Future Needs and Opportunities in Nanotechnology for Aerospace Applications – A NASA Perspective

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NIA Nanotechnology Workshop

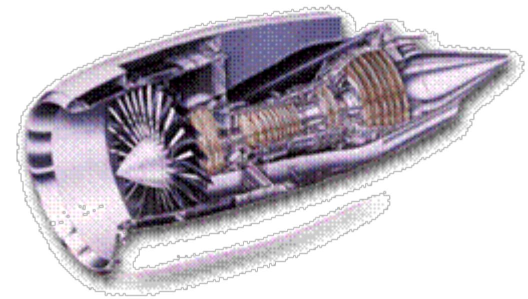
2-21-14

Outline

- Benefits of Nanotechnolgy 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

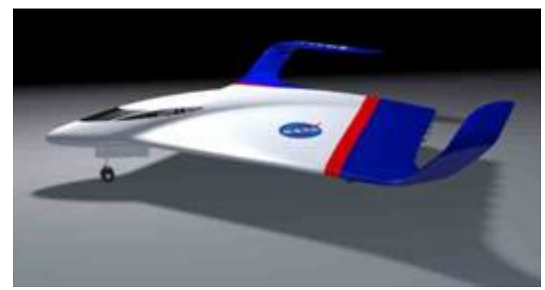
Critical Concerns for Aerospace Systems

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

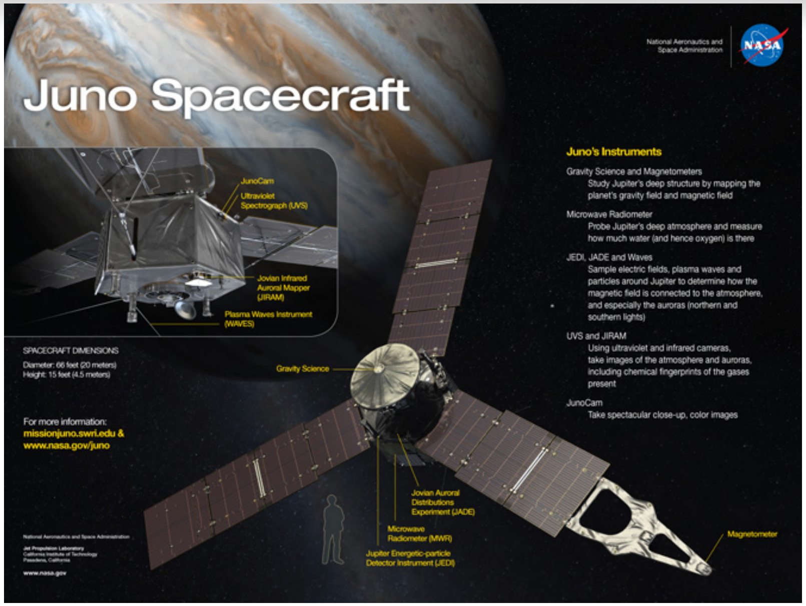


How Nanotechnology Impacts Materials Properties

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
  - Nano structure 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 (λ/10) and nanostructure

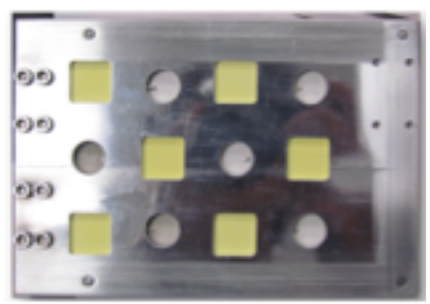
Nanotechnology Has Made it into Space



CNT Nanocomposites for Charge Dissipation

Silica Aerogels

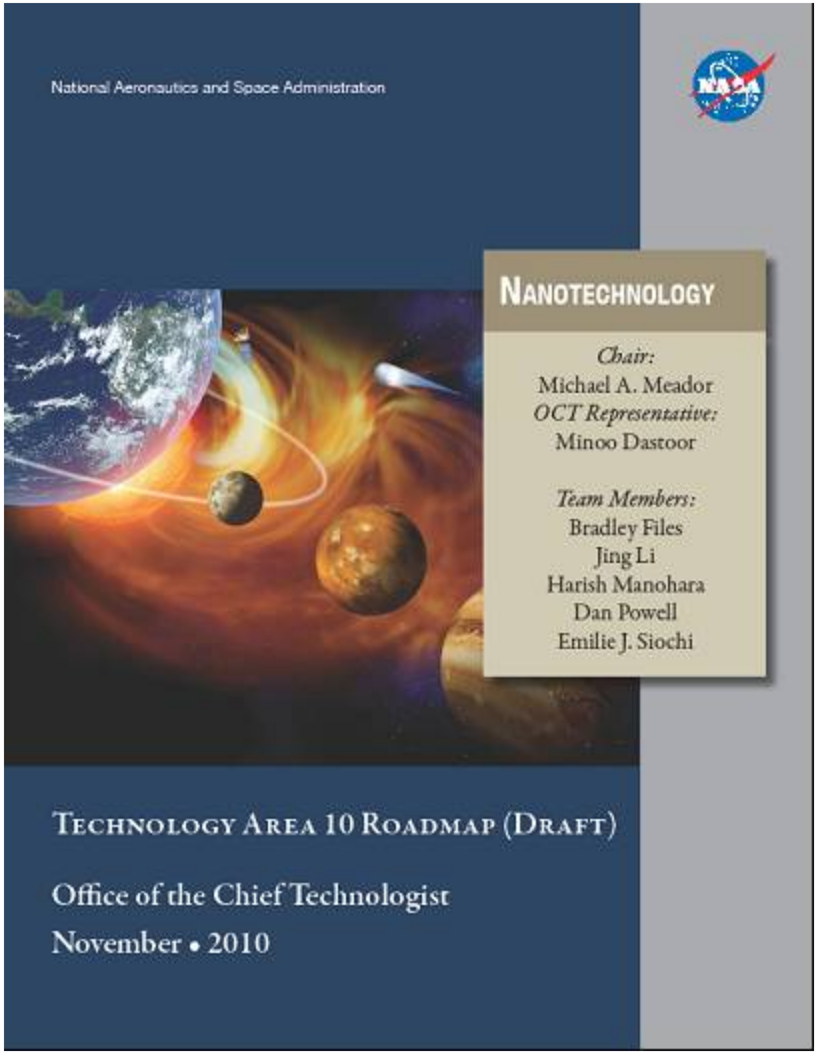
CNT "Electronic Nose"



Polyimide Aerogels

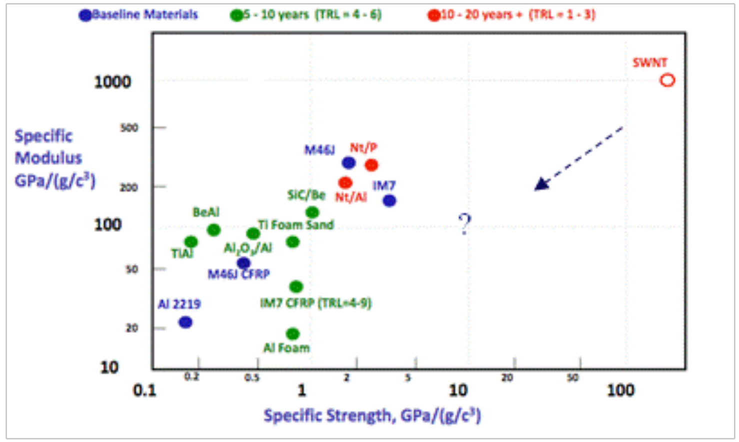
NASA Nanotechnology Roadmap

- 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

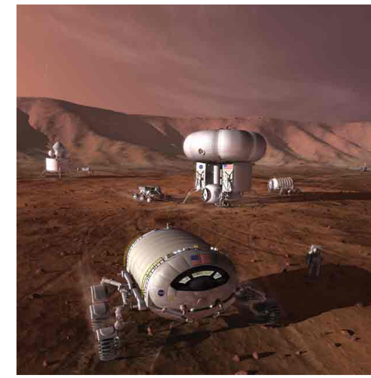


Grand Challenges

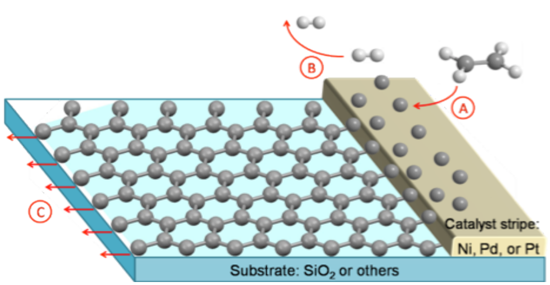
Nanopropellants



Ultralightweight Materials



Structurally Integrated Energy Generation and Storage



Graphene Electronics

- 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

Hierarchical Integration

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

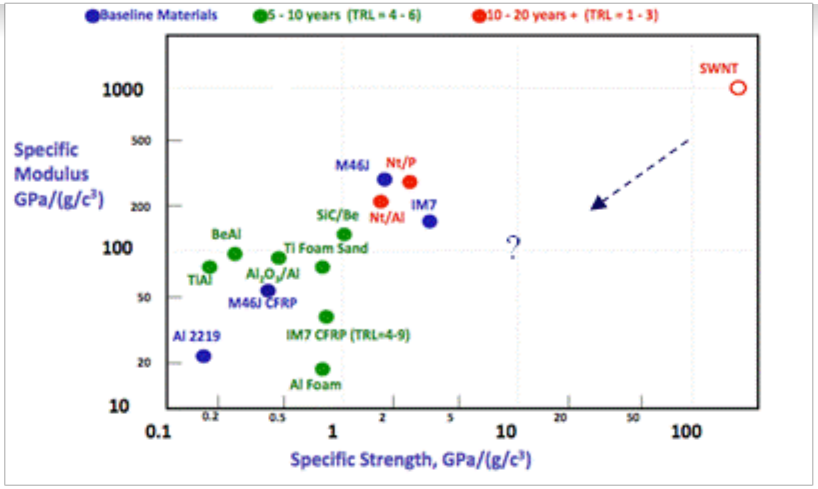
- Carbon nanostructure based high strength reinforcements
- Durable nanoporous materials (polymers,fibers, metals or hybrids) less than half the density of monolithics
- Addition of nanoscale fillers to improve strength and toughness

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:

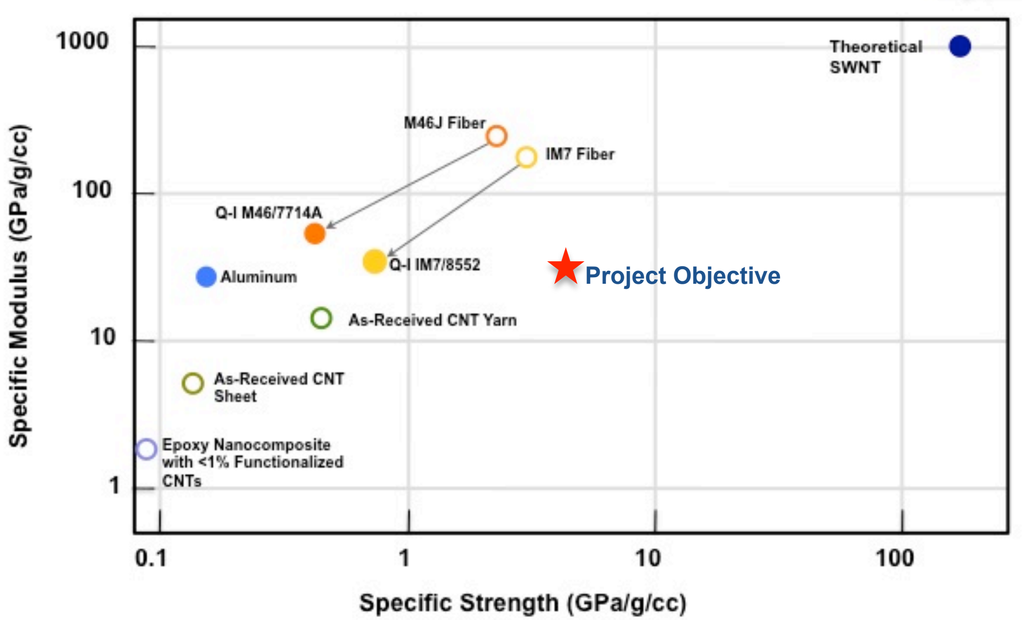
- Development of reliable, reproducible, and controlled nanomaterials synthesis processes on a large scale
- Development of tailored geometries at nano and macro scale for structural components
- Fabrication methods that can be practically implemented at bulk or macro scale
- Early assessment of systems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

Time to Mature to TRL 6: 5-10 years

Potential for Partnering with Other Agencies:

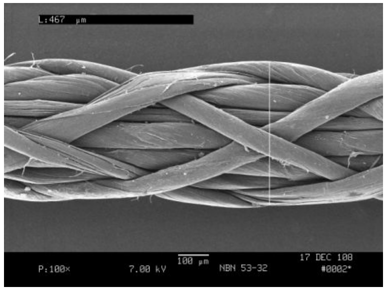
- Partnerships under NNI Nanomanufacturing SI

State of the Art for Nanocomposites



- 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

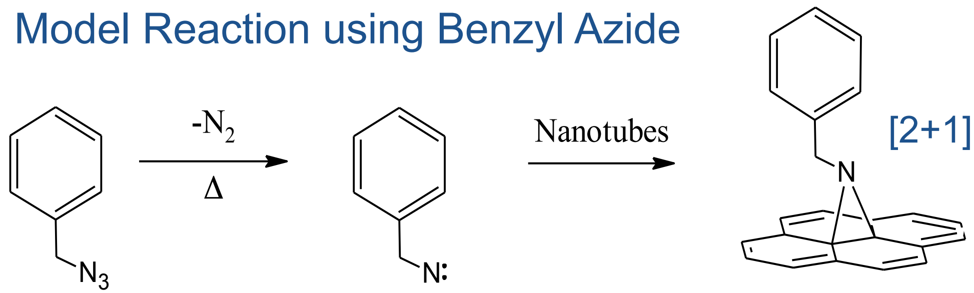


- **What are we trying to do?**
  - Develop carbon nanotube (CNT) reinforced composites with 1.5 to 2 times the strength of conventional carbon fiber composites, such as those used in the Boeing 787
- **Why is it important?**
  - Use of these ultra-lightweight materials in place of conventional composites 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

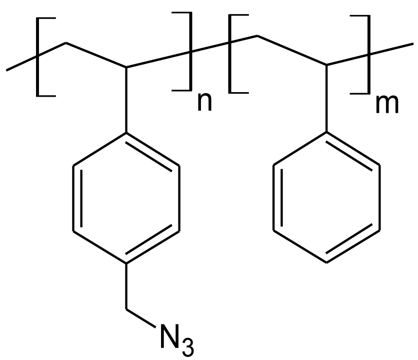
Polymers Bearing Nitrene Precursors for Nanotube Crosslinking

Model Reaction using Benzyl Azide

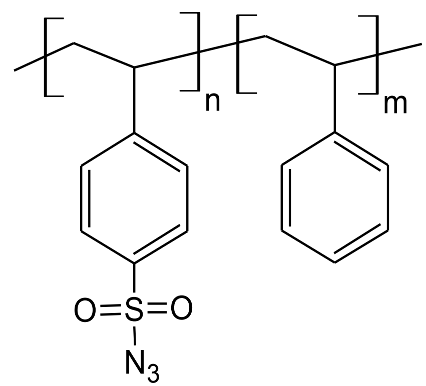


[2+1] cycloaddition of nitrene to nanotube walls

BzAz

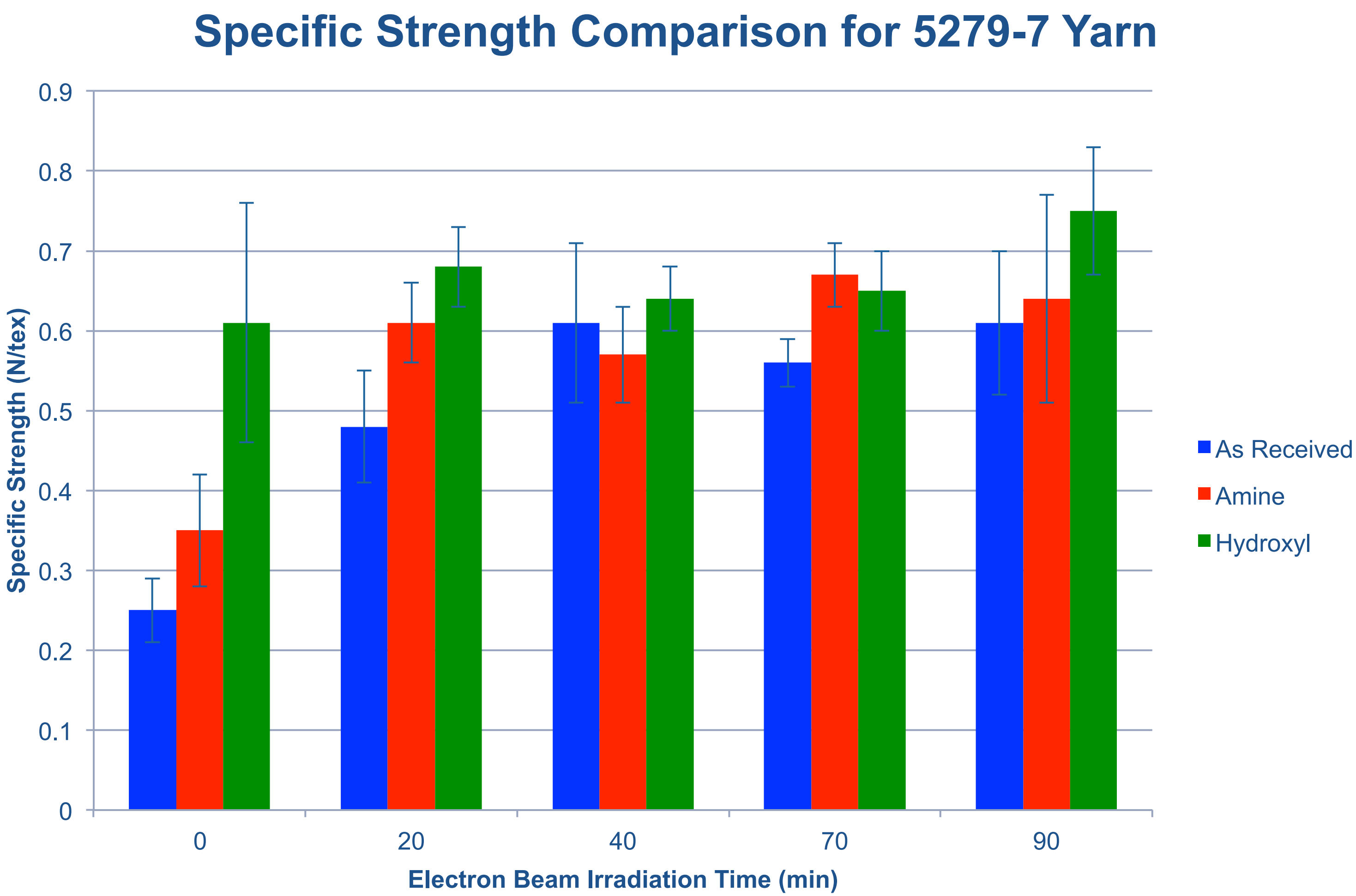


Poly(styrene-*co*-vinylbenzyl azide)
PSVBAz

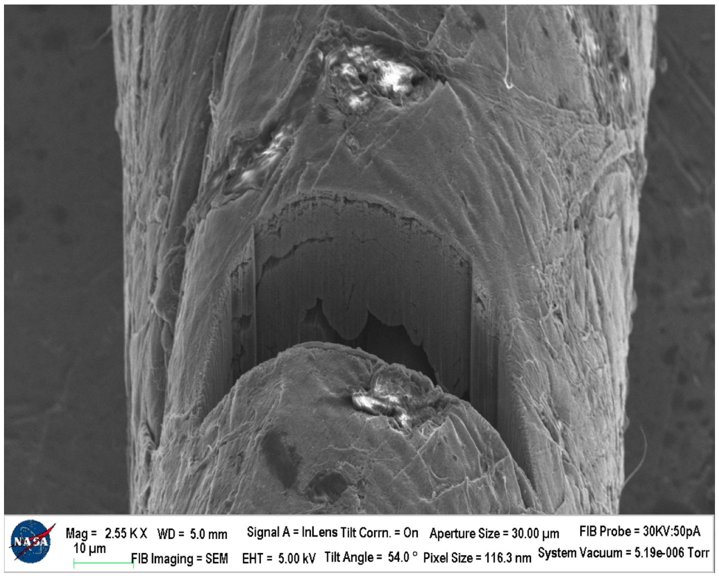


Poly(styrene-*co*-styrenesulfonyl azide)
PSSfAz

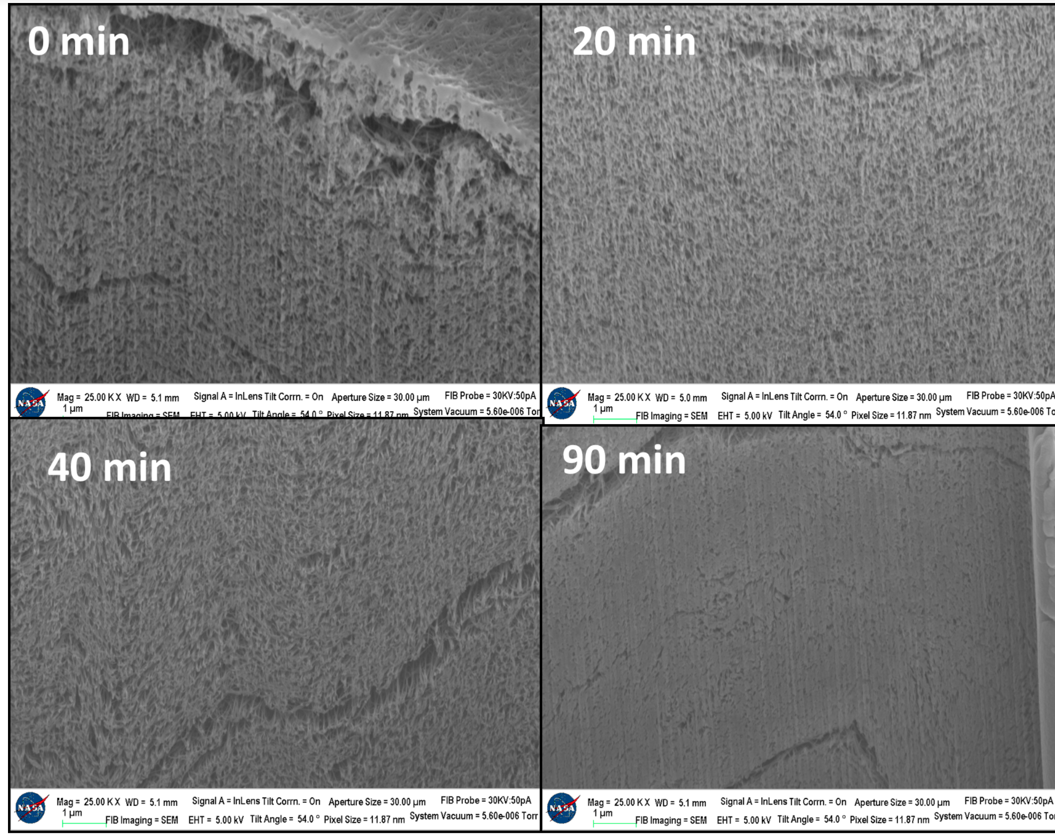
Functionalized Enhances Effects of E-Beam Crosslinking of CNT Yarns



SEM Images of Yarn Cross-Sections Indicates E-beam Induced Coalescence of CNTs

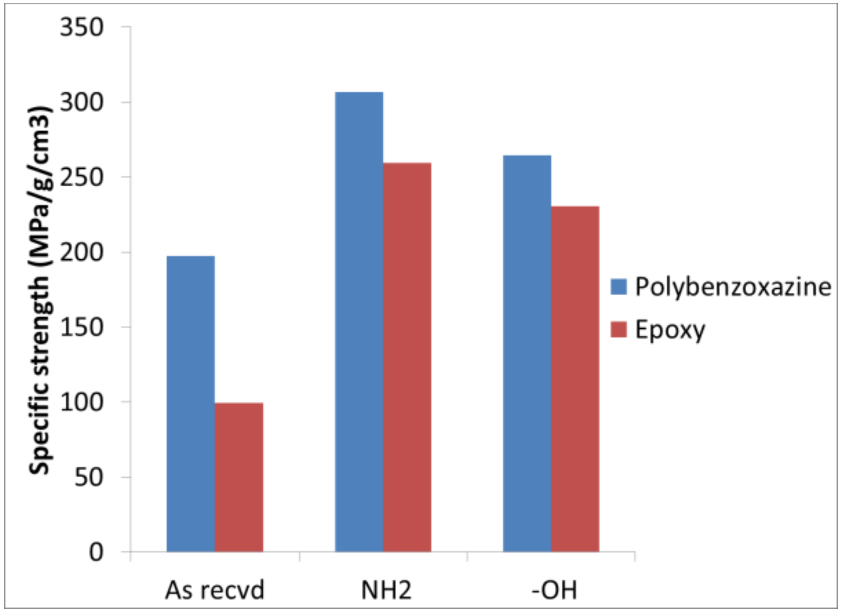


Used FIB to machine a trough into CNT yarns to image cross-section

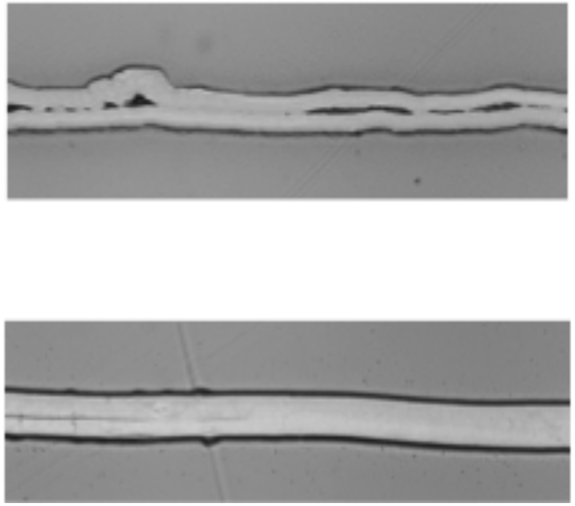


Voids evident in unirradiated CNT yarns appear to collapse and CNTs coalesce with increasing irradiation time

Functionalization Promotes Wetting of CNT Sheets



Specific tensile strength of laminates improved with functionalization

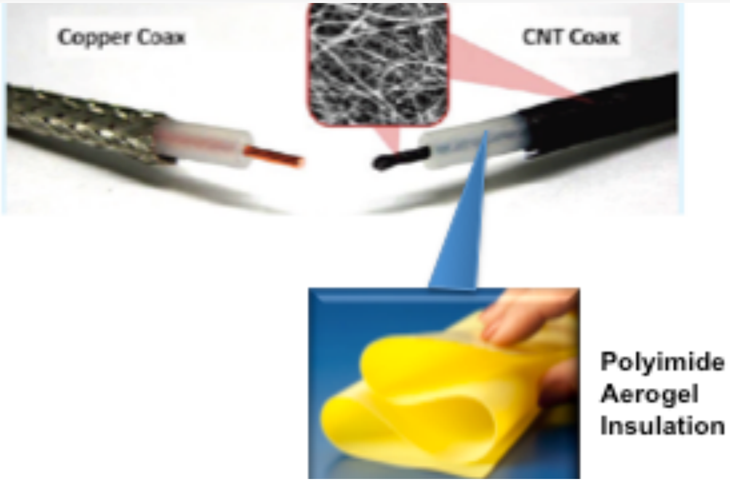


Optical photomicrographs of 2-ply CNT/epoxy composite processed without (top) and with (bottom) coupling agent

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



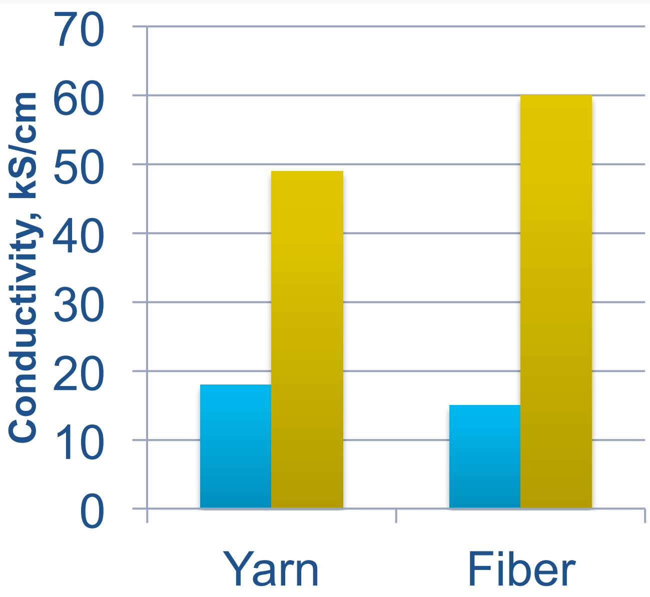
Approach

- 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 interacalation 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

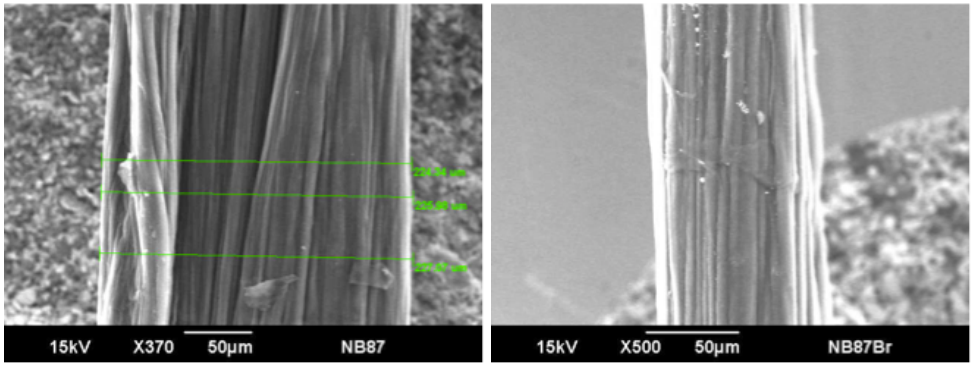
Cost, Schedule, and Status

- 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

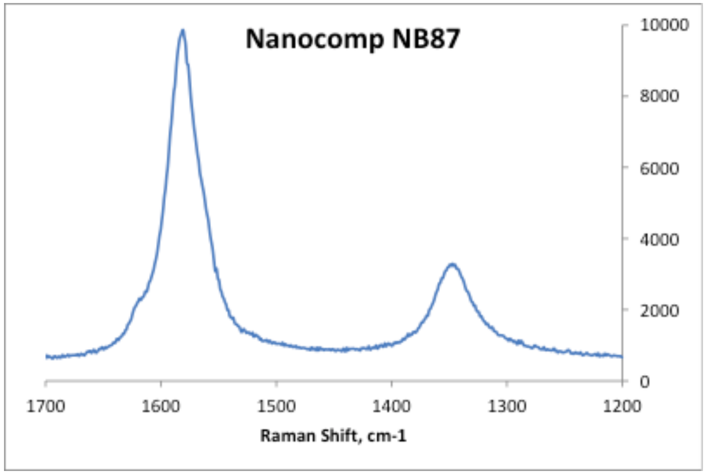


No Change in Fiber Gross Structure



Before After

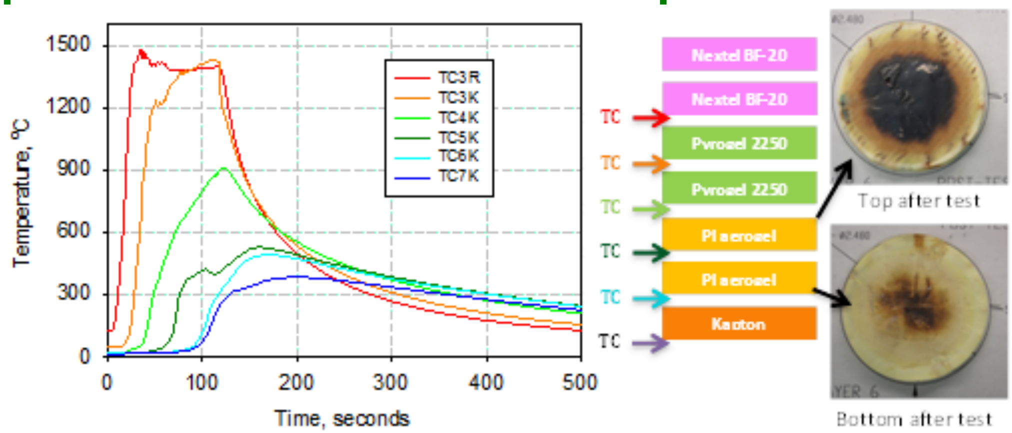
Minor Changes in Raman

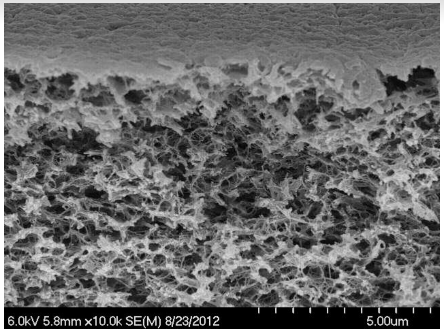


Fiber	1360/1580	σ
NB87	0.26	0.05
NB87-Br_2	0.34	0.05
NB87-I_2	0.30	0.08
NB87-ICl	0.24	0.11
NB87-IBr	0.25	0.04

High Performance Polyimide Aerogels

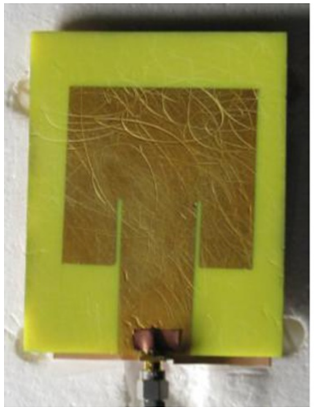
High heat flux test results indicate potential for flexible thermal protection

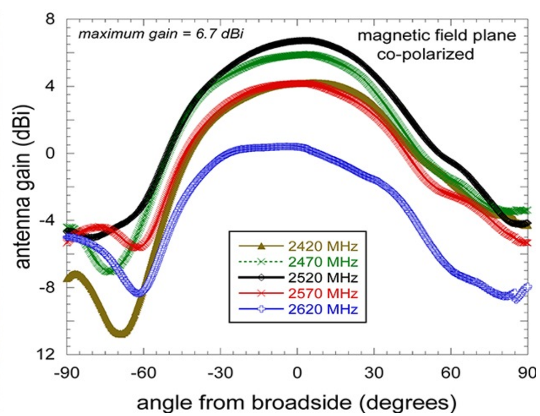




Nanoporous structure

Good compressive properties and durability





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

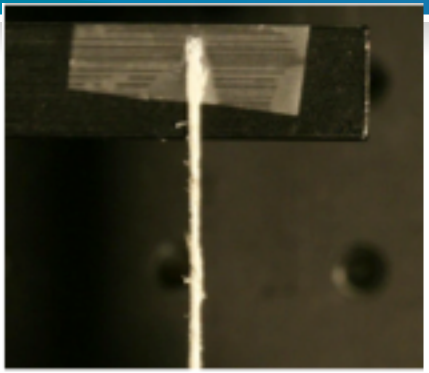
BNNT Structural Materials

Description and Objectives

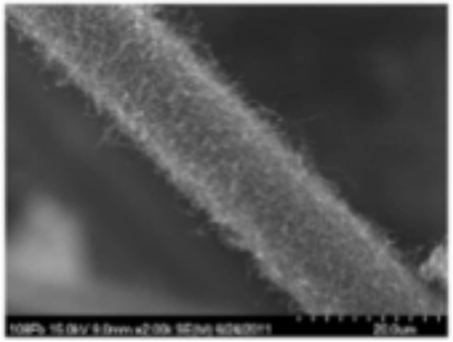
Objective: Develop alternatives to CNT reinforcements for multifunctional composites

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



BNNT Yarn
(NASA LaRC)



BNNT "Fuzzy" SiC Fiber
(NASA GRC)

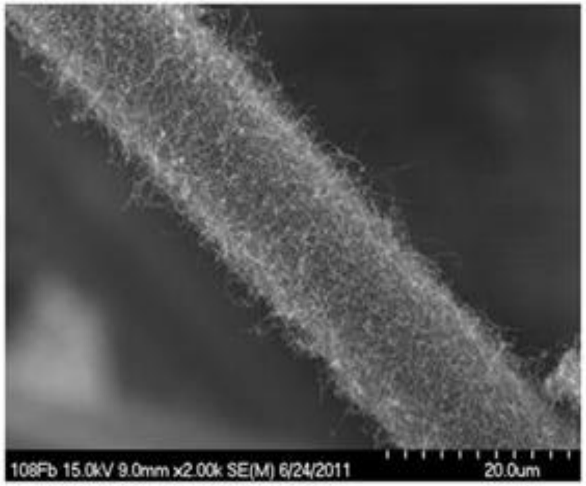
Approach

- 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

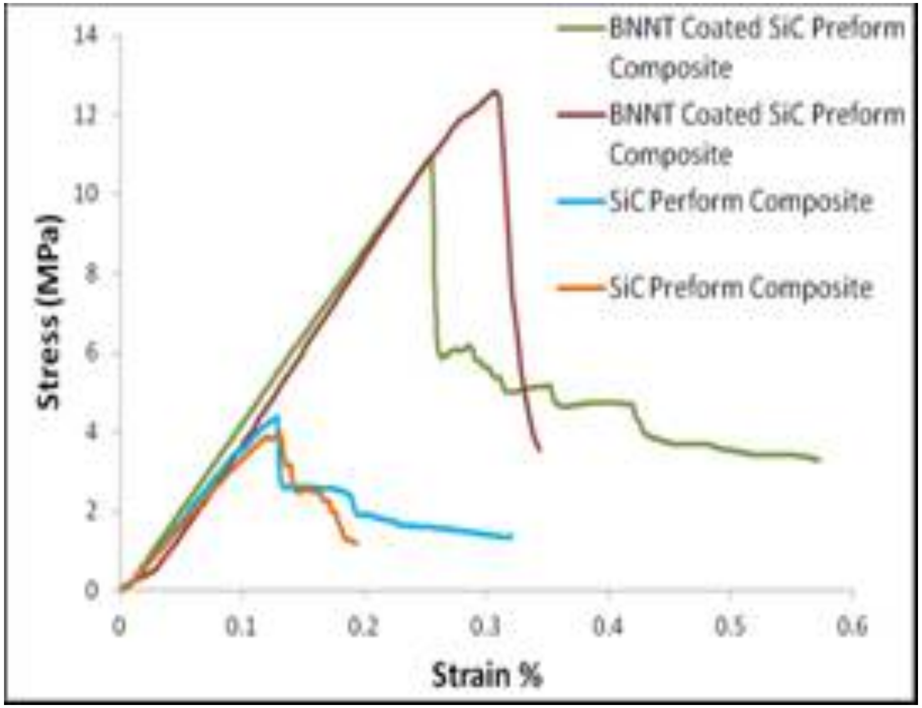
- Fabricate multi-ply composite samples consisting of aligned BNNT composite mats and fibers; determine mechanical and thermal data (8/30/14)
- Fabricate 2"x4" BNNT "fuzzy" 3-D preform CMC laminate; determine mechanical and thermal properties

BNNT Fuzzy Fiber



Demonstrated BNNT growth onto fiber substrates

- **SiC**
- **Al_2O_3**
- **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

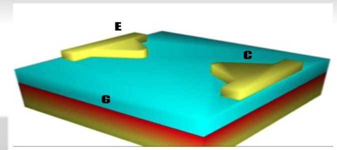
Description and Objectives

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

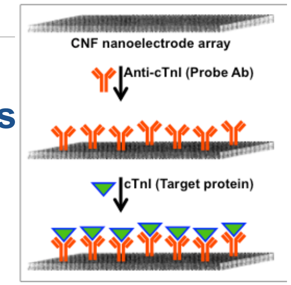
Background:

- 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

CNT Smart Phone Sensor



Vacuum Nanoelectronics



Scheme for Detection of Biomakrers with CNF

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 demonstate 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

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
- Anouncement – April
- Start - August
- http://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={1C36FF5F-549C-2349-F37F-B72365FD9D1B}&path=open

Other Space Technology Research Grants

Early Career Faculty

- Targeting faculty within 5 years of the PhD
- $200K/year for 3 years
- http://nspires.nasaprs.com/external/solicitations/solicitationAmmendments.do?method=init&solId={0E68FEE0-A7A2-EDFF-50CA-49E9E0641E18}&path=open

Early Stage Innovation

- 1 year grants
- Up to $250K
- 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
- http://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={3351C810-DEAF-4F2F-ED2E-C150772DDA2F}&path=open

Summary

- Nanotechnology has the capacity to radically change the way NASA performs missions in aeronautics and space
  - Reduced weight
  - Improved functionality
  - Increased durabilty
- 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