

Enabling the Future of Aviation through Revolutionary Materials

Aviation Unleashed – Reaching Beyond Tomorrow
Workshop, October 18-20, Hampton VA

**Presented by
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NASA Langley Research Center
October 19, 2010**

Outline of Briefing*

- **Future Materials Requirements for Aviation***
- **Case Study: Composites in Commercial Aircraft**
- **Revolutionary Materials Opportunities**
- **Realizing the potential of Materials to “Unleash Aviation”**
- **The Last Word!**

***Caveats:**

- (1) Primarily addresses structural materials for future airframe applications;
- (2) Prepared from the government (NASA) perspective;
- (3) Presents the perspective and experience of the presenter (C.E.H.)

But first, why is this important?

Reference: The Global Technology Revolution, **Bio/Nano/Materials Trends and Their Synergies with Information Technology by 2015**, Rand National Defense Research Institute, Report prepared for the National Intelligence Council, Contract DASW01-95-C-0069 2001.

Life in 2015 will be revolutionized by the growing effect of multidisciplinary technology across all dimensions of life: social, economic, political, and personal. Biotechnology will enable us to identify, understand, manipulate, improve, and control living organisms (including ourselves). The revolution of information availability and utility will continue to profoundly affect the world in all these dimensions. **Smart materials, agile manufacturing, and nanotechnology will change the way we produce devices while expanding their capabilities.** These technologies may also be joined by “wild cards” in 2015 if barriers to their development are resolved in time.

The results could be astonishing. Effects may include significant improvements in human quality of life and life span, high rates of industrial turnover, lifetime worker training, continued globalization, reshuffling of wealth, cultural amalgamation or invasion with potential for increased tension and conflict, shifts in power from nation states to non-governmental organizations and individuals, mixed environmental effects, improvements in quality of life with accompanying prosperity and reduced tension, and the possibility of human eugenics and cloning.

(Continued, next page)

Something big is going on!

Reference: The Global Technology Revolution, Bio/Nano,/Materials Trends and Their Synergies with Information Technology by 2015, Rand National Defense Research Institute, Report prepared for the National Intelligence Council, Contract DASW01-95-C-0069 2001.

This revolution is being driven by the following megatrends:

1. Accelerating pace of technological change.
2. Increasingly multidisciplinary nature of technology.
3. Competition for technology development leadership.
4. Continued globalization.
5. Latent lateral penetration. (“providing the means for the developing world to reap the benefit of technology.”)

Since this report was written in 2001, these megatrends have accelerated and are driving the worldwide pace of technology development. (*Hot, Flat, and Crowded*, Thomas L. Friedman, Farrar, Straus, and Giroux, 2008)

Does this apply to civil aviation, to materials development?

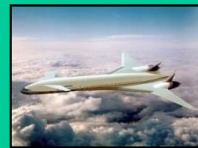
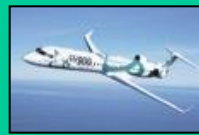
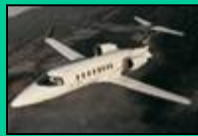
Future Materials Requirements for Aviation

Aviation Vehicle Sectors

Flexible

Scheduled

Autonomous



PAV

GA

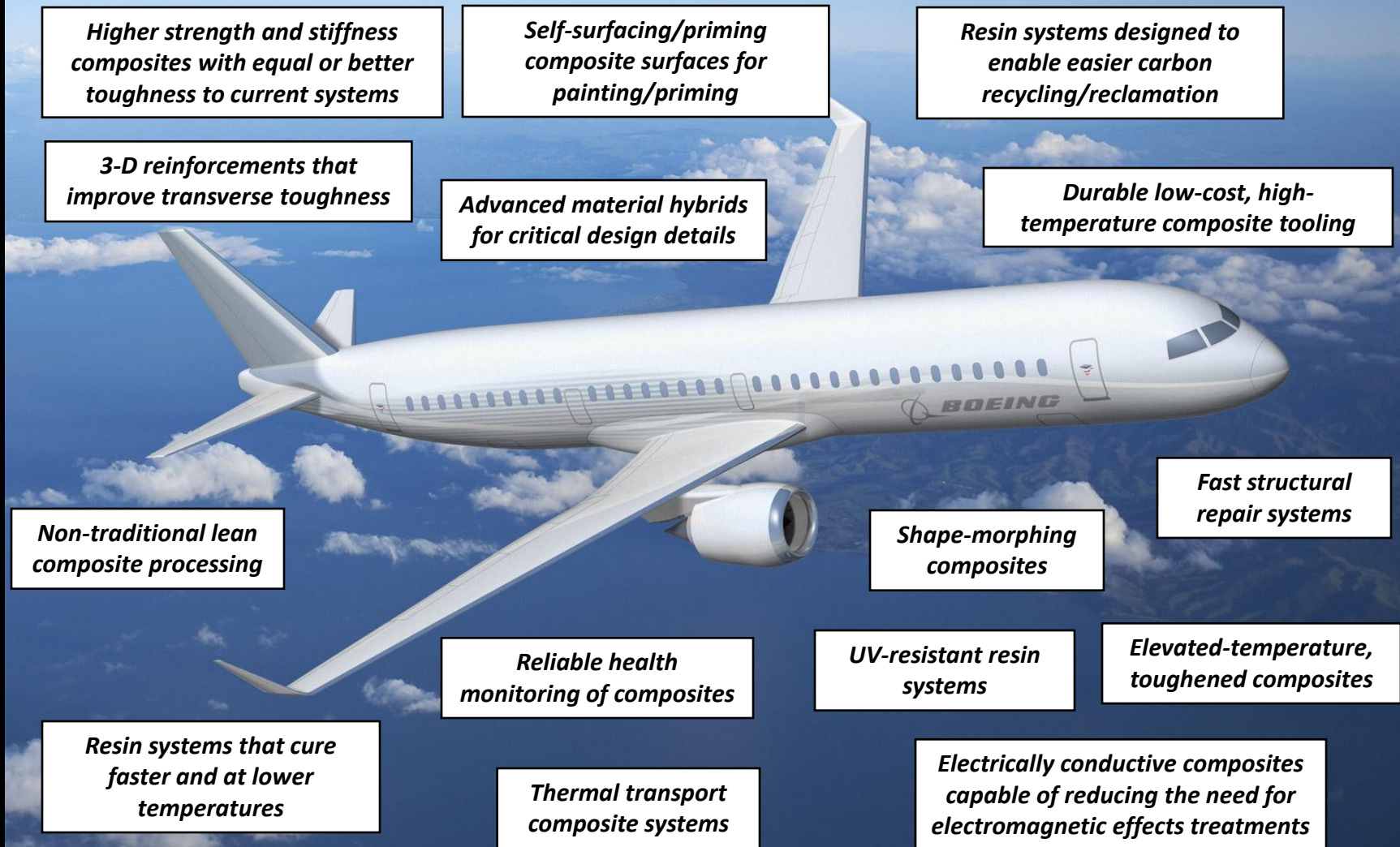
Biz Jets

Regional

Long-Haul

UAV

Materials Requirements/Needs for Transport Aircraft



Provided to NASA for this presentation by
The Boeing Company, September 2010

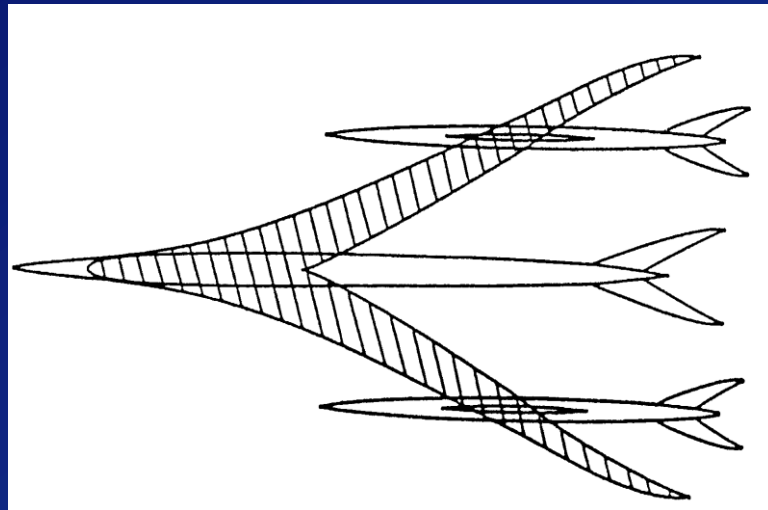
The Future: Non-Conventional Configurations (L/D ~ 40+)



Truss-Braced Wing

Subsonic CTOL

- Truss-braced wing, tip engines
- Advanced blended wing body
- Ring Wing (DDL at wing tip)
- Double fuselage
- Thin wing and unswept for NLF
- Circulation control for take-off



Pfenninger Extreme Arrow

Supersonic CTOL

- Pfenninger extreme arrow, strut-braced
- Low chord wings and suction LFC
- Thrust vectoring for control
- Flow separation control at cruise

“Fluid Mechanics, Drag Reduction and Advanced Configuration Aeronautics”, *Dennis M. Bushnell*, NASA/TM-2000-210646, Dec 2000

Materials are Enabling to NASA Aeronautics Program Goals

FAP / Subsonic Fixed Wing Project Goals

- Reduce fuel burn by >70%
- Reduce NOx emissions by >75%
- Reduce noise by 71 dB (cumulative, 3 measurements)
- Reduce runway Field length by >50% (exploit community airports)

FAP / Supersonic Project Goals

- Reduce Airport noise: 10-20 EPNdB (EPN=Effective perceived noise)
- Reduce Sonic Boom: 65-70 PLdB Low Boom; 75-80 PLdB Overwater (PL=perceived level)
- Increase Fuel Efficiency: 4.5 pass-miles per lb of fuel (~5X over N+1 goal)
- Reduce High Altitude Emissions: impact minimized or eliminated (<5 NOx g/kg fuel)

FAP / Subsonic Rotary Wing Project

- Develop Actively-controlled rotorcraft: 100 kt speed improvement over SOA, noise contained within landing area, 90 pax/10 ton payload
- Develop Integrated aeromechanics/propulsion system: 50% main rotor speed reduction
- Reduce Cabin Noise: internal cabin noise at level of regional jet with no weight penalty

FAP / Hypersonic Project

- Develop air-breathing propulsion technology for Two-Stage-to-Orbit Vehicles
- Develop light weight, reusable 3000°F structurally-integrated Thermal Protection Systems
- Decrease uncertainty in aeroheating prediction by 50%
- Develop tools and technologies to enable high-mass planetary entry

Subsonic Advanced Aircraft Concepts Phase 1 Studies

Boeing, GE, Ga Tech

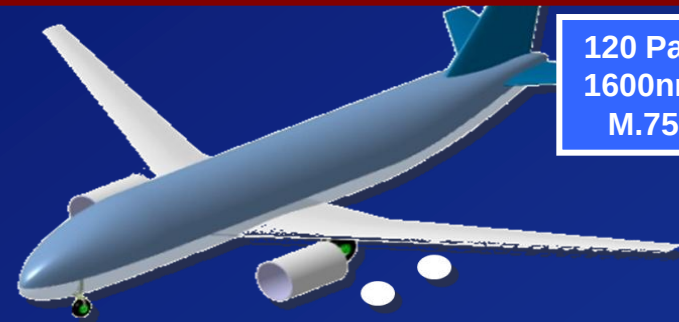
154 Pax
3500nm
M.70



- Ultra-high modulus/strength fibers (wings)
- Metal-Matrix Composites (landing gear)
- Very high toughness composites (wing, fuselage)
- High-Temperature Polymer Composites (nacelles)
- Multifunctional nanocomposites (wing, fuselage)
- Durable ceramics and CMCs (engines & nacelles)

Northrop Grumman, RR, Tufts, Sensis, Spirit

120 Pax
1600nm
M.75



- Ultra-high performance fibers
- Carbon Nanotube electrical cables
- Shape memory alloys (nacelles)
- Ceramic matrix composite (combustors)
- Advanced metallics (higher toughness)

GE, Cessna, Ga Tech

20 Pax
800nm
M.55



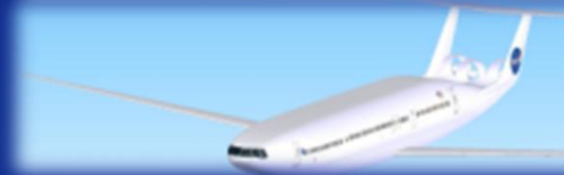
- Advanced Composite protective skin (High Risk)
- Advanced composites for engine (Medium Risk)

MIT, Aurora, P&W, Aerodyne

354 Pax
7600nm
M.83



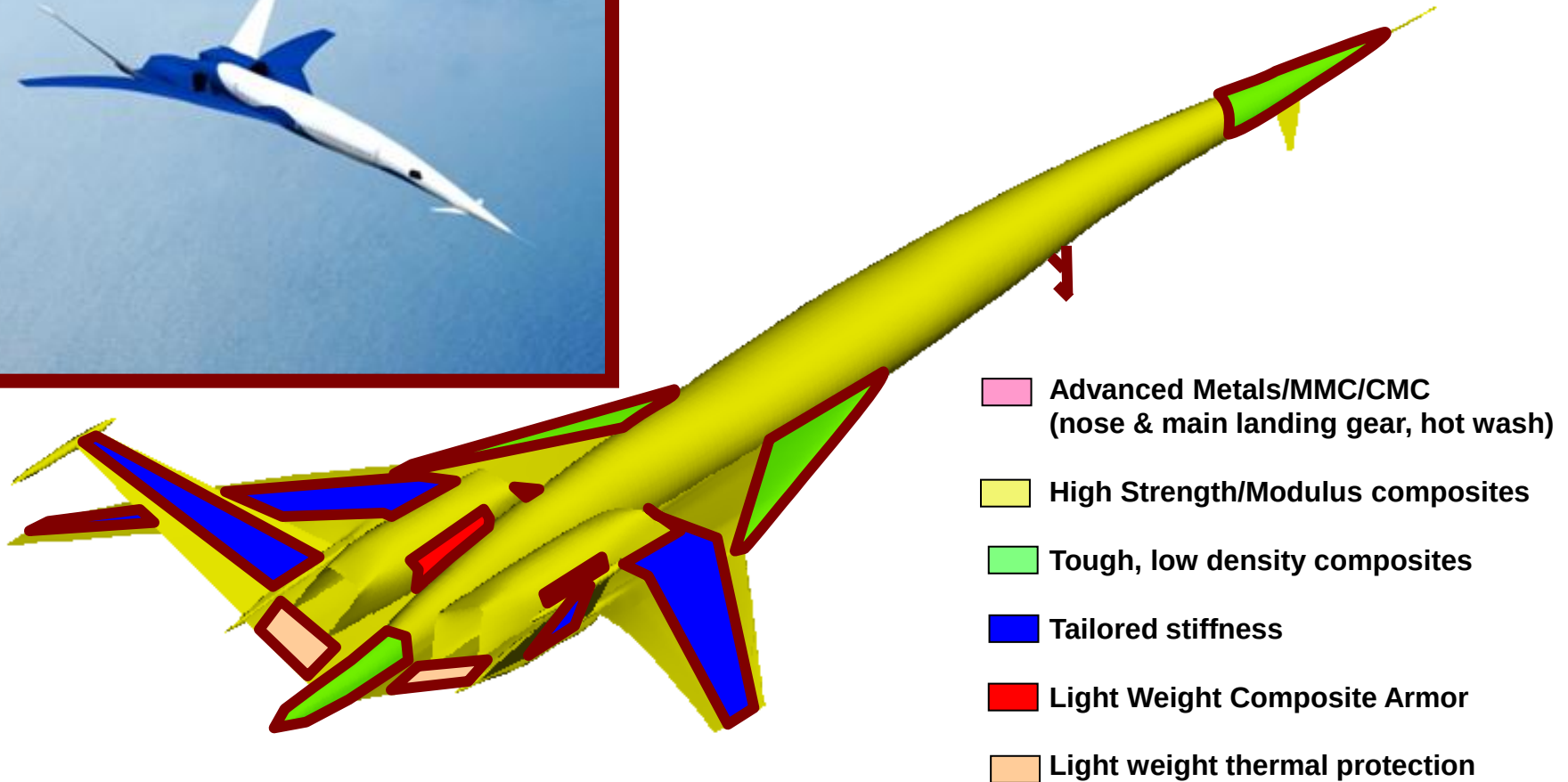
180 Pax
3000nm
M.74



- Advanced structural materials (2X over Aluminum)

Supersonic Advanced Aircraft Concepts Phase I Studies

Boeing N+3 Vehicle Concept

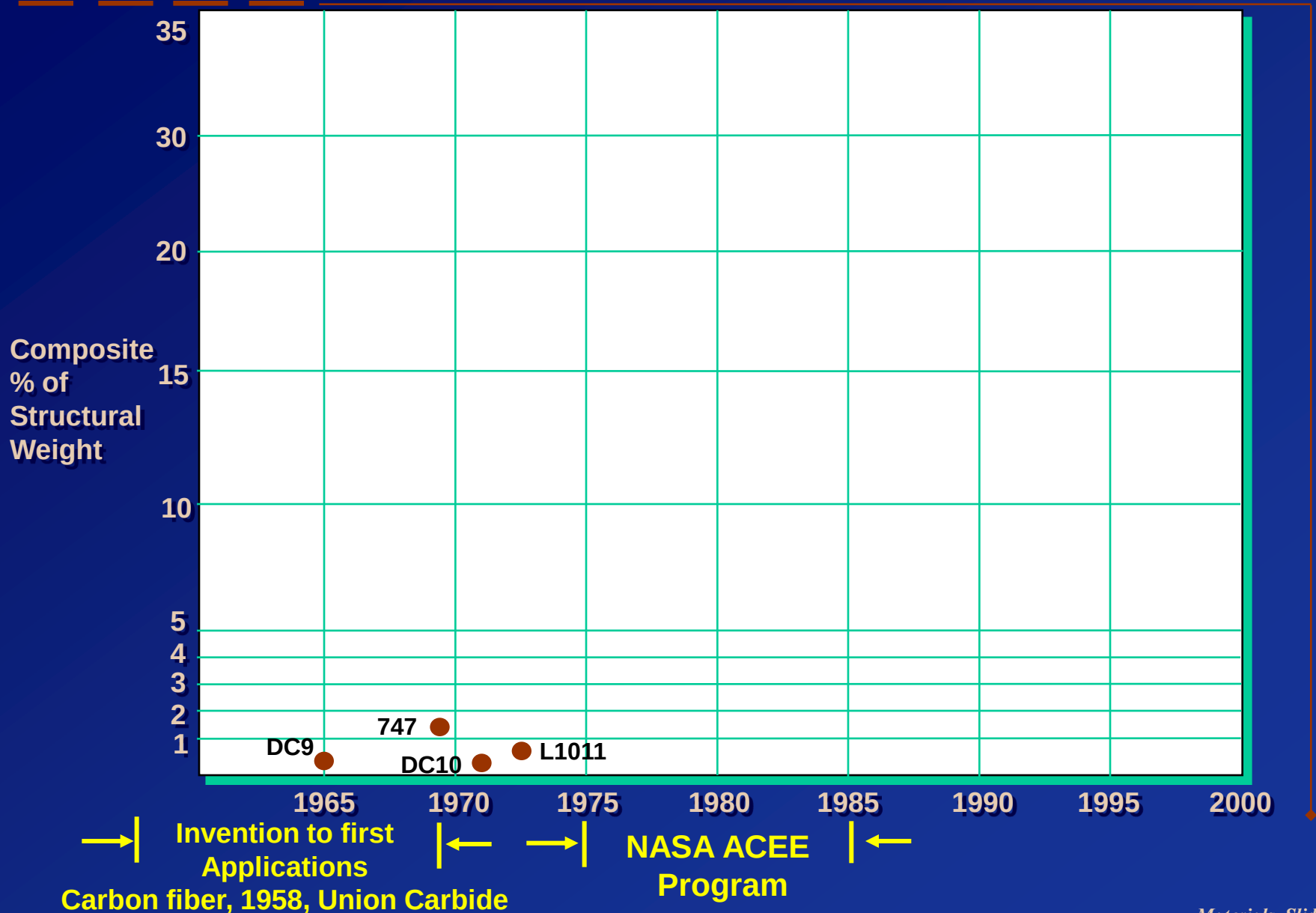


Welge, Nelson, Bonet, "Supersonic Vehicle Systems for the 2020 to 2035 Timeframe," AIAA-2010-4930, June, 2010.

Case Study: Composites in Commercial Aircraft

- **NASA Aircraft Energy Efficiency Program (1975-1985)**
 - Obtain actual flight experience
 - Obtain environmental exposure data
- **NASA Advanced Composites Program (1989-2000)**
 - 25% structural weight reduction
 - 20% structural fabrication cost reduction
- **Boeing 787 (2010)**

Composites in Commercial Transport Aircraft (1970-75)



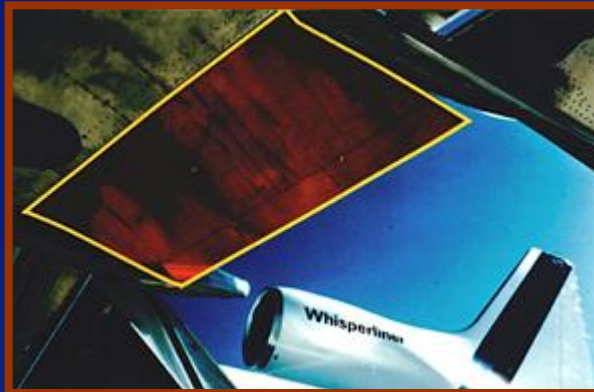
Structural Composites in Civil Aircraft (ACEE Program)



Boeing 727 composite elevator



Boeing 737 composite horizontal stabilizer



Lockheed L-1011 composite aileron



Douglas DC-10 composite Rudder and vertical stabilizer

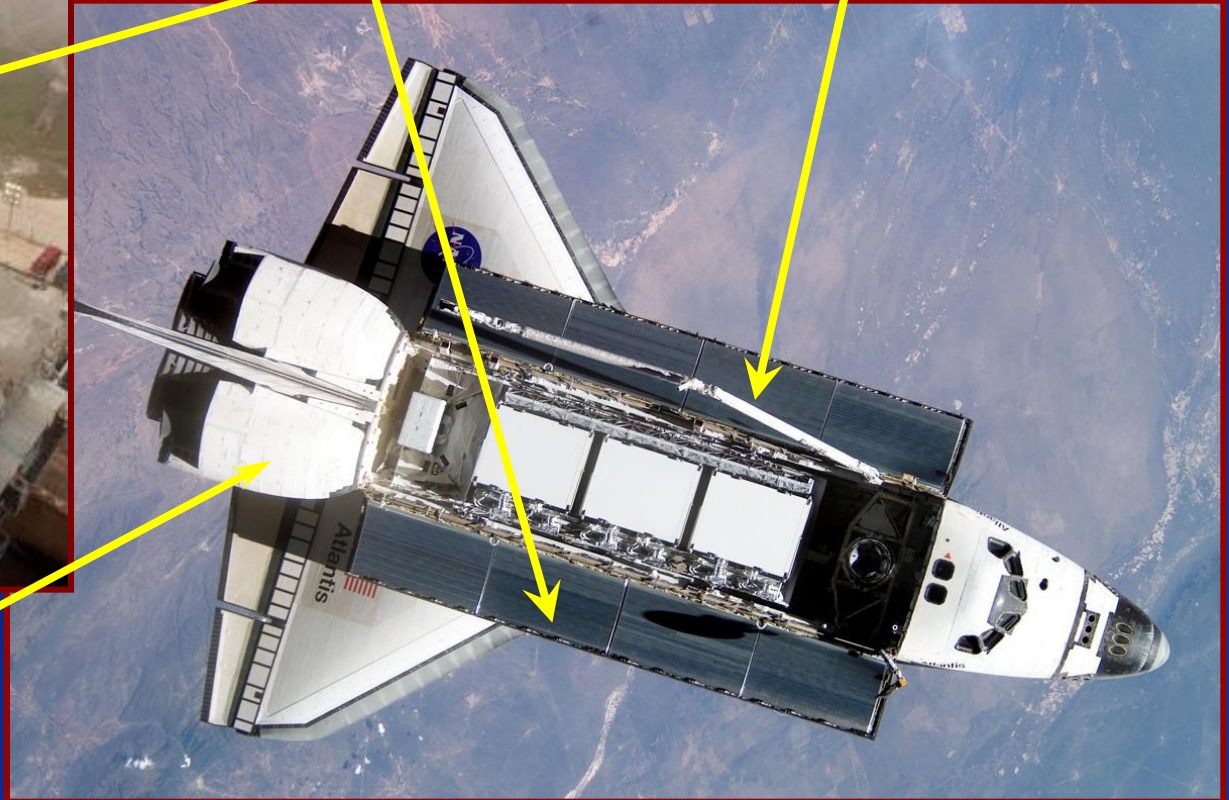
350 Composite components accumulated over 3.5 million flight hours by 1993!

The NASA programs were more than just civil aviation!



Payload Bay Doors

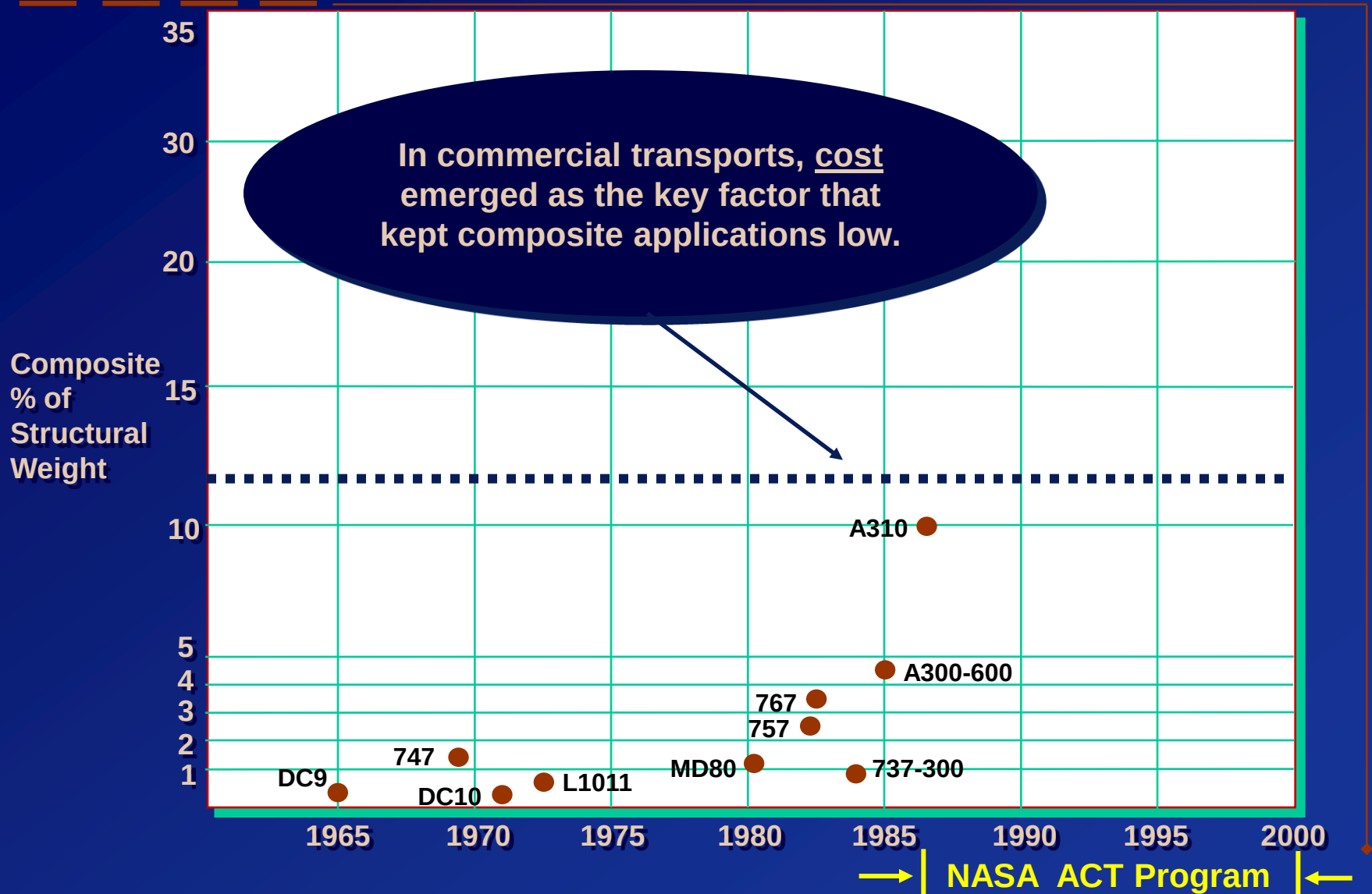
Robotic Arm



OMS Pods

STS orbiter payload bay doors were the largest composite structure ever designed and built circa late 1970's. First flight in 1981

Composites in Commercial Transport Aircraft (1980-85)



The combined national effort was highly leveraged: DoD and NASA!



- **B-2 Primary Structure Is Almost All Composites**
- **First flight test was July 17, 1989**
- **Wing is almost as large as B-747**

Reference: Jane's All the Worlds Aircraft

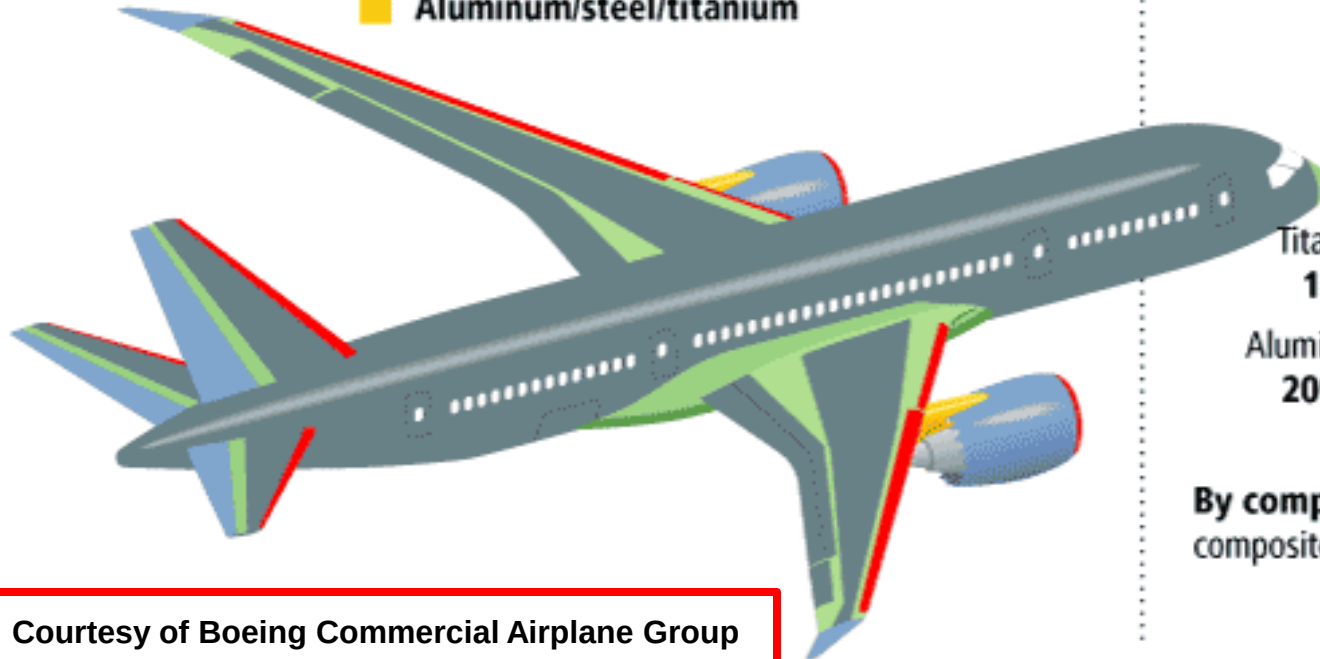
NASA / BOEING STITCHED WING (ACT) PROGRAM

41-ft Long Stitched semi-span wing at 95% Design Ultimate Load

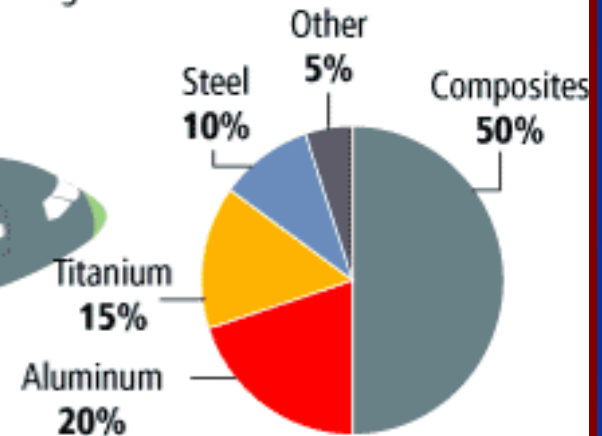


Composite Material Used in the Boeing 787 (2000's)

Materials used in 787 body



Total materials used By weight



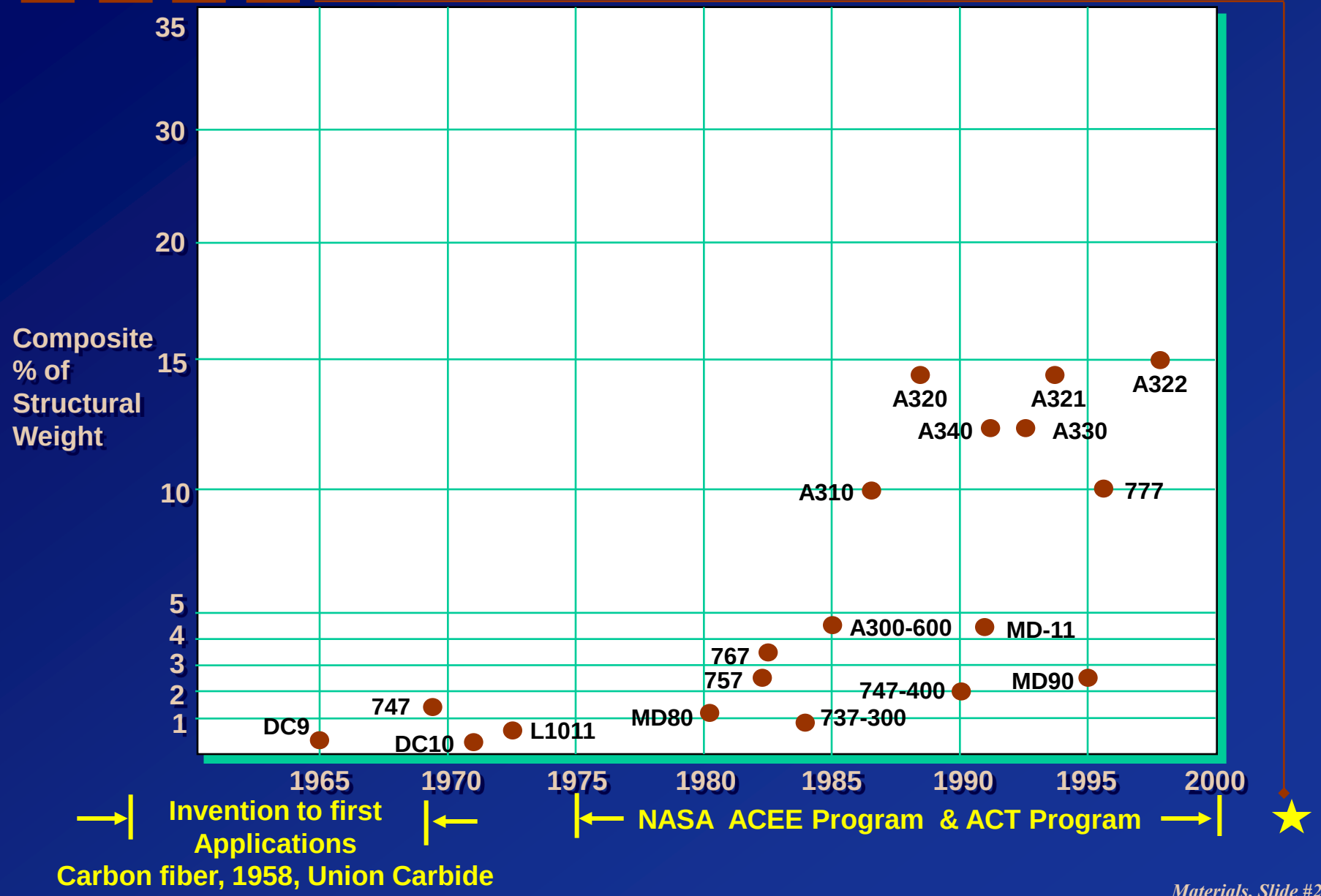
By comparison, the 777 uses 12 percent composites and 50 percent aluminum.

Courtesy of Boeing Commercial Airplane Group

B787 exceeds the original goals of the ACT Program established in 1988!

About half the 787, including its fuselage and wings, is constructed of composite materials, making the airplane 40,000 pounds lighter than airplanes of similar size that are constructed of conventional materials. The 787 is about 20 percent more fuel efficient and produces 20 percent fewer emissions.

Composites in Commercial Transport Aircraft (2010)



Lessons Learned*

1. **Leadership:** foresight and commitment
2. **Sustained commitment**
3. **Model for success:** base research + technology development programs
4. **Proactive education and training**
5. **Multidisciplinary research**
6. **Building block approach**
7. **Structural Analyses:** new analysis codes and capabilities
8. **Bridging technologies:** exploiting unusual synergies (pharmaceutical industry, textile industry)
9. **Uncertainty planning:** none of the projects were fully funded in their original plan
10. **Archiving data:** focus on interfaces and hand-offs
11. **Personnel mobility**
12. **Motivated by grand challenges**

*Reference: **Structural Framework for Flight: NASA's Role in Development of Composite Materials for Aircraft and Space Structures**, Tenney, Davis, Johnston, and McGuire, NASA XP-2010, XXX, 2010

Revolutionary Materials Opportunities

Primary Source of Data

Reference: A Survey of Emerging Materials for Revolutionary Aerospace Vehicle Structures and Propulsion Systems, NASA TM-211664, Harris (LaRC), Shuart (LaRC), and Gray (GRC), May 2002



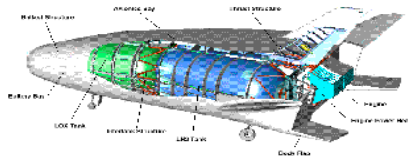
Application of Advanced Materials to 2nd Gen. RLV

Leading Edges / Nose Caps

- Hot-structure control surfaces (TRL=5)
- High-temperature heat pipes (TRL=4)
- Active cooling (TRL=4)

Thermal Protection System

- High-temperature metallics (TRL=5)
- Advanced ceramics (TRL=4)
- Refractory composites (TRL=4)
- Advanced flexible insulation (TRL=6)



Primary Structure

- High-temperature polymeric composites (TRL=5)
- High-temperature metal composites (TRL=4)
- Manufacturing process scalability (TRL=4)
- Validated design and analysis methods (TRL=4)
- Nondestructive evaluation (TRL=4)

Cryotanks

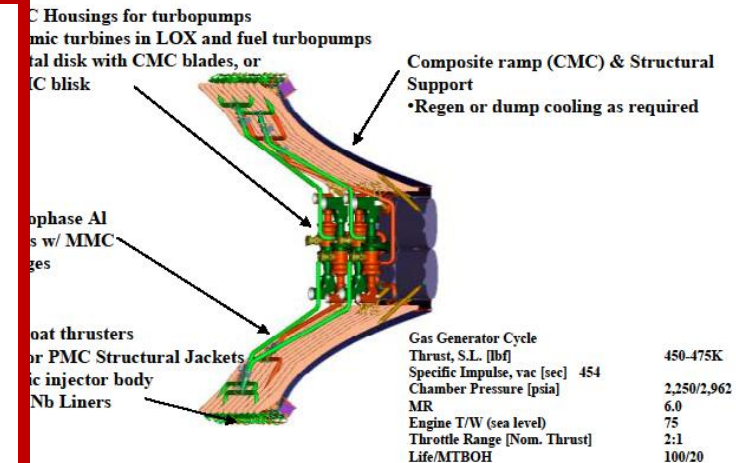
- Nonautoclave curing (TRL=3)
- Manufacturing process scalability (TRL=4)
- Nondestructive evaluation (TRL=4)
- Vehicle health monitoring (TRL=3)
- Integrated TPS / cryoinsulation (TRL=4)

Technology Readiness Level (TRL) Scale is 1 - 9

Materials Survey #6



Application of advanced materials to the Current Aerospike Propulsion System Concept



Materials Survey #34

Observation: Recent literature review suggests that the survey is still relevant; not much seems to have changed since the original survey.



Metallic and MMC materials for vehicle structure and habitats

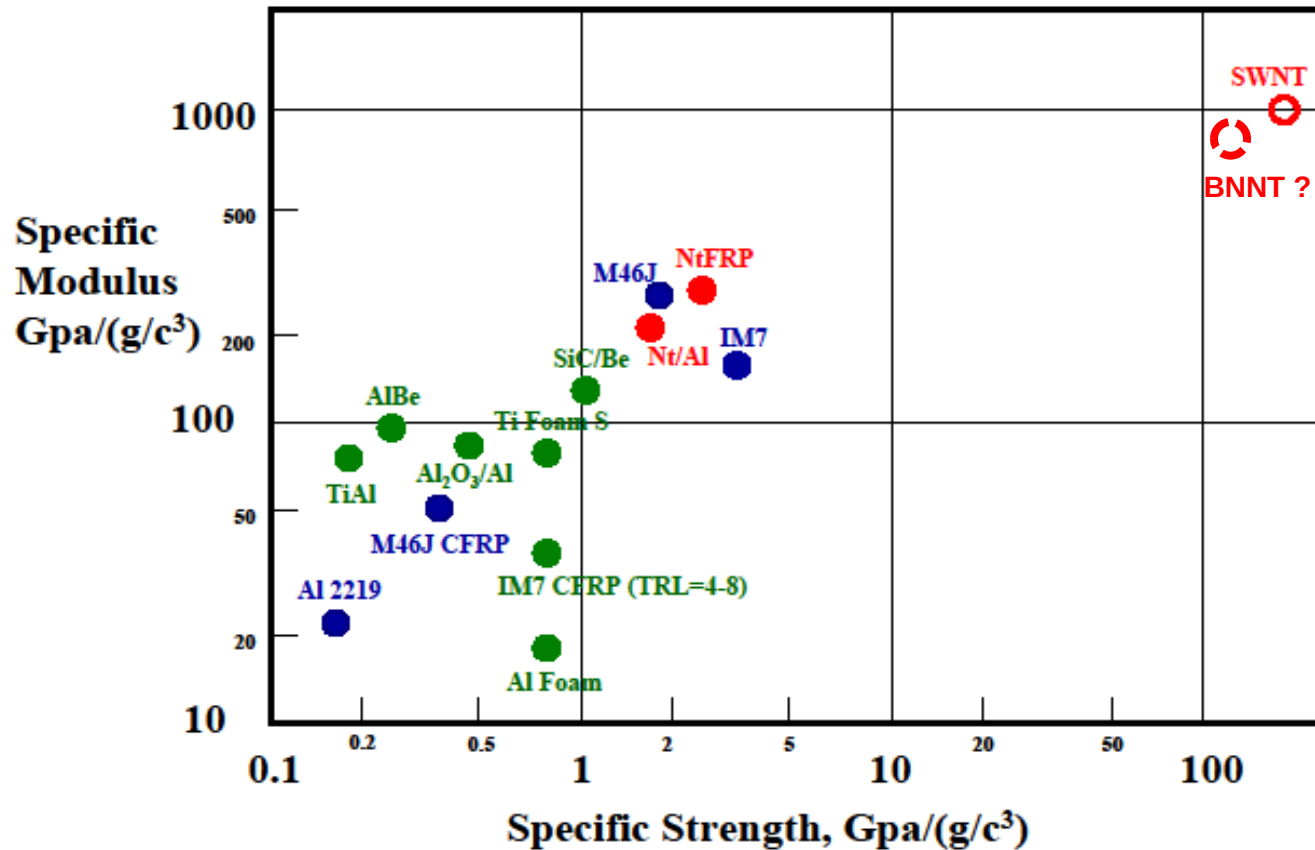
	<u>reference</u> Aluminum 2219-T87 ISS Crew Modules	<u>5-10 vts</u> TiAl Alloy (measured)	<u>5-10 vts</u> Al ₂ O ₃ / Al Composite (measured)	<u>5-10 vts</u> Aluminum Foam (theoretical)	<u>5-10 vts</u> Al-Be Alloy (measured)	<u>5-10 vts</u> Ti Foam Sandwich (measured)	<u>5-10 vts</u> SiC / Be Composite (estimated)	<u>10-20 vts</u> NT / Al Composite (theoretical)
Tensile Strength	0.46 Gpa	0.70 Gpa	1.65 Gpa	1.0 Gpa	0.5 Gpa	0.75 Gpa	2.1 Gpa	3.3 Gpa
Tensile Modulus	73 Gpa	280 Gpa	241 Gpa	20 Gpa	210 Gpa	90 Gpa	280 Gpa	300 Gpa
Elongation	10 %	1.7 %	0.8 %	20 %	5 %	5 %	3 %	6%
Density	2.83 gm/cc	3.8 g/cc	3.4 g/cc	1.3 g/cc	2.1 g/cc	1.1 g/cc	2.2 g/cc	2.0 g/cc
Specific Strength	0.16	0.18	0.49 (3x Al)	0.8 (5x Al)	0.25 (1.5x Al)	0.7 (4x Al)	1.0 (6x Al)	1.65 (10x Al)
Specific Modulus	26	74 (3x al)	71 (3x Al)	15	100 (4x Al)	80 (3x Al)	130 (5x Al)	150 (6x Al)
Thermal Cond'ty	121 W/mK	18 W/mK	94 W/mK	50 W/mK	200 W/mK	5 W/mK	n/a W/mK	120 W/mK
Use Temp.	150 C	800	375	150	500	600	750	400
Manufacturability	TRL = 9	TRL = 6	TRL = 5	TRL = 4	TRL = 3	TRL = 4	TRL = 3	TRL = 1

Materials Survey #8



Properties of Materials for Vehicles and Habitats

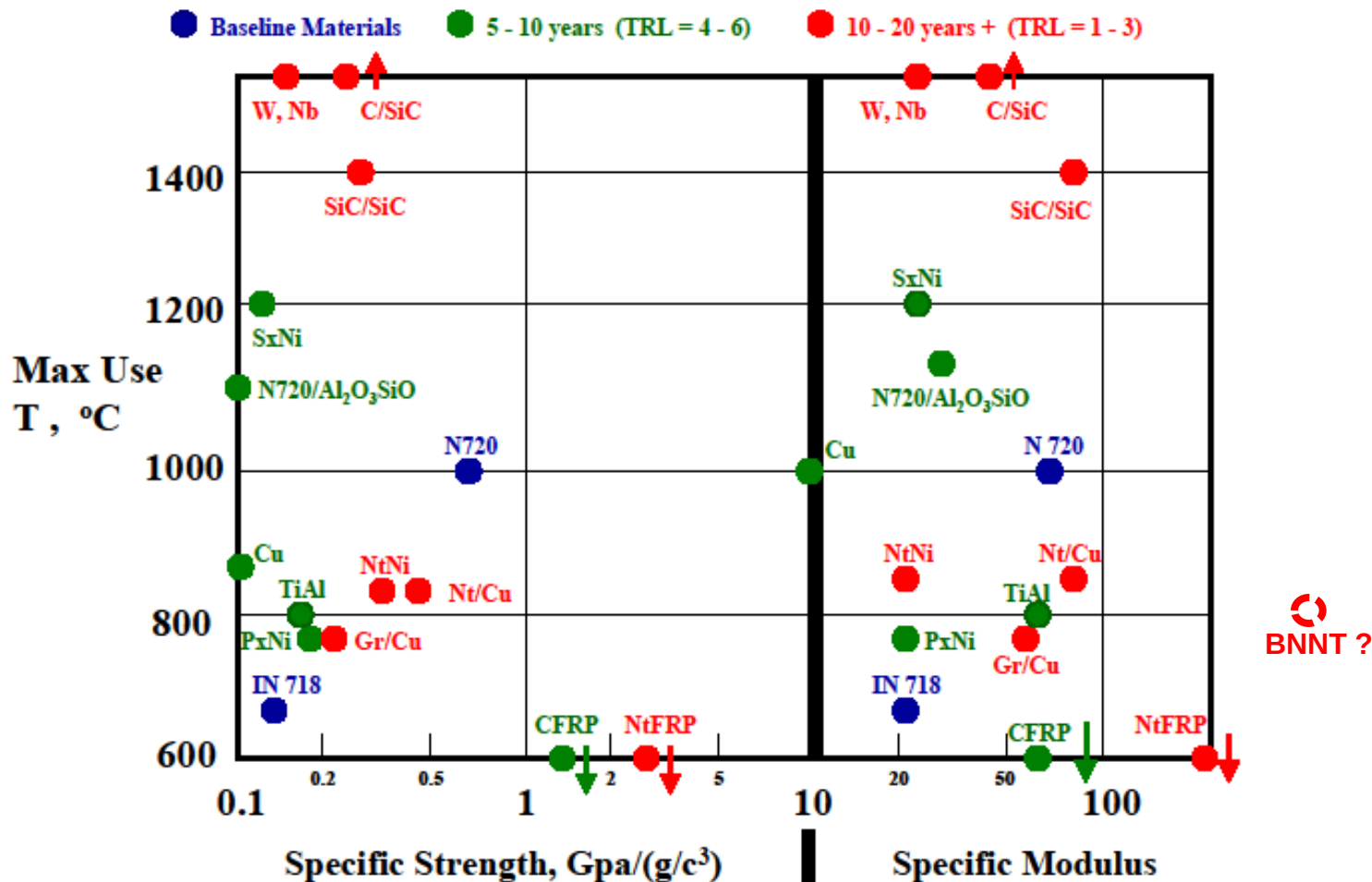
● Baseline Materials ● 5 - 10 years (TRL = 4 - 6) ● 10 - 20 years + (TRL = 1 - 3)



Materials Survey #7



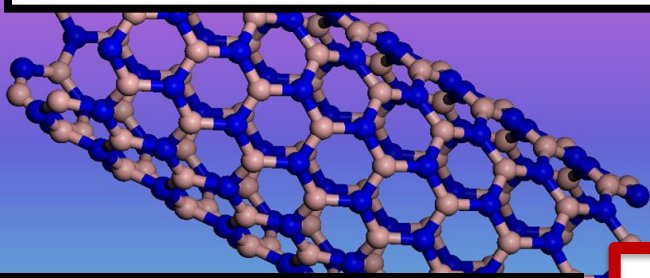
Properties of Materials for Propulsion Components



Boron Nitride Nanotubes (BNNT)

Boron Nitride Nanotube (BNNT)

Blue=boron, Grey=nitrogen



High Aspect Ratio BNNTs
invented by
NASA LaRC, DOE JLab, & NIA Team

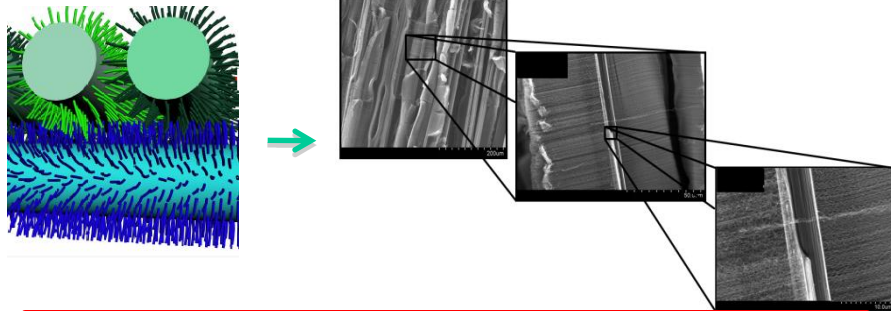
BNNT properties:

- Strength and stiffness: ~ 95% of CNT
- Service temperature: Double CNT (~ 800C+)
- Bond interface better than CNT
- Piezoelectric Constant: higher than polymers
- Electrical transport: 100% Semiconducting
- Thermal Conduction: High, ~ 600 W/mK
- Radiation shielding: excellent neutron attenuator

Smith, Jordan, Park, Kim, Lillehei, Crooks, Harrison, Very long single- and few-walled boron nitride nanotubes via the pressurized vapor/condenser method, 2009 *Nanotechnology* 20 505604

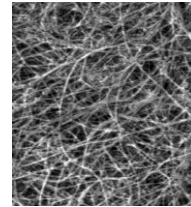
Structural CNT Nanomaterials: State-of-the-Art

CNT Forest on Carbon Fiber

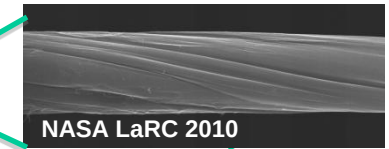
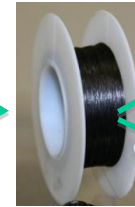


Wardle, B. L., "Literally Big Nano: Nano-Engineered Composites for Aerospace Applications," NASA Johnson Space Center, Nov. 2009.

mm Long CNTs



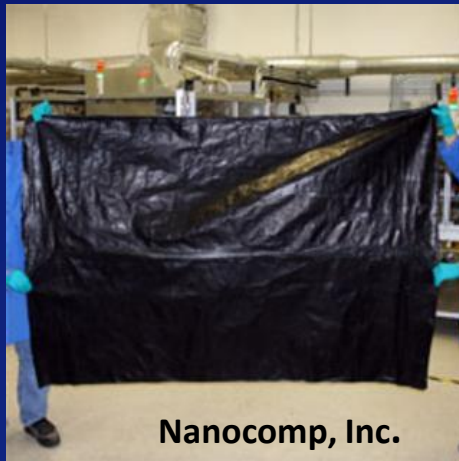
½ km Conductive CNT Yarn Spools



Lightweight Cables

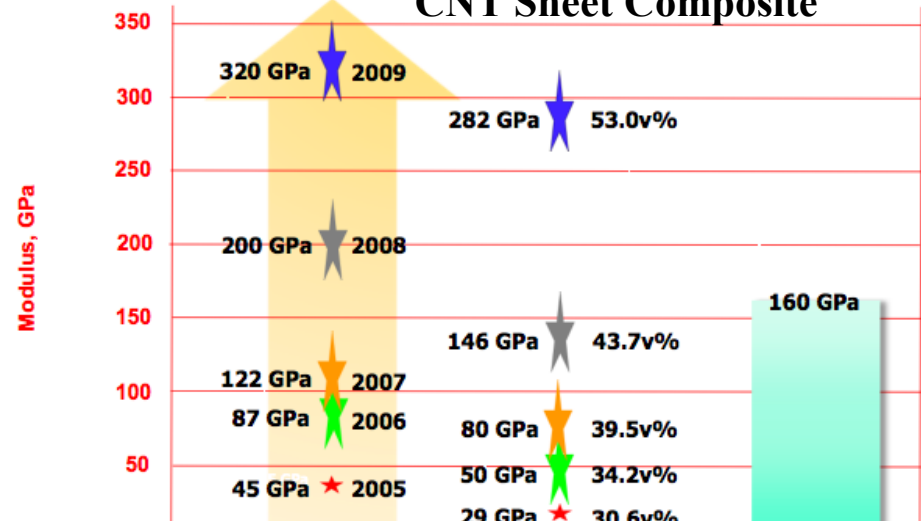
Nanocomp, Inc.

CNT Sheet



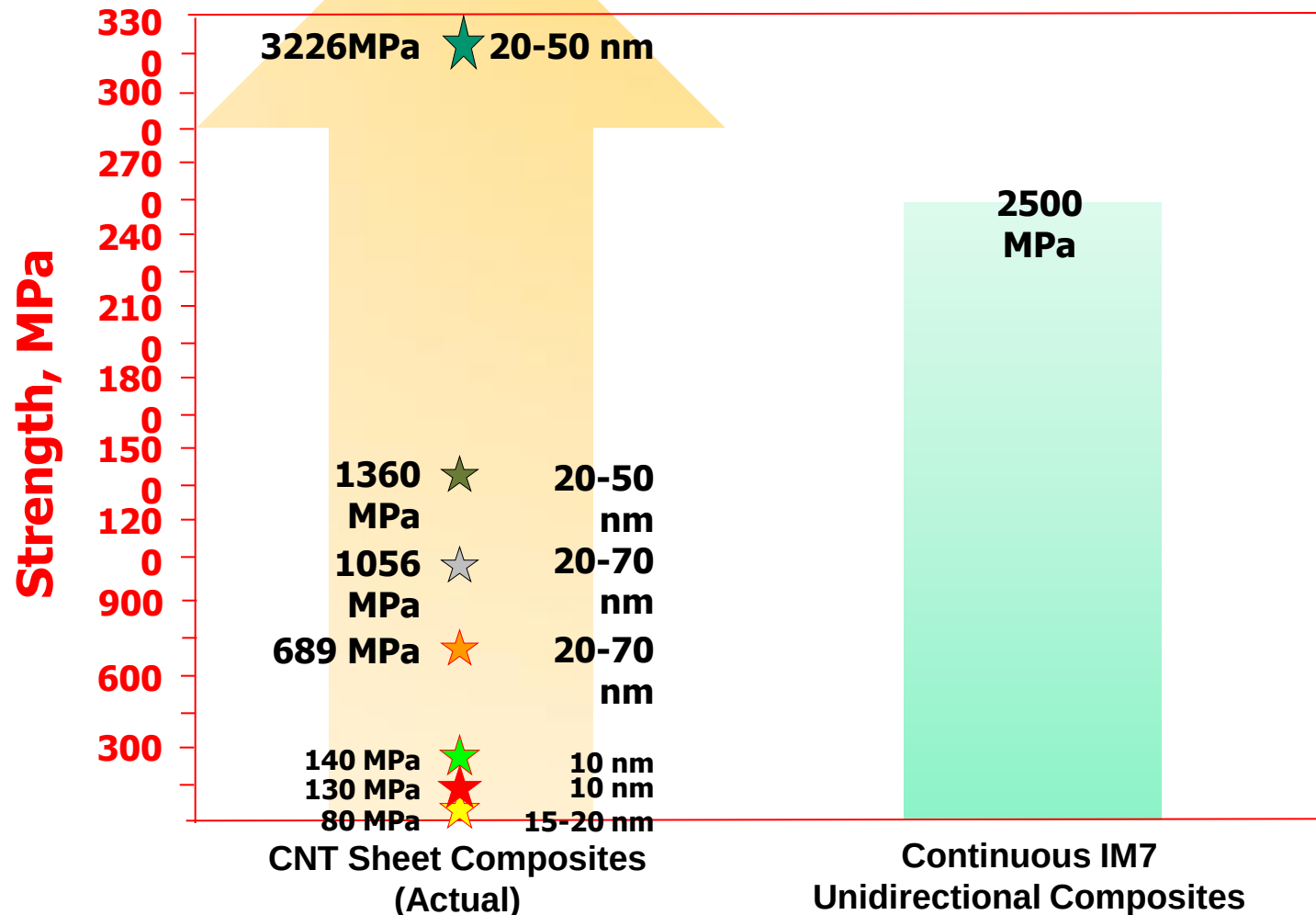
Nanocomp, Inc.

CNT Sheet Composite



Cheng, Wang, Zhang, and Liang, "Functionalized Carbon Nanotube Sheet/Bismaleimide Nanocomposites: Mechanical and Electrical Perf. Beyond Carbon-Fiber Composites," *Small*, 6(6), 763-763 (2010).

Strength: CNT Sheet Composite vs IM7 Composite



Cheng, Wang, Zhang, and Liang, "Functionalized Carbon Nanotube Sheet/Bismaleimide Nanocomposites: Mechanical and Electrical Performance Beyond Carbon-Fiber Composites," *Small*, 6(6), 763-763 (2010).

**It appears my 2002
strength/modulus predictions
(NTFRP Q/I Composite) have
been met.**

Is this a breakthrough?

Are we there yet?

Is this a breakthrough?

Yes!!

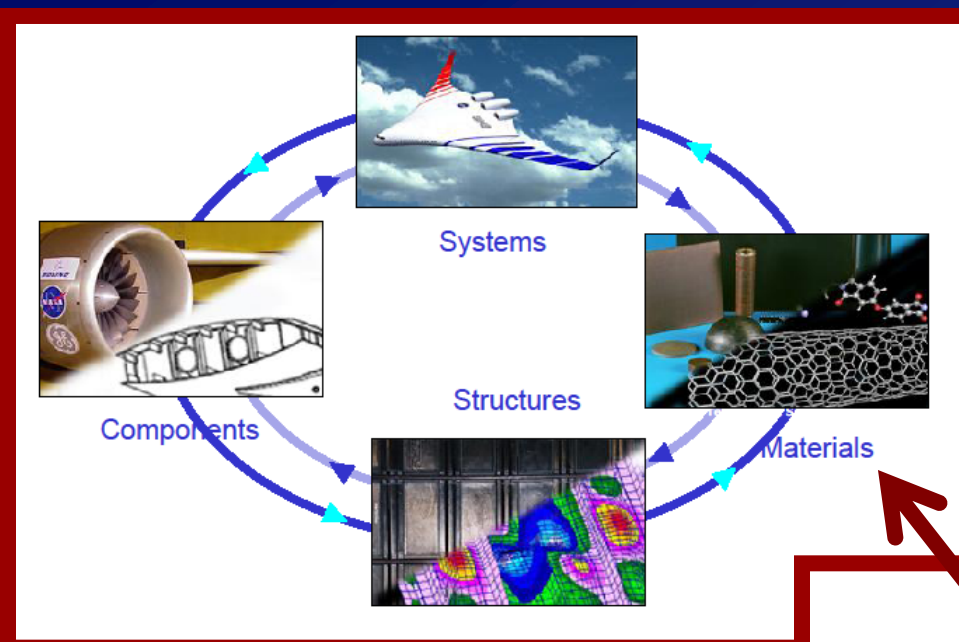
Are we there yet?

No!!

How can we get there?

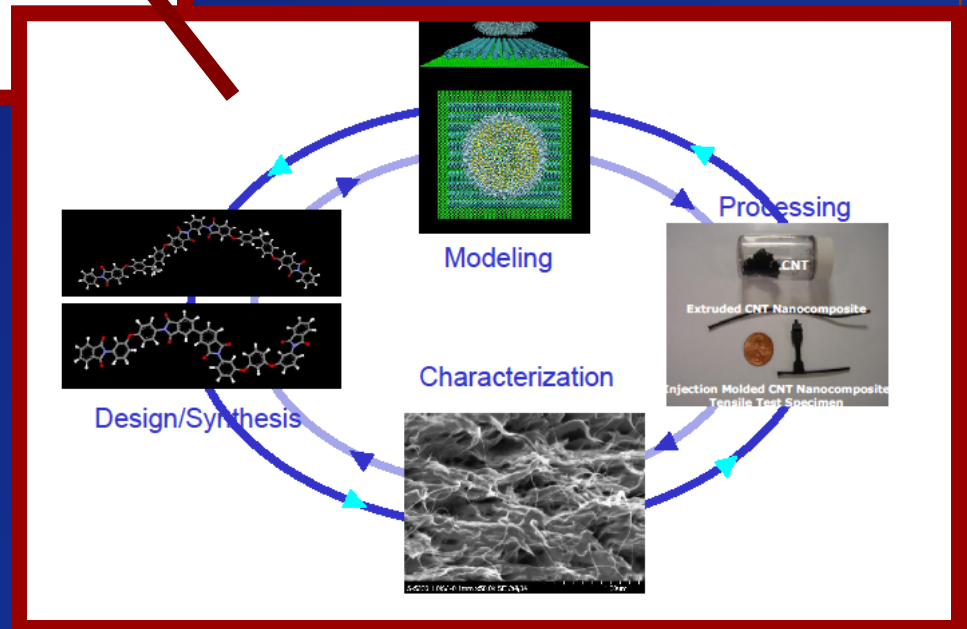
Some of the ways forward —→

Materials development cycle must become integral to product development cycle and synced to the accelerating pace of innovation

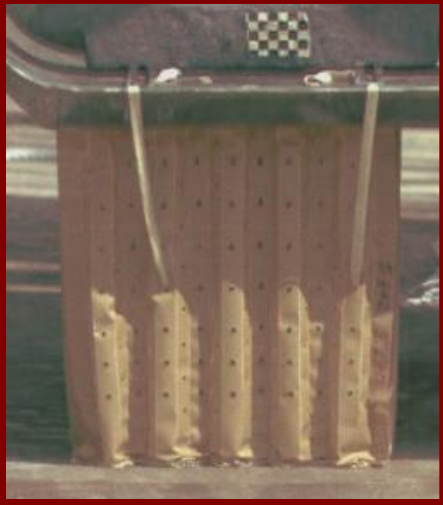


Requires a system level, multidisciplinary approach.

Are computational methods the ultimate key to success?



Novel System Level Materials / Structures Innovations

- **Deployable Honeycomb for Crash Energy Management**
 - Flexible hinge allows honeycomb to be deployed from a packed position to a rigid honeycomb
- 
- 
- 
- MD-500 Helicopter Drop Test
 - Dynamic loads on pilot reduced by 70%
 - System Deployment < 200 ms

Kellas S. and Jackson K. E., "Deployable System for Crash-Load Attenuation," *Journal of the American Helicopter Society*, Vol. 55, No. 4, October 2010.

Is this an enabling safety concept for future UAV/PAV?

Computational Materials (Modeling and Simulation)

(metals hierarchy)

Representation of Physical Mechanisms

Structural Mechanics

Continuum Mechanics

Microstructure Mechanics

Rheology

Crystal Plasticity

Gradient Plasticity

Dislocation Dynamics

Molecular Dynamics

Quantum Mechanics

Increasing fidelity, robustness,
computational expense

10^{-12}

Electrons

10^{-9}

Atoms
Dislocations

10^{-6}

Molecules
Fibers

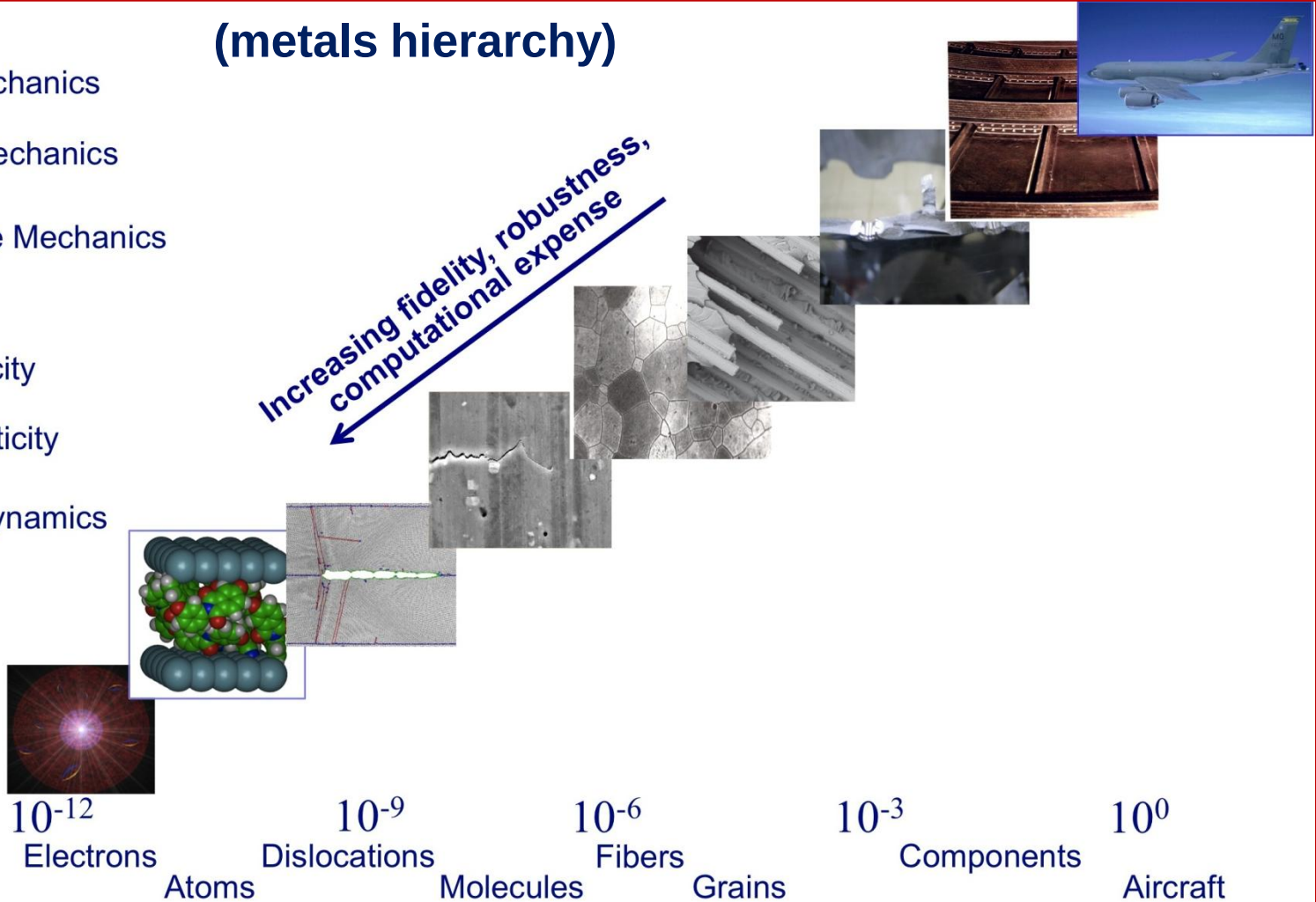
10^{-3}

Grains
Components

10^0

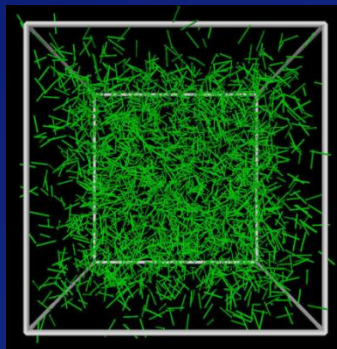
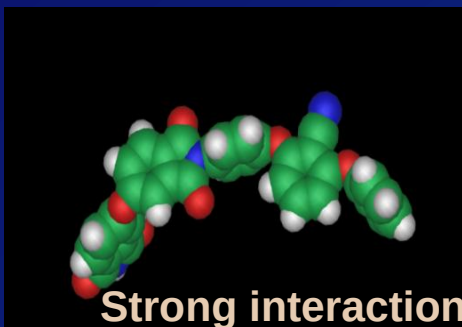
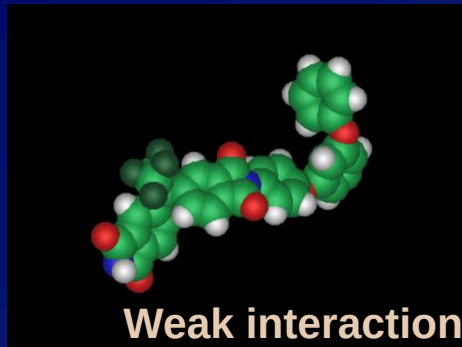
Aircraft

Characteristic Structure / Dimension (m)

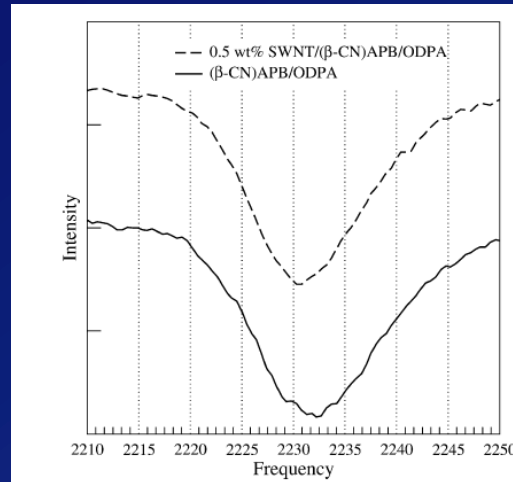


MD simulations guide invention of Nano-Composites

MD Simulations

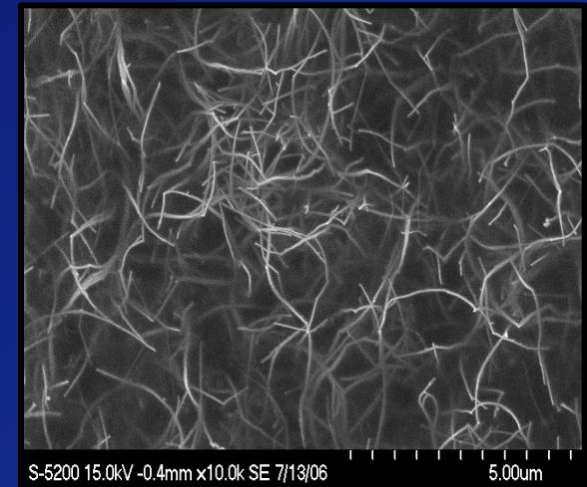


Experiment



- Infrared spectrum shows effect of charge transfer

Validation

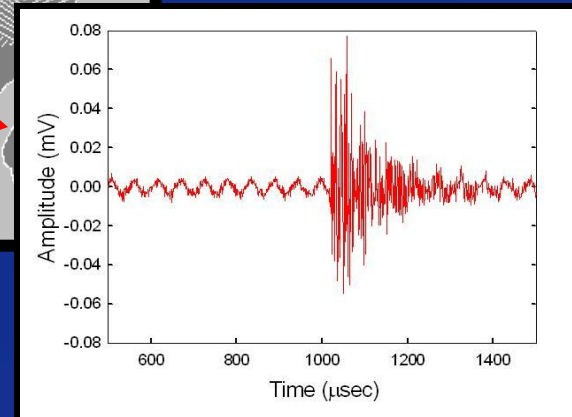
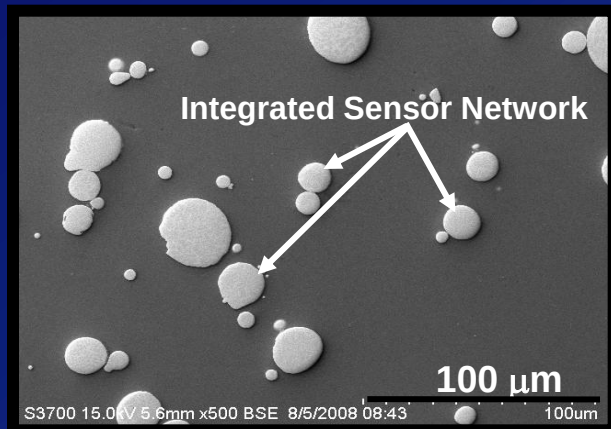
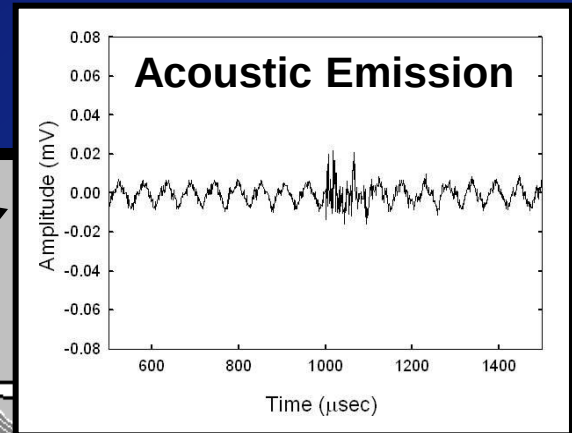
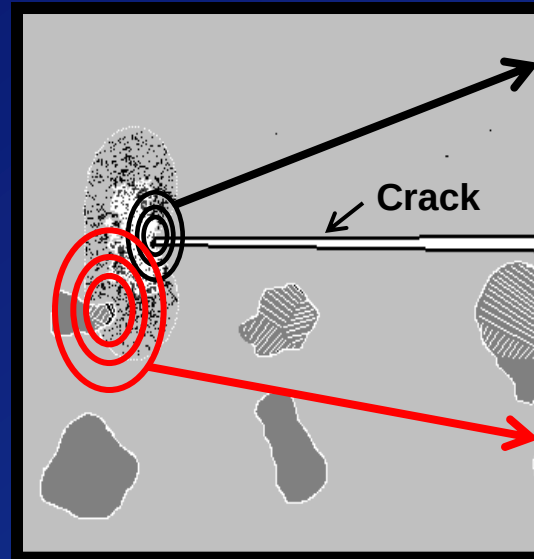
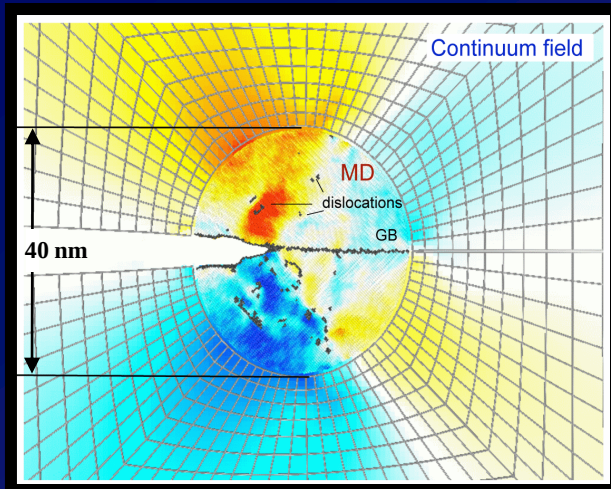


- New Poly-Transparent Nanotube Composite
- New microscope technique

Ounaies, Park, Wise, Siochi, Harrison, "Electrical Properties of Single Wall Carbon Nanotube Reinforced Polyimide Composites" *Comp Sc and Tech* 2003, 63, 1637.

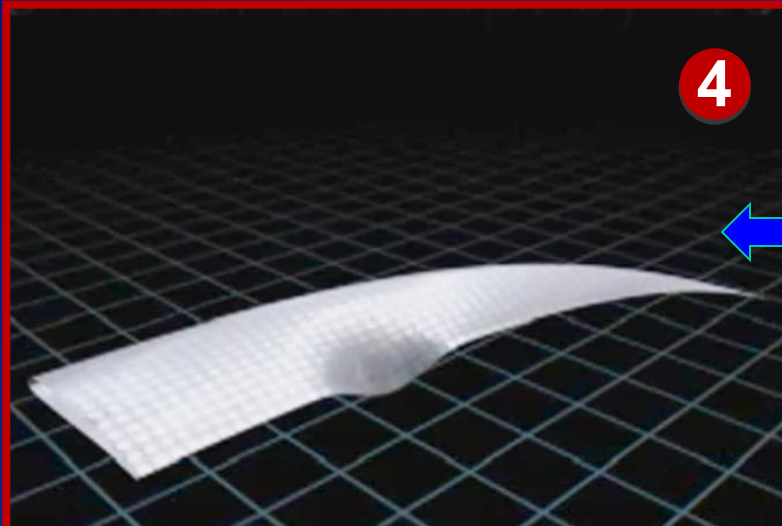
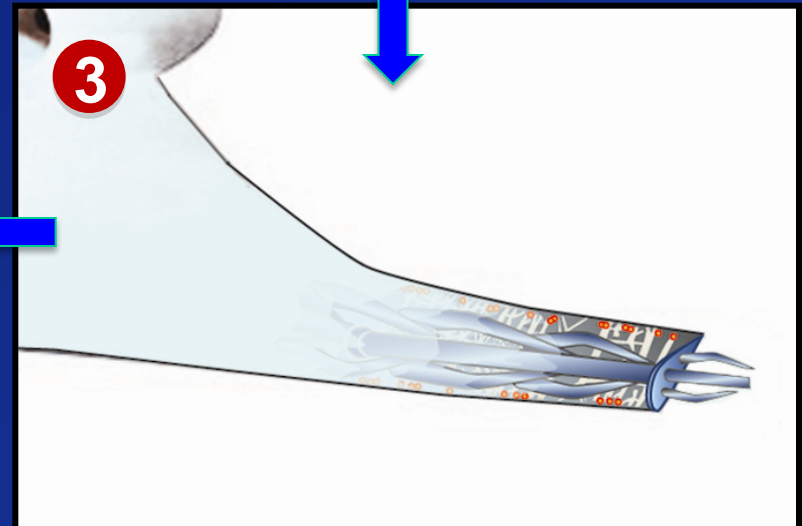
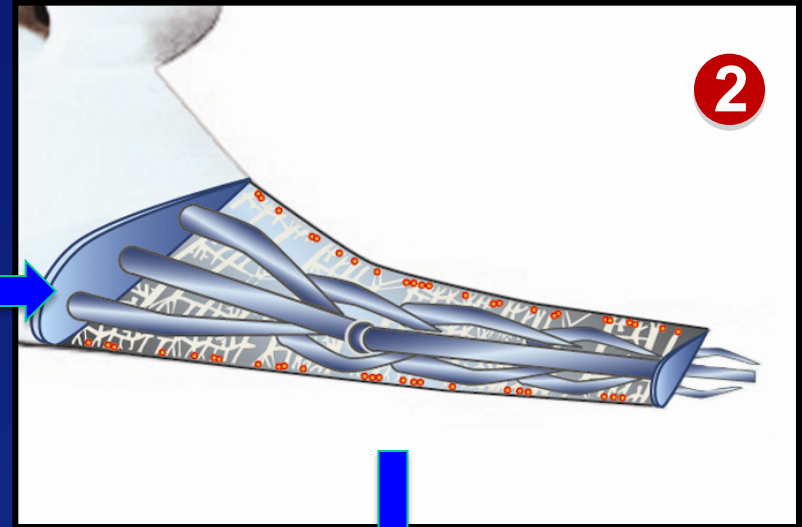
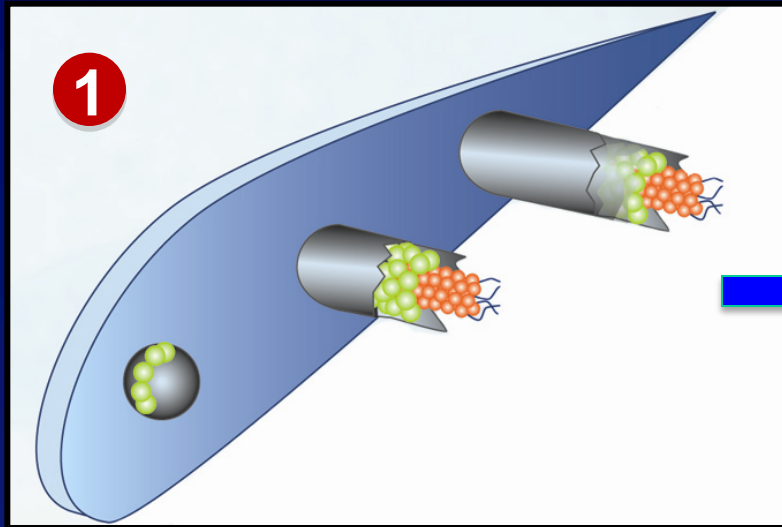
Lillehei, Kim, Gibbons, Park, "A Quantitative Assessment of Carbon Nanotube Dispersion in Polymer Matrices" *Nanotechnology* 2009, 20, 325708.

MD Simulations Guides Inventions of Sensory Metallic and “Self-Healing” Metallic

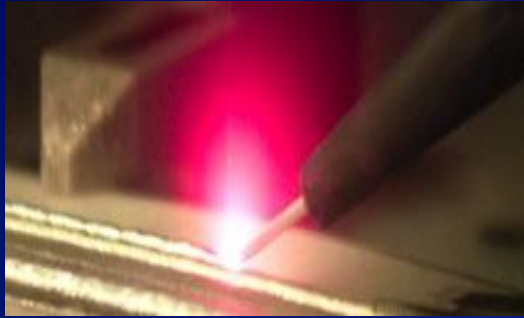


Smith, Wallace, Piascik and Glaessgen, "Self-Sensing Metallic Materials," patent pending, 2010.

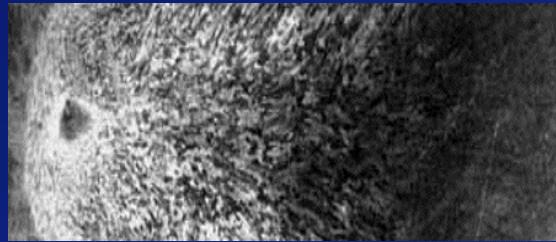
Molecular Manufacturing – Extreme Multifunctionality (as Inspired / Enabled by Biological Systems)



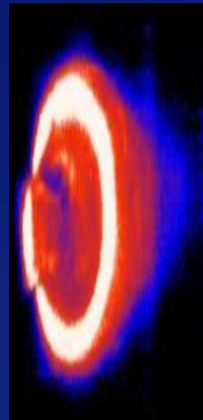
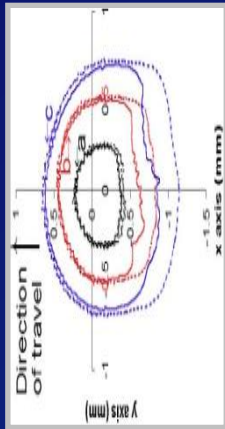
Electron Beam Freeform Fabrication (EBF³) may Revolutionize Aircraft Structures



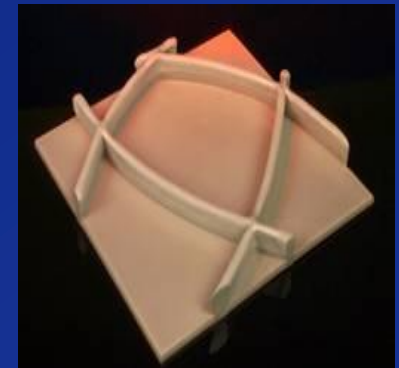
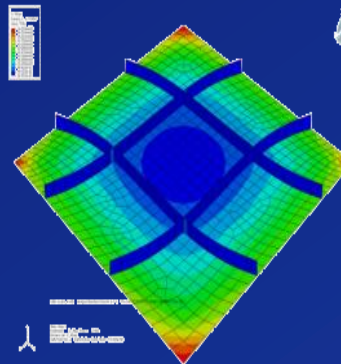
- EBF³ builds structural components directly from CAD data using electron beam and wire feed in vacuum (“green manufacturing”)



- Microstructural control



Decreasing Cu →



- Minimizes residual stresses

- Highly tailored structures concepts

Taminger, NASA Fundamental Aeronautics
2008 Annual Review, Atlanta, GA 7-9 Oct 2008.

Observations from Materials Survey

- 1. Structural materials for airframe and subsystems:** up to 2X reduction in structural weight can be achieved by carbon fiber reinforced polymers, metal matrix composites, and intermetallics; CNT composites offer as much as 10X weight reduction.
[CNT and BNNT and their composites/derivatives may change the game!]
- 2. Structural materials for propulsion components:** ceramics may offer a factor of 2 gain in use temperature but may never achieve attractive structural design allowables; advanced metallic alloys and intermetallics may offer a factor of 2 reduction in weight but only modest temperature improvements.
[BNNT exhibits thermal stability at 800C+; SiCNT under development]
- 3. Applications of new materials must be evaluated in a systems context.** Advanced structural design methods and highly efficient structural concepts will be required to fully exploit the potential benefits of biomimetic, nanostructured, multifunctional materials in revolutionary aerospace vehicles.

Realizing the potential of Materials to Unleash Aviation

Systems Studies Illustrate Aircraft GTOW Reduction Potential

Multiplier (Growth) Factors to assess impact of structural weight reduction on total aircraft take-off weight:

- Commercial transports are typically 1:2.5 - 3.5
- Fighters are typically 1:4.5 - 5.5,
- VSTOL aircraft also being about 1:4 - 5.
- PAVs can vary from 1:2.0 for CTOL to 1:5.0 VTOL.
- Launch vehicle 1:40-100
- **Reference: Ground vehicles are typically 1.1 to 1.2, being quite insensitive to weight growth.**

Impact on vehicle designs come from evaluating trade-offs and design options:

- increasing payload or systems weight,
- enabling an alternate propulsion system
- enabling new configurations
- optimizing affordability, maintainability, durability, operability/availability

Structural Weight Sensitivity: Illustrative Example

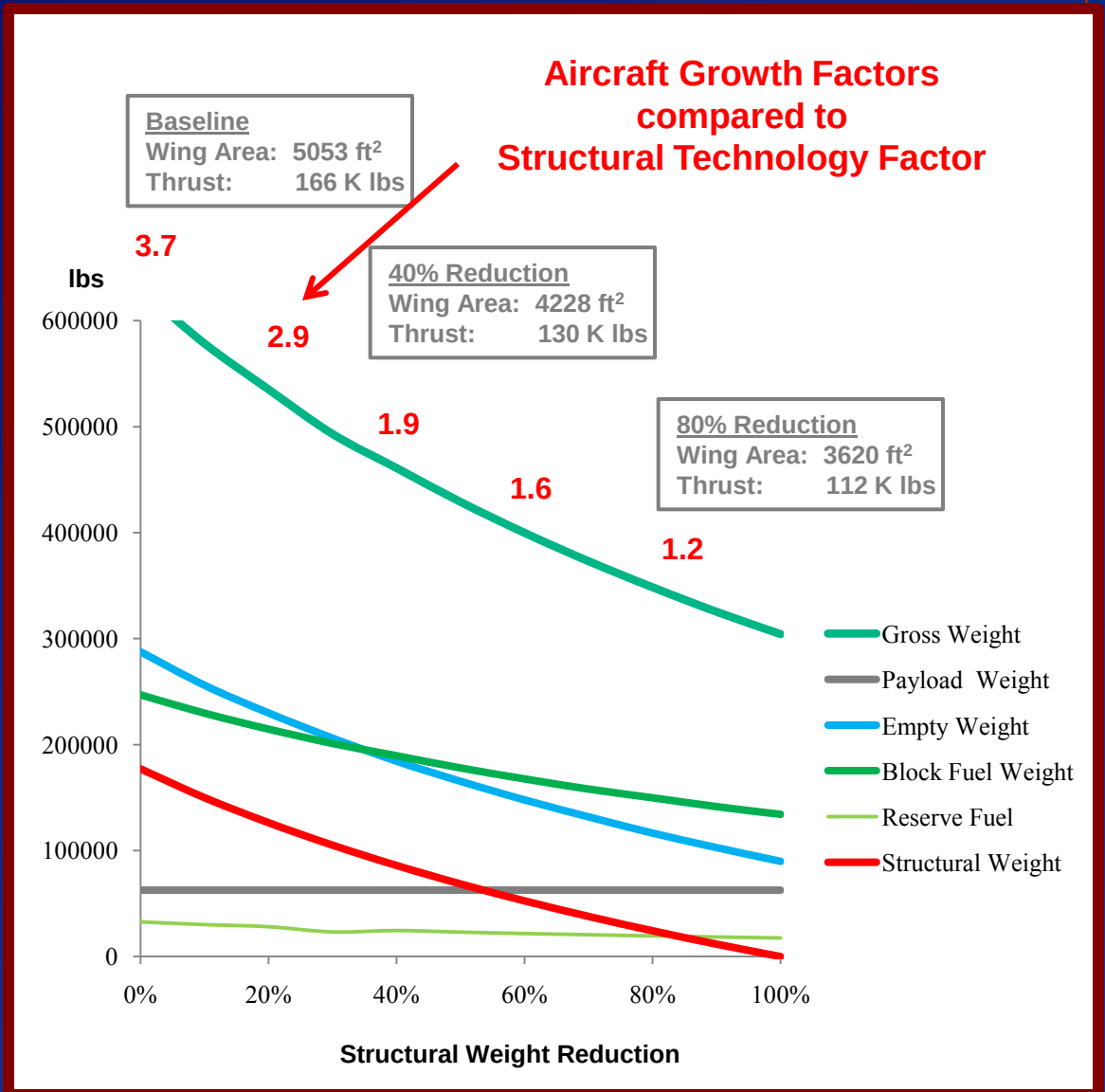
- **B 777 'like' aircraft**

- Mission
 - Payload: 300 pax
 - Range: 7500 nm
 - Cruise Mach: .85
- Active constraints
 - Takeoff field length,
 - 2nd segment climb gradient
 - Fuel volume

- **Observations**

- Diminishing returns for structural impact (other sensitivities become higher)
- GF is a measure of technology need and vehicle sensitivity

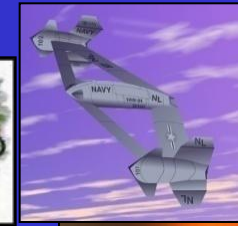
Computed by Mark Guynn and Mark Moore, SACD, LaRC, NASA, Aug, 2010



**Its not just about
weight reduction!**

Advanced Technology Development

Towards Advanced Aerospace Vehicles



Visionary Vehicles
Revolutionary Missions

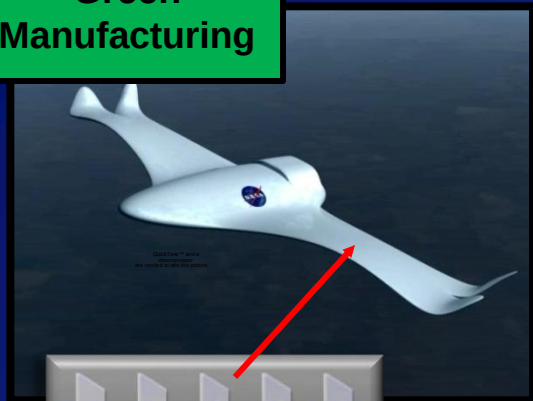
- Ultra Safe
- Whisper Quiet
- Ultra Low Emissions
- Ultra Low Fuel Burn

Time

21st Century Aerospace Vehicle Materials Technologies

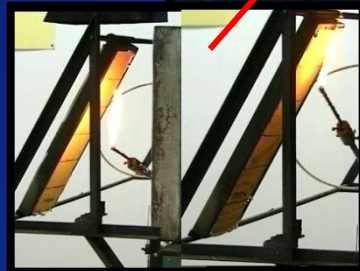
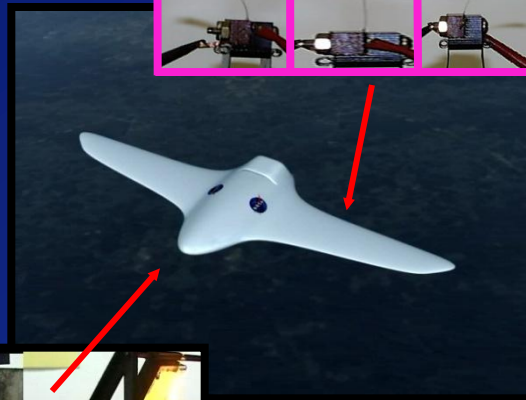
- Large deformation enabled by ultra-high elastic strain materials
- Ultra-durable, thousands-to-millions of actuations
- Ultra-low specific modulus and strength, and fracture resistant
- Highly efficient structural concepts (smart, multifunctional materials)

**Green
Manufacturing**



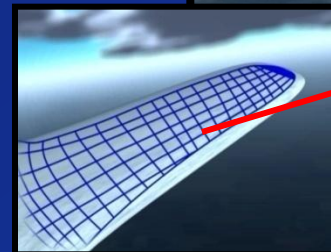
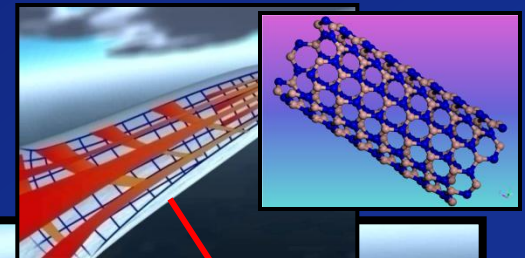
**Self-Healing
Materials**

Electroactive Materials

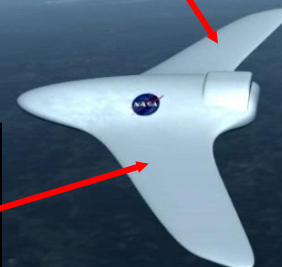


**Lightweight Flame
Retardant Materials**

**Nano-Structured
Supermaterials**

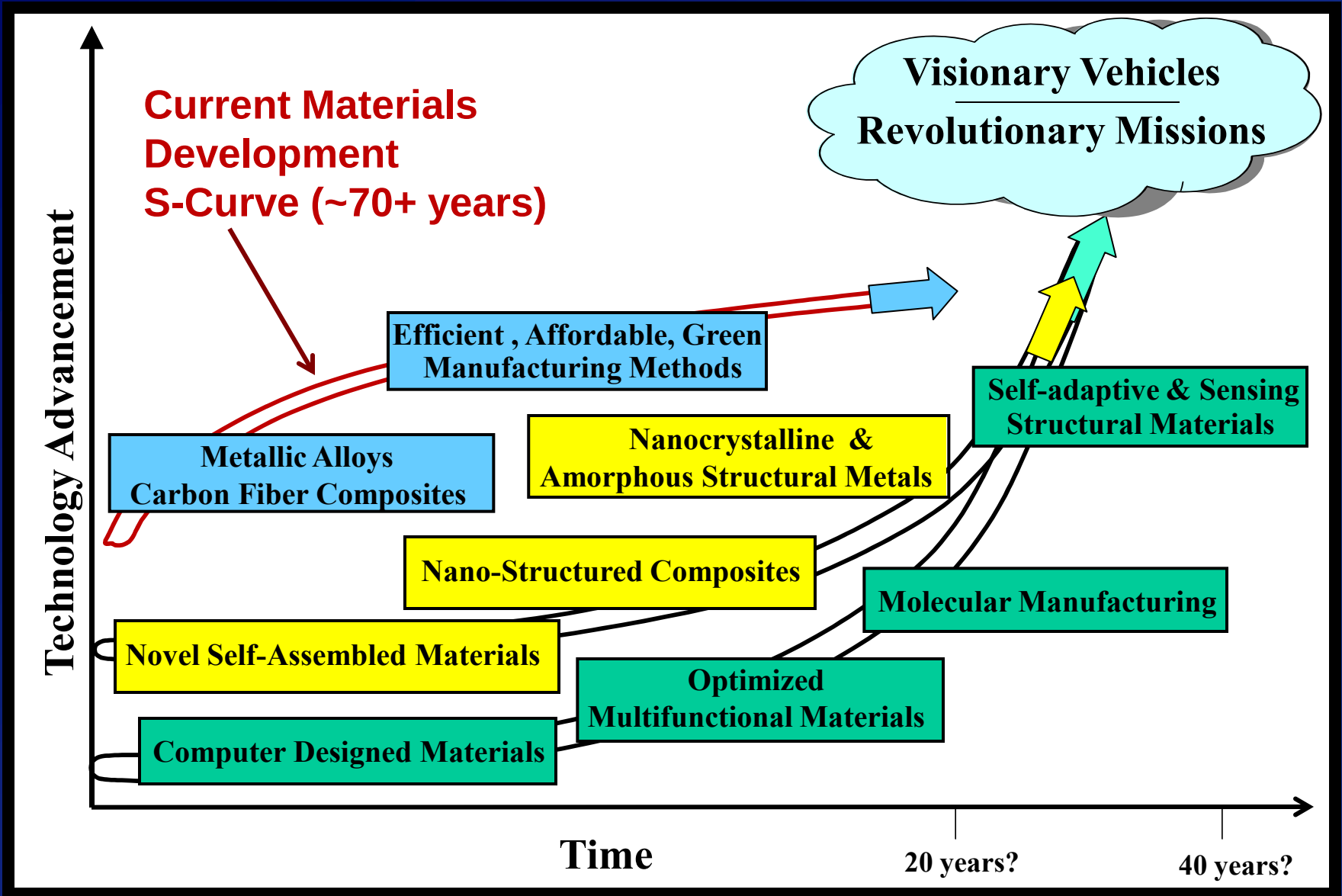


Embedded Nanosensors



**Fully
Recyclable**

Materials Development Roadmap: Must Pursue Multiple Paths



Requirements Enabled by Revolutionary Materials

Higher strength and stiffness composites with equal or better toughness to current systems

Self-surfacing/priming composite surfaces for painting/priming

Resin systems designed to enable easier carbon recycling/reclamation

3-D reinforcements that improve transverse toughness

Advanced material hybrids for critical design details

Durable low-cost, high-temperature composite tooling

Resin systems that cure faster and at lower temperatures

Elevated-temperature, toughened composites

Fast structural repair systems

UV-resistant resin systems

Shape-morphing composites

Reliable health monitoring of composites

Non-traditional lean composite processing

Thermal transport composite systems

Electrically conductive composites capable of reducing the need for electromagnetic effects treatments

Charlie's Guesses of the development timeline, color coded from the notional development roadmaps

Charlie's Grand Challenges for the Materials Community

1. **Perfect** nanostructured materials formation/processing to **achieve** near theoretical properties
[carbon (<400C), boron-nitride (800+C), and silicon-carbide (1000+C) nanotubes; graphene sheets; and nanostructured metallics, both crystalline and amorphous]
2. **Master** molecular assembly and manufacturing; and **eliminate/control** microstructural defects
3. **Complete** the physics coupling of the length scales from quantum mechanics to continuum mechanics; and **master** the time domain computational methods to model the time-dependent physical processes that govern materials formation
4. **Replace** the “edisonian method” of new materials invention with computationally-guided invention
5. **Develop/achieve** net-shape forming manufacturing methods; and **extend** rapid prototyping to include new product design/development
6. **Replace** macroscale coupon testing with physics-based computational methods to predict electrical/mechanical/physical properties and design allowables (may require stochastic methods to predict effects of defects on properties)
7. **Implement** multidisciplinary research/design/development approaches to **achieve** multifunctionality (won't get there by materials science alone)

What can we achieve if we are successful?

- New classes of materials with nearly theoretical properties that are superior to all conventional engineered materials in use today
[enabling to virtually every future NASA mission in civil aviation and space exploration]
- Dramatic reductions in the time from materials invention to new products
[materials design/development consistent with the accelerating pace of technology and product innovation]

The last word!

*We do live in a
material world!!*