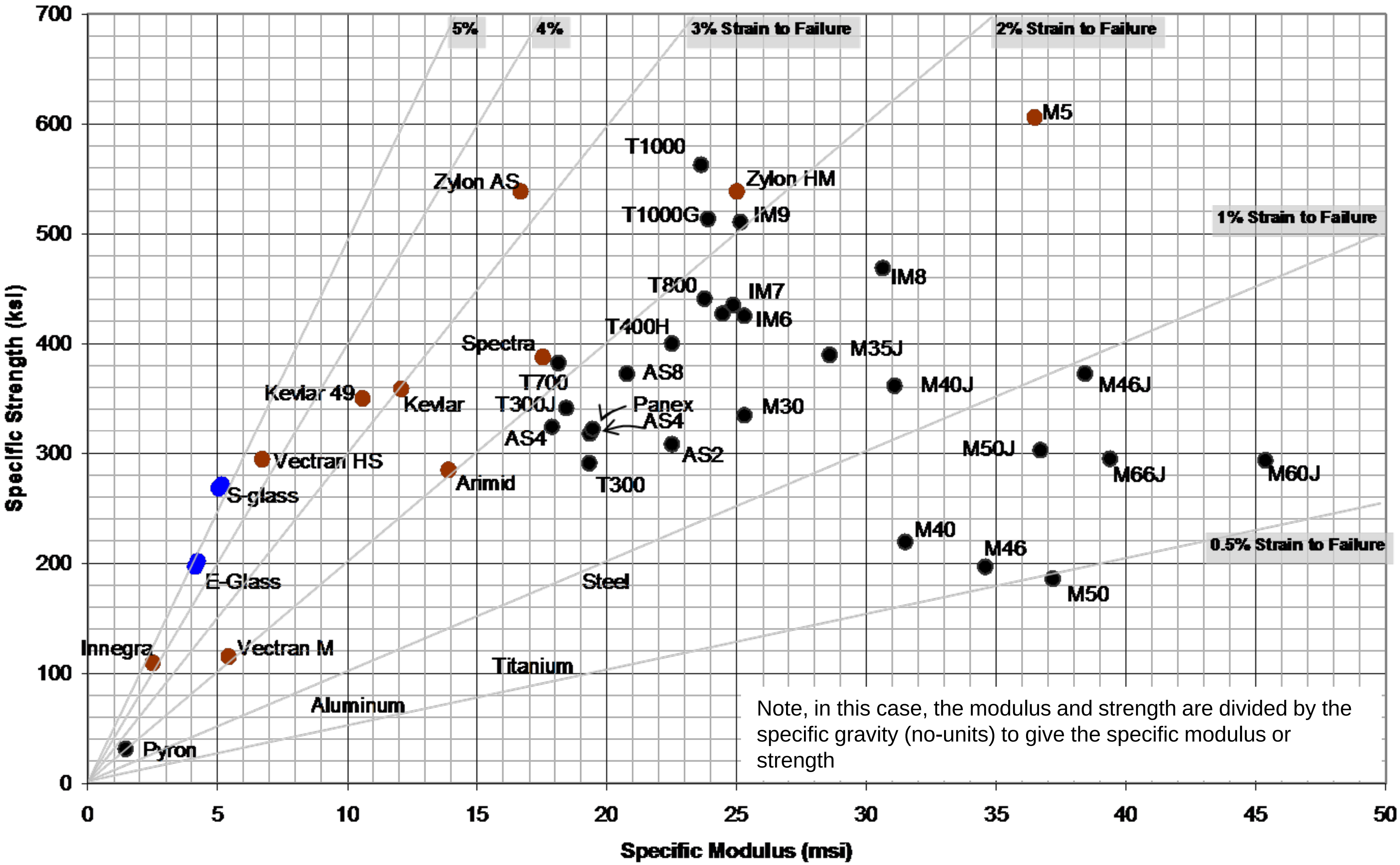


. . . Also for other Energy and Industrial Uses



*500,000 units of compressed gas cylinders would require 27 Metric Tonnes

Specific Strength and Modulus



DOE High Priority MR&D Needs

Table 10: Summary of High-Priority Manufacturing R&D Needs: Hydrogen Storage

Develop process technologies for reducing the cost of carbon fiber

Currently, composite tanks require high-strength fiber made from carbon-fiber grade polyacrylonitrile precursor. The price of the carbon fiber is typically about $20/kg. Reducing the cost of the fiber by about 60%, or about $6/kg, would yield significant savings in the unit cost of composite tanks. Manufacturing R&D is needed to develop lower cost, lower energy decomposition process for carbon fibers, such as microwave or plasma processing.

Develop new manufacturing methods for high-pressure composite tanks

New manufacturing methods are needed that can speed up the cycle time, that is, the per unit fabrication time. Potential advances in manufacturing technologies include faster filament winding (e.g., multiple heads), new filament winding strategies and equipment, continuous versus batch processing (e.g., pultrusion process). New manufacturing processes for applying the resin matrix, including tow-pregs for room temperature curing, wet winding processes, and fiber imbedded thermoplastics for hot wet winding, should also be investigated.

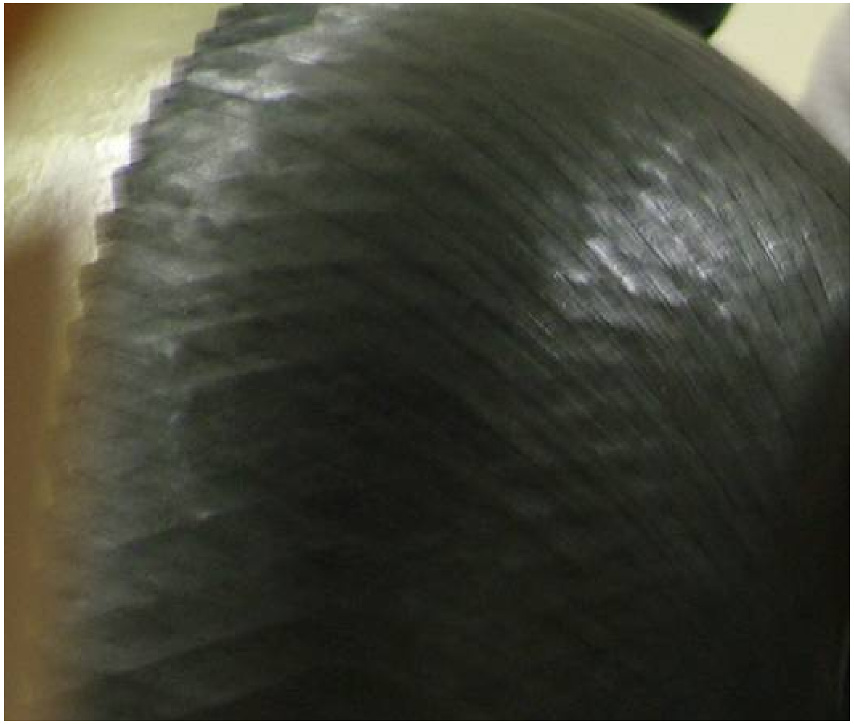
Develop manufacturing technologies for conformable high-pressure storage systems

Although this is a design issue (improved energy density), new manufacturing methods for carbon fiber winding and fiber placement manufacturing could also be applied to improve conformability of tanks by allowing modified cylindrical tank shapes to be manufactured.

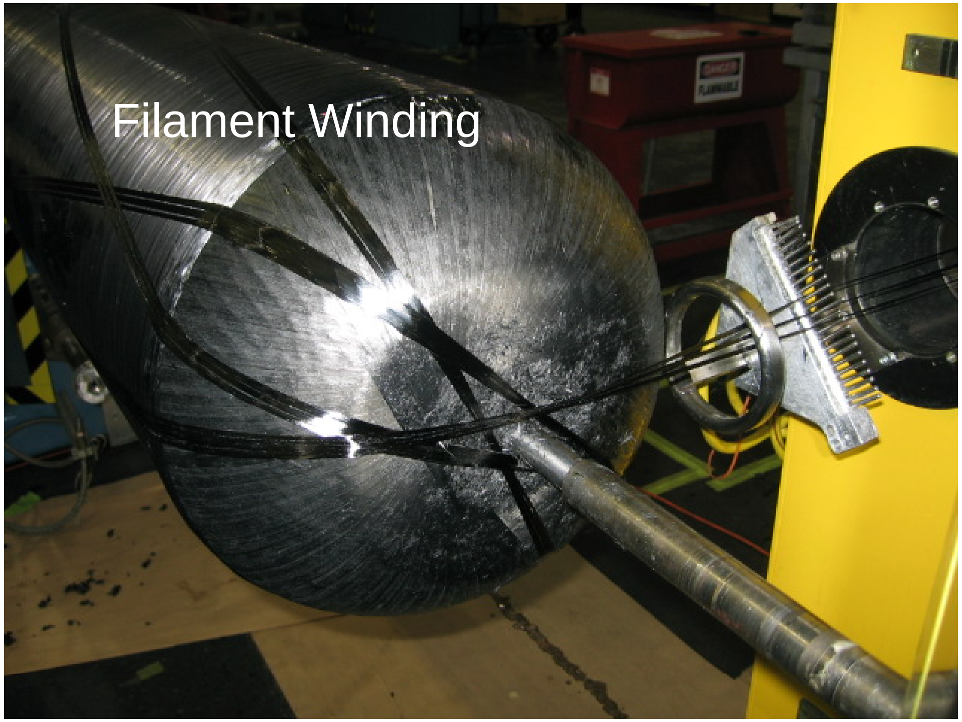
Improve fiber placement processes

Fiber placement technologies can reduce unit costs by reducing the amount of carbon fiber needed by as much as 20%-30%. This approach may also allow some improvement in conformability of high pressure tanks. However, the process is slow. New methods and equipment are needed to improve manufacturing cycle time.

Hybrid Process



Fiber Placement



Filament Winding

Project Objectives

Filament winding process is not optimal

- Allows no easy dropping/picking-up of tows
- Build up of thickness at dome (ends) must pass across length of cylinder
- Results in 15 to 20% added weight
- Lower quality laminate – higher porosity, lower fiber volume

Fiber placement process is not optimal

- Slow process, 2 lb/hr lay down, compared to 30 lb/hr for filament winding
- Expensive equipment
- More touch labor

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

- Optimal elements of flexible fiber placement & commercial filament winding

With the aim of achieving:

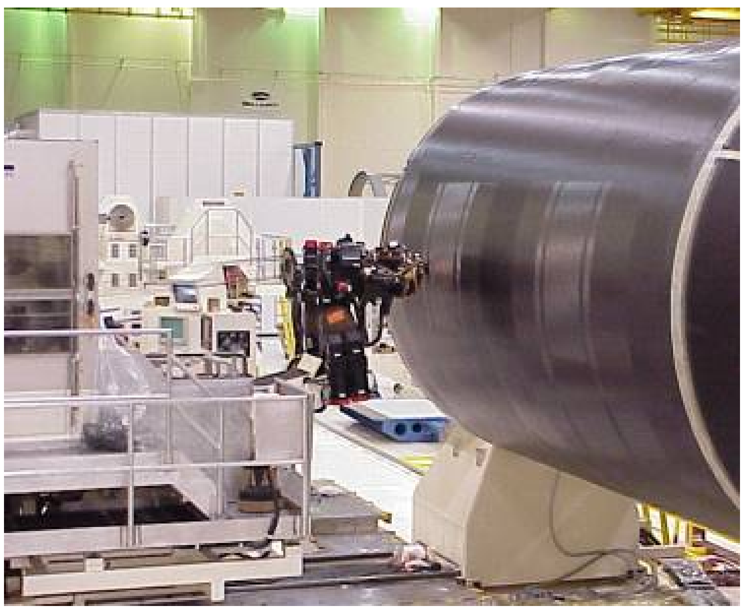
- A manufacturing process with lower composite material usage, cost & higher efficiency

Fiber Placement Technology

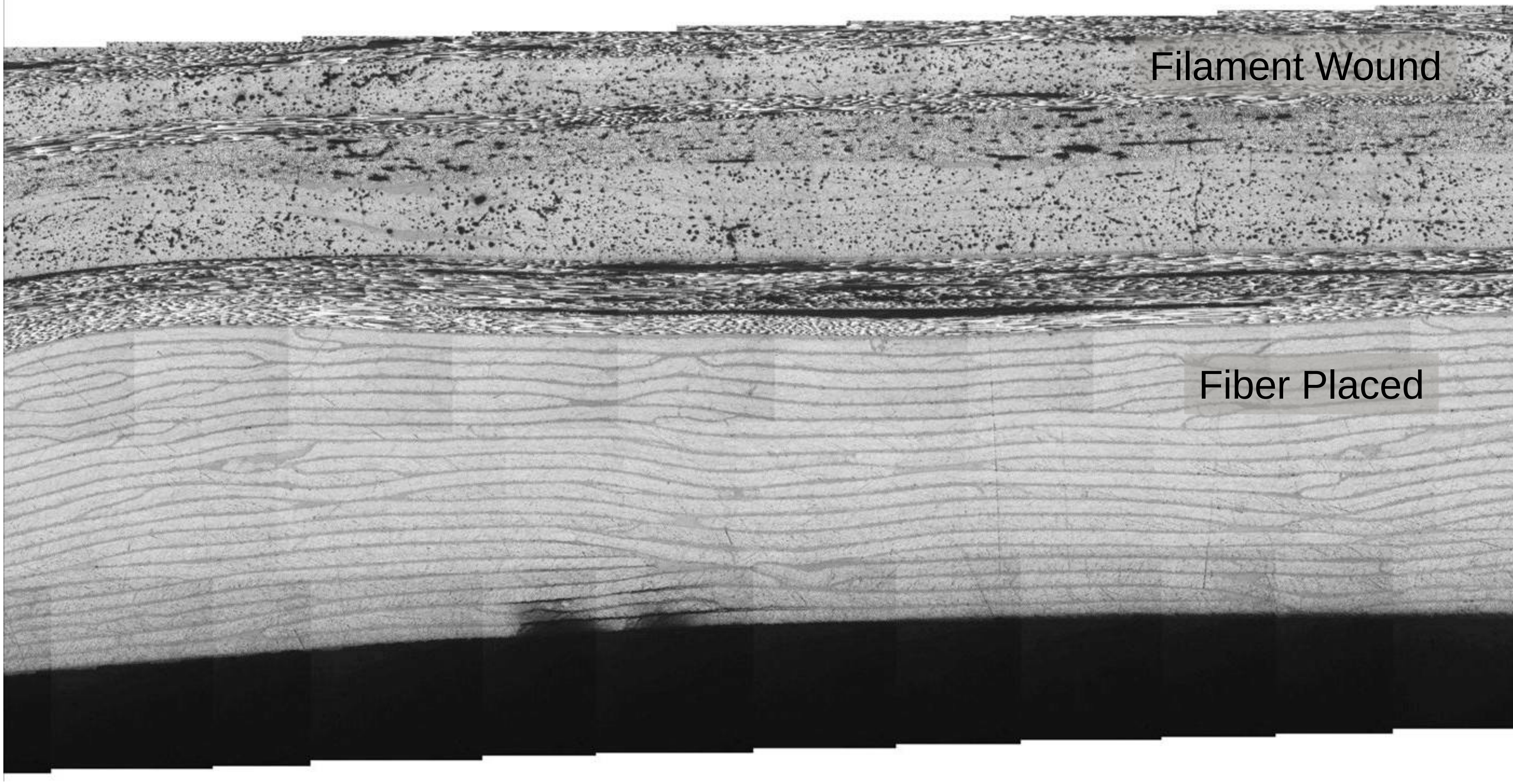
Ref: Boeing Released, BOE031709-109, by K. M. Nelson on Jan 29, 2010.

- **Fiber placement, a CNC process lays multiple strips of composite material on demand.**
  - **Allows maximum weight efficiency**
  - **Only places material where it is needed**
  - **Steering of fiber allows greater design flexibility**

- **Existing machines don't meet the all objectives**
- **Process is scalable to smaller parts**
- **Software available for smaller machines**

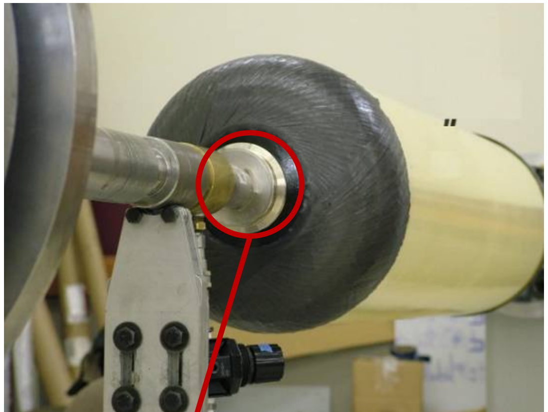


Microstructure



First Tank Fabrication and Test

Ref: Boeing Released, BOE031709-109, by K. M. Nelson on Jan 29, 2010.



The smallest polar opening AFP can make currently

The regions (domes) covered by the localized reinforcement were protected 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. 76.0 kg in the baseline tank (FW alone)

11.1 kg Savings!

Tank Cost Analysis

Quantum and Boeing's manufacturing experience was used to estimate the $/kg of Filament Wound (FW) and Automatic Fiber Placed (AFP) Composites.

Hybrid composite design provided the mass of Filament Wound and Automatic Fiber Placed Composites.

Cost model included materials, labor, overheads, balance of system, manufacturing equipment and factory space costs.

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.**

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

Ref: Boeing Released, BOE012010-035, by K. M. Nelson on Jan 29, 2010.

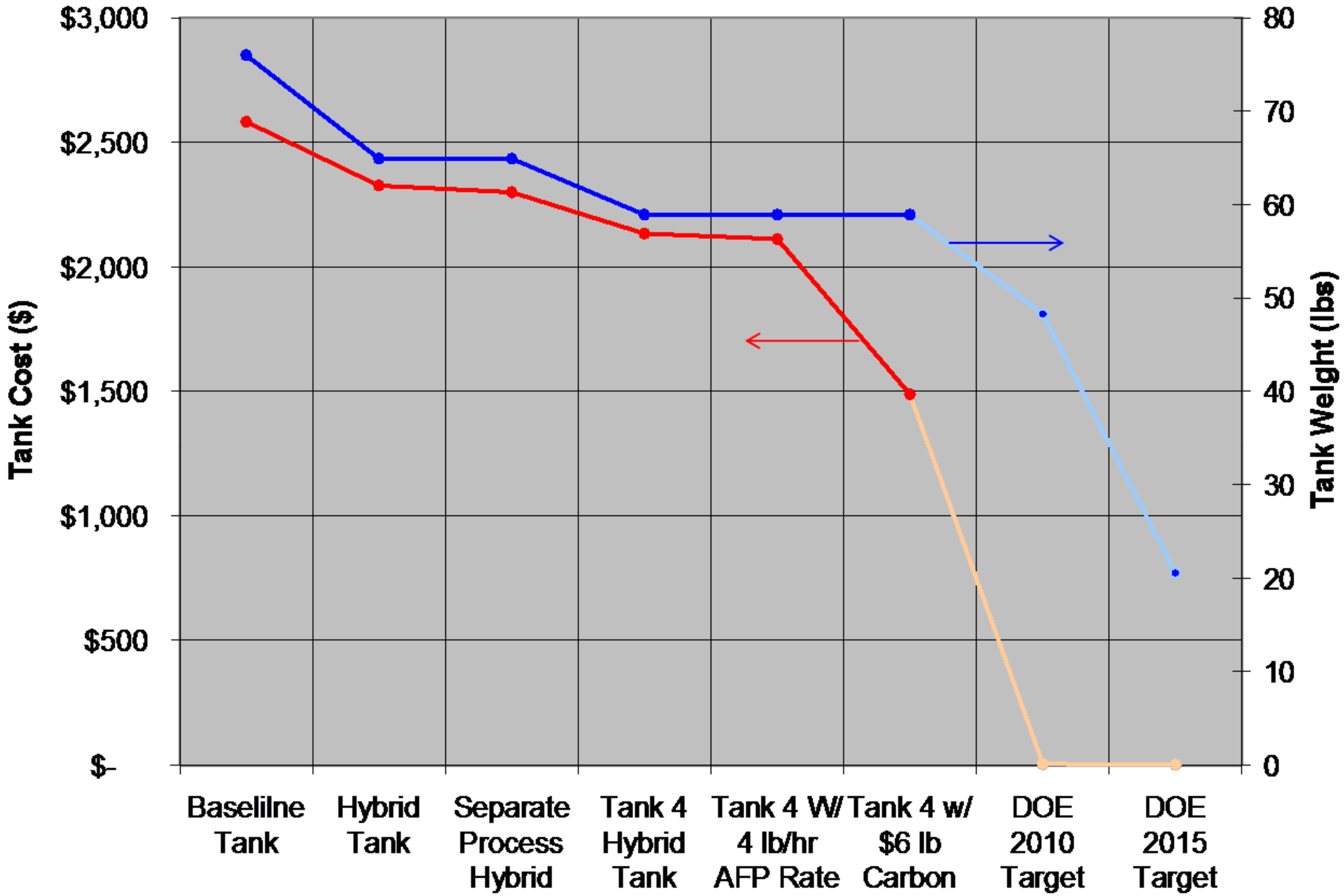
		Type IV Tank	Hybrid FW + AFP Reinforced	
Summary Table		Baseline 129L	Fully Integrated	Separate
		Filament Wound	FW and AFP	FW and AFP
Composite Mass, kg	FW	76	63.4	63.4
	AFP		1.5	1.5
Total Composite Mass, kg		76	64.9	64.9
# Manuf. Cells for 500K/yr	FW	191	242	159
	AFP		484	165
Tank Costs				
FW Composite		$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)

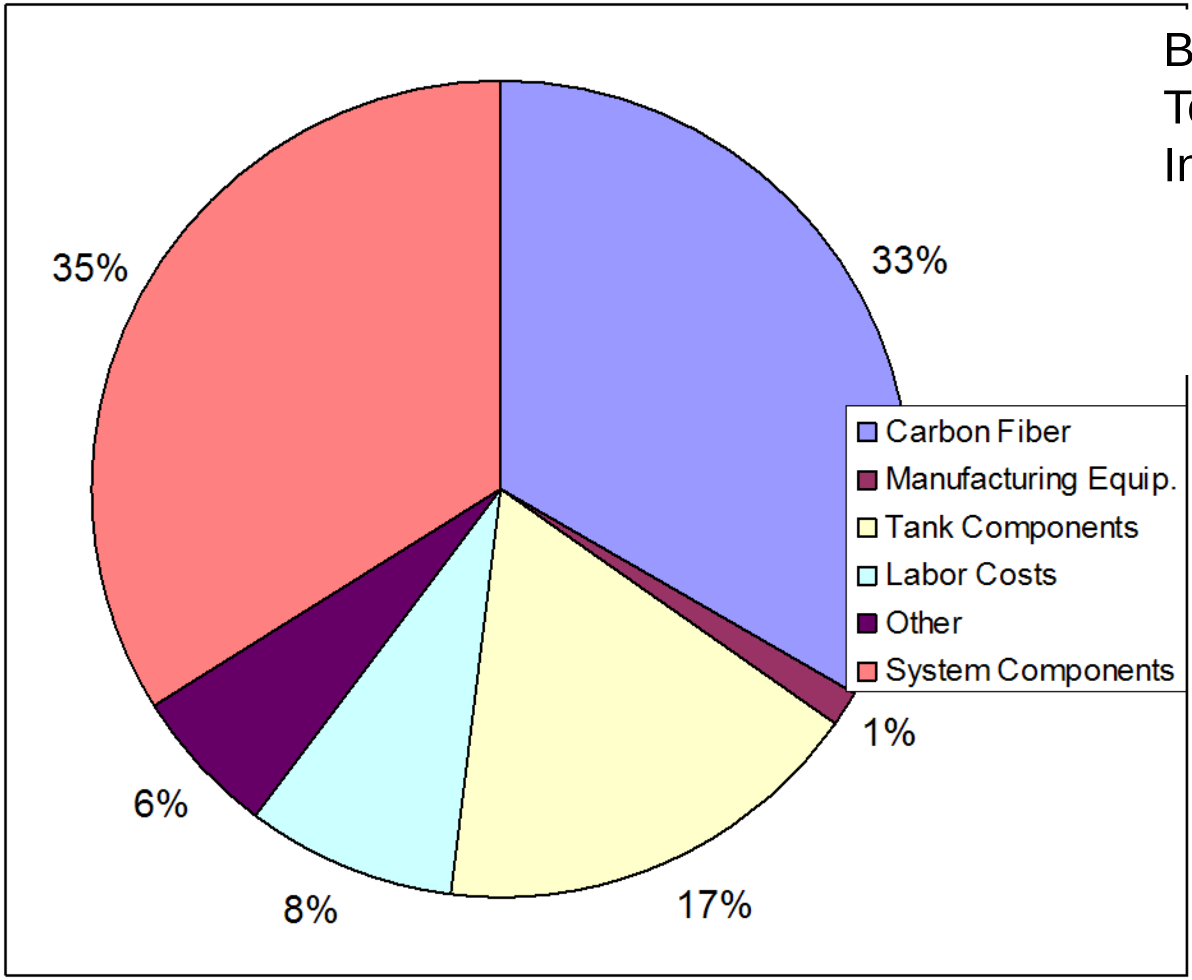
***Cost numbers provided by Pacific Northwest National Labs. See Notes.**

Cost* and Tank Weight Compared to DOE Targets



***Cost numbers provided by Pacific Northwest National Labs. See Notes.**

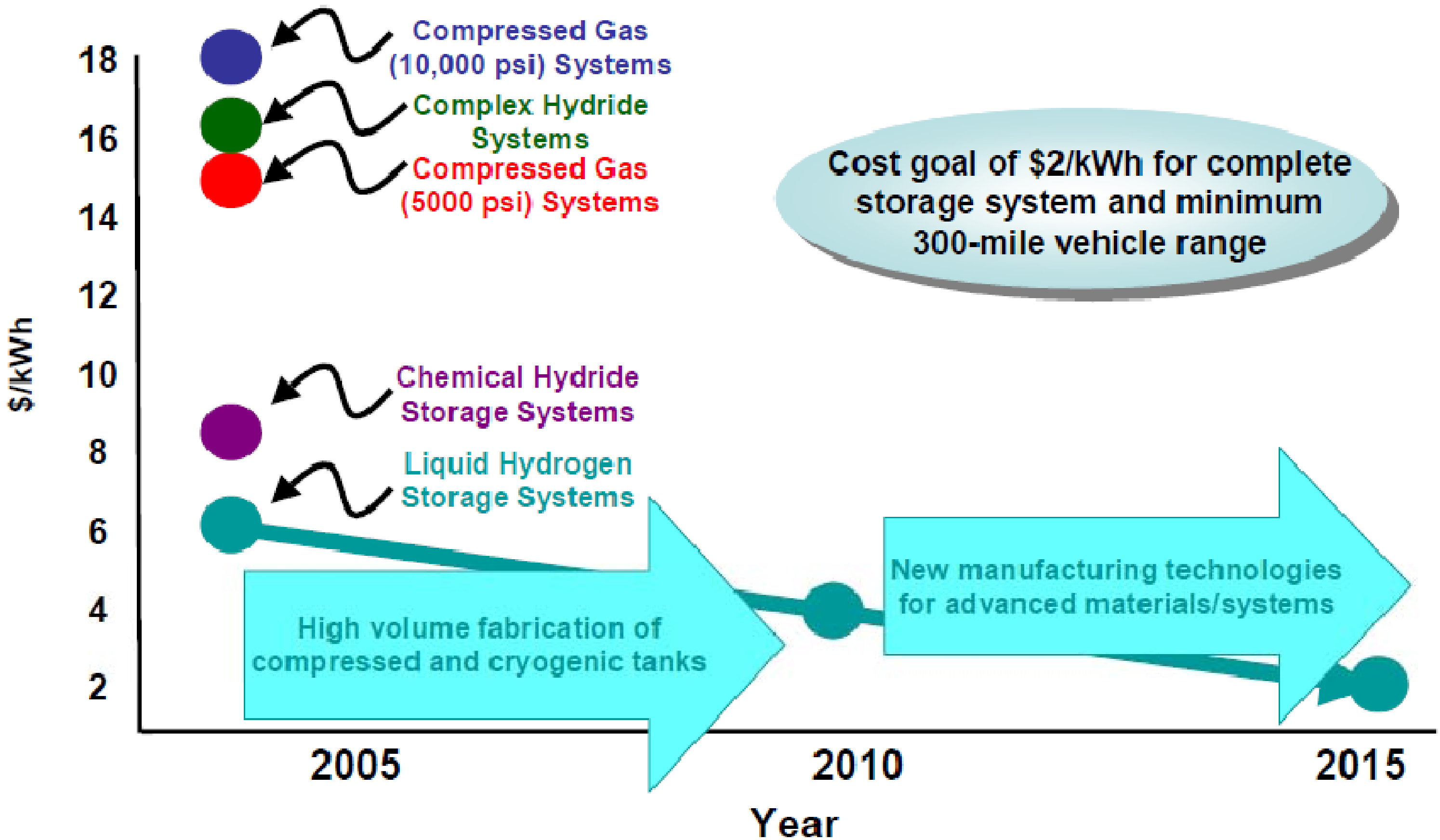
Breakdown of System Costs



Baseline System
Total Cost =$3864
Includes:
- Tank Hardware
- System Hardware
- 500,000 Units per Year

***Cost Numbers Derived from PNNL Cost Analysis. See Notes.**

DOE Cost Goals

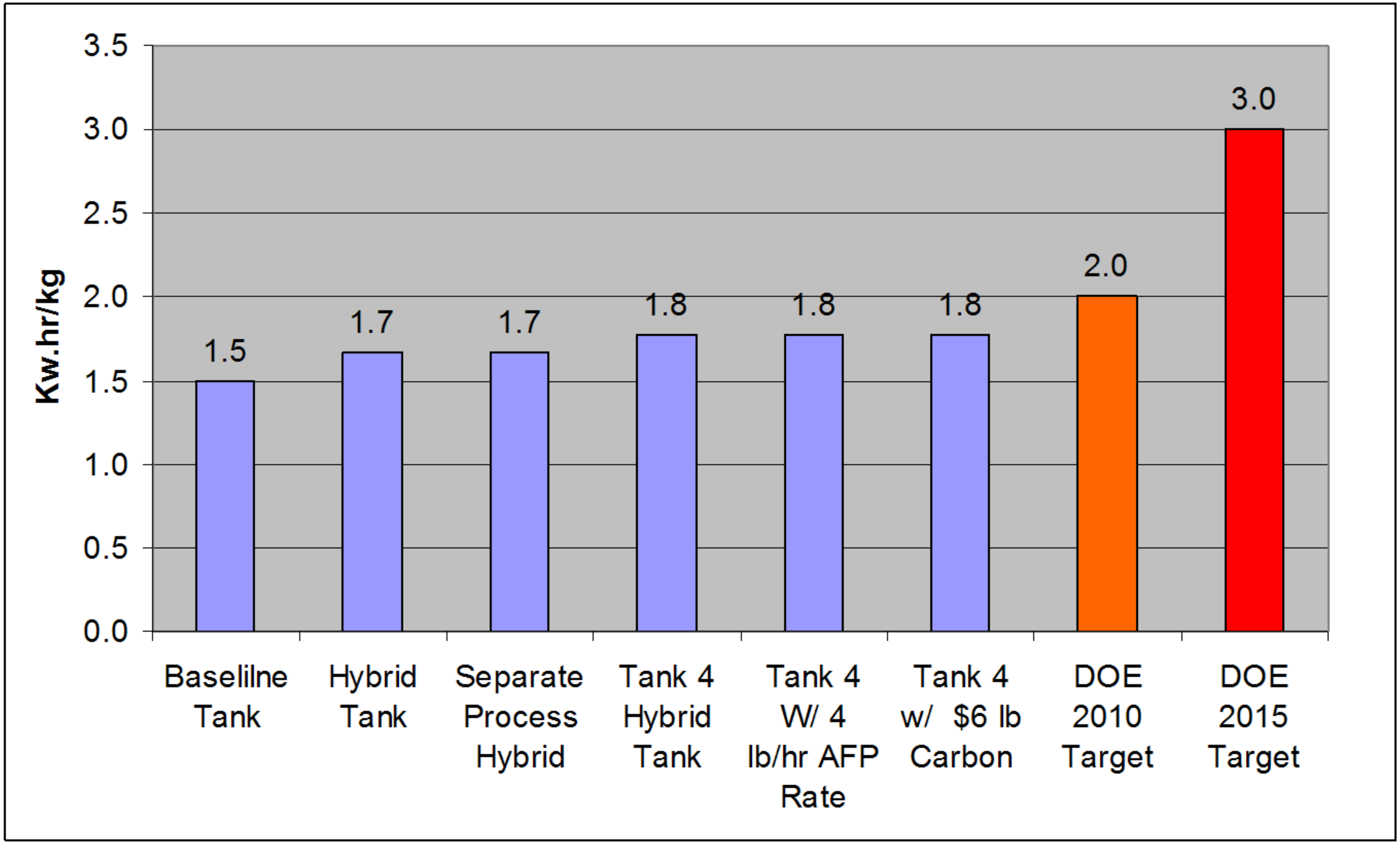


DOE Energy Storage Goals

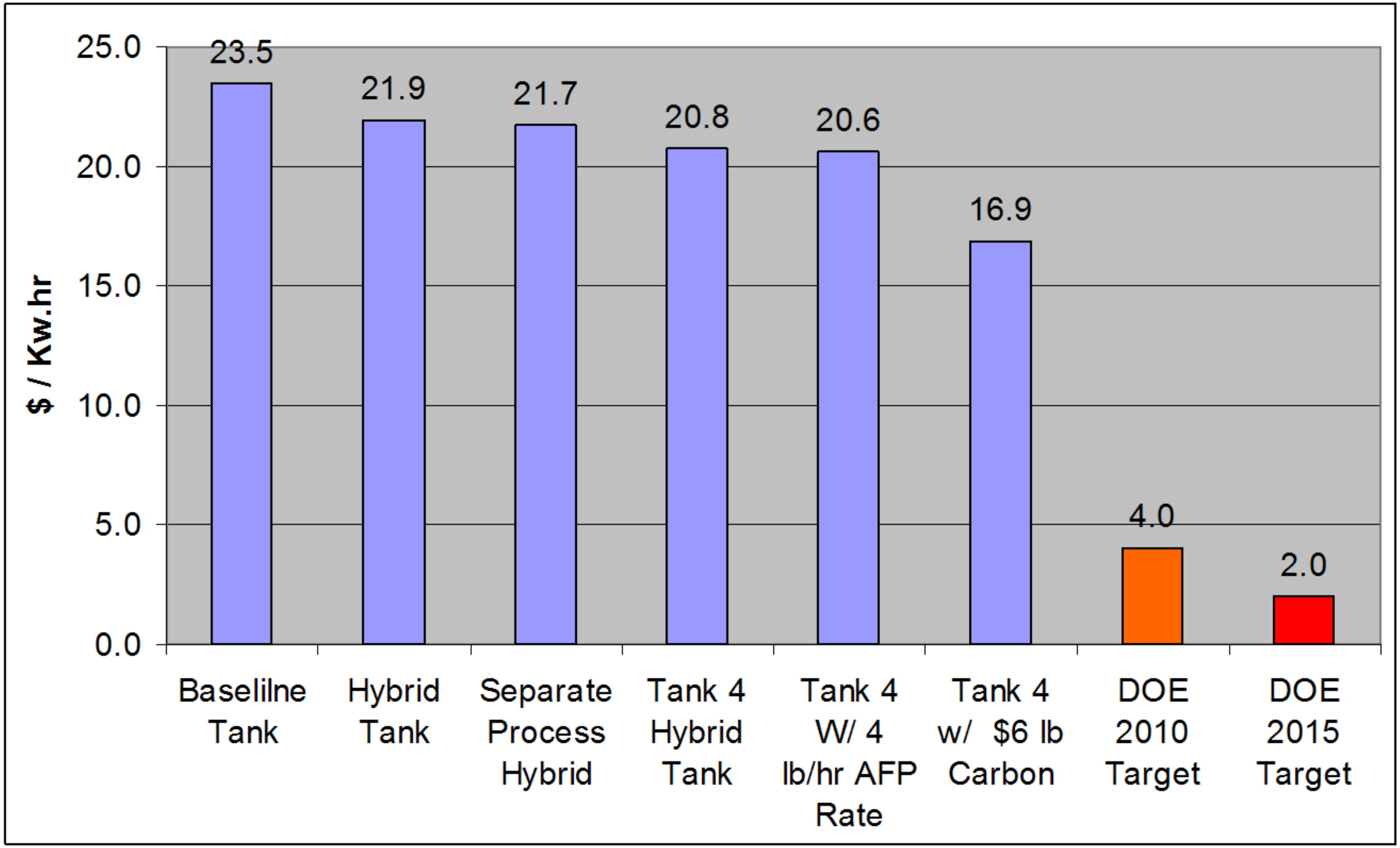
The current (as of 2009) high pressure, i.e. 700 bar (10,000 psi) gaseous, hydrogen storage

- Goal is a 5-kg H_2 storage vessel
- 2010 target for on-board hydrogen storage is:
  - $4/kWh by 2010
  - 2 kWh/kg (6 wt%)
  - 1.5 kWh/L
- By 2015 target is:
  - $2/kWhr by 2015 (~$300 for a 5-kg hydrogen system).
  - 3 kWh/kg (9 wt%)
  - 2.7 kWh/L

Specific Energy Compared to DOE Goals



Cost* Efficiency Compared to DOE Goals



***Based on $11/lb Carbon Fiber. Cost Numbers Derived from PNNL Cost Analysis. See Notes.**

Observations

- **Based on the system cost:**
  - Carbon fibers drive 33% of system cost
- **Based on tank cost:**
  - Raw carbon fibers are 50% of tank costs
  - Composite part of tank is 86 to 89% of total cost
- **Reduce fiber cost from 11 to $6/lb would:**
  - Reduce tank cost by 24%
  - Reduce system cost by 15%
- **Hardware components are expensive: 52% (of system cost)**
  - Valves, Regulators, Sensors, End Bosses, Fittings
  - Explore ways of reducing these costs.
- **Realistic, aggressive DOE cost goals**
  - Cost Efficiency == $/KwH
    - $1700* for full system
    - Realistic goal = 10 $/KwH
  - Specific Energy == KwH/kg
    - Driven by fiber performance.
    - Realistic goal == 2 KwH/kg (2010 Goal)
- **Refurbishing tanks**
  - 30-year life time is longer then vehicle life
  - Use refurbished tanks in lower-cost new vehicles
  - Residual value of tank after 15-years maybe 40% of new
- **1.80 vs. 2.25 Factor of Safety?**

***Cost Numbers Derived from PNNL Cost Analysis. See Notes.**

Built for the Environment

- **Reduction in hazardous chemicals and overall waste**
- **Significant reduction in tooling**
- **30-40% reduction in manufacturing assembly time**
- **Process creates repeatable first-time quality**
- **Much better buy-to-fly ratio**

Manufacturing techniques drive environmental performance

New Head Design

Ref: Boeing Released, BOE031709-109, by K. M. Nelson on Jan 29, 2010.

- **Structural efficiency increases with smaller fiber-placed polar openings**
- **Heads must be designed to minimize clearance with the boss**
- **Programming focused on geodesic paths for minimal shear loading of composite**