Outline

- Benefits of Nanotechnology to NASA Missions
- Nanotechnology Space Technology Roadmap and Grand Challenges
- Examples of Current Research on Lightweight Nanostructured Materials
- NASA and the NNI
- Potential Funding Opportunities
- Summary
Critical Concerns for Aerospace Systems

Weight
- Reduced fuel consumption & emissions
- Reduced launch costs
- Enabler for many vehicles

Functionality/Performance
- Reduced fuel or power consumption
- Multifunctionality – reduced weight

Durability
- Safety and reliability
- Maintenance down-time and costs
- Extreme environments
Nanotechnology enables discrete control of desired materials properties:

- **Mechanical**
  - Dictated by particle size (Griffith criteria), morphology and strength of interfaces (chemistry and roughness)
  - High aspect ratios and surface areas radically changes nanocomposite properties relative to host material
  - Molecularly perfect, highly ordered, defect free structures, e.g. carbon nanotubes, leads to maximized properties (not just mechanical)

- **Thermal**
  - Emissivity influenced by particle size and enhanced surface area/roughness
  - Thermal conductivity controlled by particle size (phonon coupling and quantum effects) and nanoscale voids

- **Electrical**
  - Nanostructure and defects influence conductivity and bandgap energy (conductivity, current density, thermoelectric effects)
  - High aspect ratios enhance field emission and percolation threshold
  - Nanoscale dimensions lead to inherent radiation resistance

- **Optical**
  - Transparency and color dominated by size effects
  - Photonic bandgap controlled by size ($\lambda/10$) and nanostructure
Nanotechnology Has Made it into Space

CNT Nanocomposites for Charge Dissipation

Silica Aerogels

Polyimide Aerogels

NIA Nanotechnology Workshop 2-21-14
• Drafted 20+ year technology roadmap for development of nanotechnology (TRL 6) and its insertion into NASA missions
  – Includes both mission “pull” and technology "push”
  – Covers four theme areas
    • Engineered Materials and Structures
    • Energy Generation, Storage and Distribution
    • Propulsion
    • Sensors, Electronics and Devices
  – Used to guide future funding decisions
• Identified 18 Key Capabilities enabled by nanotechnology that could impact current and future NASA missions
• Identified 5 Grand Challenges with potential for broad Agency impact
• Reviewed by NRC – report published in 2012
• Roadmaps are being updated in FY14
Nanotechnology Grand Challenges

Nanopropellants

Graphene Electronics

Ultralightweight Materials

- High priority items identified by the Nanotechnology Roadmap Team for NASA investment and/or collaboration with other agencies
- Working these technologies as budget and overall NASA priorities allow

Structurally Integrated Energy Generation and Storage

Hierarchical Integration

NIA Nanotechnology Workshop 2-21-14
**Grand Challenge: Ultralightweight Structural Nanomaterials**

**Objective:** Reduce density of state-of-the-art structural composites by 50% and equivalent or better properties.

**Approach:** Use nanomaterials with combination of high performance characteristics
- Carbon nanostructure based high strength reinforcements
- Durable nanoporous materials (polymers, fibers, metals or hybrids) less than half the density of monolithics
- Addition of nanoscale fillers to improve strength and toughness

**State-of-the-Art:**
- Aluminum and Titanium alloys, carbon fiber reinforced polymeric composites, ceramic matrix composites, metal matrix composites

**NASA Benefits/Applications:**
- Potential vehicle dry mass savings of up to 30%
- Enhanced damage tolerance for improved safety
- Enable design concepts with tailored performance
- Enabling technology for environmentally friendly vehicles
- Enabling technology for extreme environment operations

**Technical Challenges to TRL 6:**
- Development of reliable, reproducible, and controlled nanomaterials synthesis processes on a large scale
- Development of tailored geometries at nano and macro scale for structural components
- Fabrication methods that can be practically implemented at bulk or macro scale
- Early assessment of systems payoffs in cost, operational safety and reliability.

**Time to Mature to TRL 6:** 5-10 years

**Potential for Partnering with Other Agencies:**
- Partnerships under NNI Nanomanufacturing SI
Remarkable properties of CNTs has not been realized in composites

- Bulk of the studies have focused on dispersion of CNTs in a matrix or composite
  - Improvements in mechanical, thermal and/or electrical properties reported
  - Amount of nanotubes that can be used and resulting properties limited to a few wt %
    - CNTs agglomerate due to van der Waals forces – inhomogeneous materials, defects
    - Viscosity of polymer increases with increasing CNT content making processing difficult

- Better approach is to incorporate the CNT into the reinforcement
  - Achieve higher loading levels, control placement within the composite
  - “Drop-in” replacement for carbon or other fiber reinforcements
Nanotechnology Enabled Ultralightweight Structures

• **What are we trying to do?**
  • Develop carbon nanotube (CNT) reinforced composites with 1.5 to 2 times the strength of conventional carbon fiber composites, such as those used in the Boeing 787

• **Why is it important?**
  • Use of these ultra-lightweight materials in place of conventional composites in aerospace vehicles will enable a 30% reduction in vehicle weight
  • Ultra lightweight materials were identified as one of 16 top technologies by the NRC in their reviews of the Space Technology Roadmaps

• **How are we doing this?**
  • Improve the strength of available CNT sheets, tapes and yarns through a combination of processing improvements and post-processing treatments
  • Measure the improvements in mechanical properties by testing CNT reinforcements and composites
  • Develop/identify manufacturing approaches for CNT reinforced composites
  • Validate these materials by design, fabrication, ground and flight testing of a CNT reinforced composite overwrap pressure vessel
Nitrene Cross-linking

**Polymers Bearing Nitrene Precursors for Nanotube Crosslinking**

Model Reaction using Benzyl Azide

$$\text{BzAz}$$

[2+1] cycloaddition of nitrene to nanotube walls

Poly(styrene-co-vinylbenzyl azide) (PSVBAz)

Poly(styrene-co-styrenesulfonyl azide) (PSSfAz)

NIA Nanotechnology Workshop 2-21-14
Functionalized Enhances Effects of E-Beam Crosslinking of CNT Yarns

Specific Strength Comparison for 5279-7 Yarn

- As Received
- Amine
- Hydroxyl

Electron Beam Irradiation Time (min)
Specific Strength (N/tex)
SEM Images of Yarn Cross-Sections Indicates E-beam Induced Coalescence of CNTs

Used FIB to machine a trough into CNT yarns to image cross-section

Voids evident in unirradiated CNT yarns appear to collapse and CNTs coalesce with increasing irradiation time

NIA Nanotechnology Workshop
2-21-14
Functionalization Promotes Wetting of CNT Sheets

Specific tensile strength of laminates improved with functionalization

Optical photomicrographs of 2-ply CNT/epoxy composite processed without (top) and with (bottom) coupling agent
CNT/Aerogel Wires and Cables

**Description and Objectives**
- Assess the developing low conductivity CNT wires and yarns and polymer aerogel electrical insulation for low mass electrical power and data cables
  - Understand the effects of intercalation methods on CNT wires and yarns (Nanocomp, General Nano, Rice)
  - Develop fabrication methods for polymer aerogel wire and cable insulation
  - Assess electrical and thermal behavior of existing CNT data cables
- Complete screening of CNT wires/yarns and intercalation chemistries for improved electrical conductivity (7/30/14)
- Evaluate polyimide aerogels as CNT wire insulation materials (8/30/14)

**Approach**
- Assess the application of low conductivity CNT wires and yarns and polymer aerogel electrical insulation for low mass electrical power and data cables
  - Understand the effects of intercalation methods on CNT wires and yarns (Nanocomp, General Nano, Rice)
  - Develop fabrication methods for polymer aerogel wire and cable insulation
  - Assess electrical and thermal behavior of existing CNT data cables

**Cost, Schedule, and Status**
- Complete screening of CNT wires/yarns and intercalation chemistries for improved electrical conductivity (7/30/14)
- Evaluate polyimide aerogels as CNT wire insulation materials (8/30/14)
Halogen Intercalation Increases Yarn/Fiber Electrical Conductivity

No Change in Fiber Gross Structure

Minor Changes in Raman

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High Performance Polyimide Aerogels

High heat flux test results indicate potential for flexible thermal protection

Nanoporous structure

Good compressive properties and durability

Aerogel substrate enables antennas with 67% higher bandwidth, higher maximum gain than PTFE at 1/10th the weight
**BNNT Structural Materials**

**Description and Objectives**

**Objective:** Develop alternatives to CNT reinforcements for multifunctional composites

**Background:**
- Use of BNNT additives improves properties of polymers and ceramics – same limitations as observed with CNTs
- Scalable approach for BNNT demonstrated, fibers produced from spinning of BNNTs
- BNNT/ceramic fuzzy fibers, fabrics and 3-D preforms developed – demonstrated 3X improvement in strength of 3-D preform reinforced SiC composite

**Approach**
- Determine feasibility of currently available spun BNNT fibers and BNNT fuzzy fibers as polymer and ceramic reinforcements
  - Assess feasibility of scale-up of current synthesis methods
  - Determine effects of fiber incorporation on composite mechanical properties and fracture toughness

**Cost, Schedule, and Status**
- Fabricate multi-ply composite samples consisting of aligned BNNT composite mats and fibers; determine mechanical and thermal data (8/30/14)
- Fabricate 2”x4” BNNT “fuzzy” 3-D preform CMC laminate; determine mechanical and thermal properties
Demonstrated BNNT growth onto fiber substrates
- SiC
- Al₂O₃
- 3-D preforms

SiC CMC reinforced with BNNT decorated SiC preform had 3X higher strength at room temperature than conventional SiC preform reinforced CMC
Nanotechnology Derived Chem-Bio Sensors

**Description and Objectives**

**Objective:** Develop autonomous sensor platforms for the detection of chemical and biological species with high sensitivity and selectivity

**Background:**
- Autonomous sensor platforms have broad NASA applications in IVHM, astronaut health management, planetary exploration
- NASA CNT sensors were demonstrated for trace gas detection on ISS and toxic emissions with LAFD
- Vacuum nanoelectronics developed with potential for THz switching speeds

**Approach**
- Assess the feasibility of CNT and CNF based sensor platforms for use in astronaut health management and planetary exploration
  - CNF sensors for detection of biomarkers (troponin, myoglobin, cardiac reactive protein)
  - Ammonia and other impurities in closed loop life support (ECLSS) systems
  - Sensor embedded drills for planetary exploration
- Identify deficiencies for further R&D

**Cost, Schedule, and Status**
- Determine sensitivity of CNT smart-phone sensors for ammonia detection (7/30/2104)
- Fabricate CNF sensor array and demonstrate ability to detect biomarkers for cardiac disease (8/30/2014)
The National Nanotechnology Initiative (NNI)

- Established in 2001 under an Executive Order from President Bill Clinton
- NASA was a founding member
- Intent of the NNI is to provide a framework for member agencies to work together to:
  - Advance world-class nanotechnology research
  - Foster the transfer of technologies into products for commercial and public benefit
  - Develop and sustain educational resources, a skilled workforce and the supporting infrastructure and tools to advance nanotechnology
  - Support the responsible development of nanotechnology

National Nanotechnology Initiative
Collaborative research and development that will advance understanding and control of matter at nanoscale for:
- National economic benefit
- National security
- Improved quality of life

Signature Initiatives
- Sustainable Nanomanufacturing
- Nanoelectronics for 2020 and Beyond
- Nanotechnology Enhanced Solar Energy Capture and Conversion
- Nanotechnology for Sensing
- Nanotechnology Knowledge Infrastructure
Space Technology Research Fellowships

- New graduate fellowship program
- Open to US citizens and Permanent Residents
- 1 year initial support + additional 1 year for MS and 3 years for PhD
- $60K Total Award - $30K stipend + $10K tuition and books + $1K health insurance + $9K university allowance + $10K NASA on-site R&D allowance
- Application includes statement of Educational Research Area of Inquiry and Goals (up to 5 pages) describing a research problem that the student would like to solve
- STRF recipients will be assigned a NASA mentor and will perform part of their thesis research at NASA Centers
- Call for proposals – November
- Proposals due – January
- Announcement – April
- Start - August
Other Space Technology Research Grants

Early Career Faculty
- Targeting faculty within 5 years of the PhD
- $200K/year for 3 years

Early Stage Innovation
- 1 year grants
- Up to $250K
- [http://www.nasa.gov/home/hqnews/2012/oct/HQ_12-373_Early_Stage_Proposals.html](http://www.nasa.gov/home/hqnews/2012/oct/HQ_12-373_Early_Stage_Proposals.html)

NASA Innovative Aerospace Concepts (NIAC)
- Two phase awards –
  - Phase I (feasibility studies) – up to $100K
  - Phase II – technology development – longer duration, more $s
• Nanotechnology has the capacity to radically change the way NASA performs missions in aeronautics and space
  – Reduced weight
  – Improved functionality
  – Increased durability
• The Nanotechnology Space Technology Roadmap identifies challenges and capabilities that can be addressed with nanotechnology
• NASA is moving out on addressing some of the challenges identified in the roadmap
  – Lightweight, high strength structural materials – CNT and BNNT
  – Lightweight cables for power and data
  – Compact, low power chem/bio sensors
• NASA nanotechnology R&D is well aligned with NNI Signature Initiatives
• NASA is always looking for collaborations to accelerate technology development and tech transfer