Scalable Nanomanufacturing (SNM)

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SNM Program

- **Started:** *2011, in response to NSI: Sustainable Nanomanufacturing*
- **Grants:** *$1.5M max. over 4 years, $250-375K per year*
- **Total Budget:** *Average/year $8-12M*
- **Across Divisions:** *ENG—CMMI, ECCS, CBET, EEC, IIP and MPS—DMR, CHE*
- **NSF POCs:**
  - *Khershed Cooper, ENG/CMMI*
  - *Bruce Kramer, ENG/CMMI - Advisor*
  - *Nora Savage, ENG/CBET*
  - *Mona Zaghloul, ENG/ECCS*
  - *Carole Read, ENG/EEC*
  - *Rajesh Mehta, ENG/IIP*
  - *Lynnette Madsen, MPS/DMR*
  - *Timothy Patten, MPS/CHE*

SNM: Solicitation

Objective: Research to *overcome the key scientific and technological barriers* that prevent the production of useful nanomaterials, nanostructures, devices and systems at an *industrially relevant scale,* reliably, and at low cost and within *environmental, health and safety guidelines*

Emphasis: Frame proposals in the context of the eventual manufacture of demonstrably *useful nano-enabled products in high volume and at low cost*

- Address scale-up *– large area, continuous, parallel, roll-to-roll …*
- Encourage multi-disciplinary collaboration *– ENG (Electrical, Mechanical, Chemical, Biomedical …), MPS (Chemistry, Materials Research, …)*
- Encourage industrial collaboration *– planned activities, experimental test-beds, tangible meaningful collaboration*
- Address a portion of the NM value chain *– building-blocks → nanostructures → nanocomponents & devices → nano-subsystems & systems*

SNM: Research

- *Novel scalable processes and methods for large-area or continuous manufacturing* of nano-scale structures and their assembly/integration into higher order systems
- *Fundamental scientific research in well-defined technical areas* that are strongly justified as approaches to overcome critical barriers to scale-up and integration of nano-scale processes
- *Design principles for production systems* leading to nanomanufacturing platforms; identification of metrology, instrumentation, standards and control methodologies needed for process control and to assess quality and yield

Fundamental principles for volume manufacturing of nano-enabled products

SNM: Research Areas

Materials and Structures

- **C-based:** CNT, Graphene, Bucky-tape, CNT Fibers, Cellulosic
- **0D:** Nanoparticles, QDs, Core-shell, Janus, Hierarchical, Composite
- **1D:** Nanowires, Nanopillars, Nanotubes, Nanofibers, Nonwovens
- **2D:** MoS_2, BN, TMDs
- **3D:** Nanoporous, Aerogels, Electrodes, Arrays, Gratings, Metamaterials

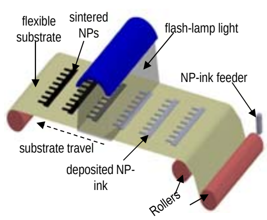
Processes and Methods

- **Chemical/Thermal:** Combustion, Plasma, Hydrothermal, Drawing, Etching
- **Vapor-based:** CVD, PVD, PECVD, Laser CVD, ALD, MLD
- **Solution-based:** Coating, Casting, Colloids, Electrospray, Electrophoresis, Electrospinning, Electroetching, Microfluidics, Microreactors, Ink-jet Printing
- **Lithography/Patterning:** BCPs, AFM, DPN, NIL, PL, Laser Beam, E-beam, Ion-beam
- **Assembly:** Self, Directed, Molecular
- **Bio-inspired:** DNA, Virus, Protein, Diatoms
- **Mechanical:** Exfoliation, Nanomachining
- **3D Nanomanufacturing:** 3D Printing, Holographic

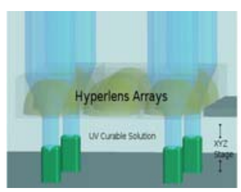
Applications

- **Environmental:** Water Purification, Analytical Separation
- **Chemical:** Catalysis, Gas Storage
- **Energy:** Storage, Conversion, Batteries, Supercapacitors, PVs, Solar Cells, Fuel Cells
- **Electronics:** ICs, Flexible, Storage Memory, 3D Devices, TFTs, EM-Shielding
- **Optoelectronics/Photonics:** Imaging, Waveguides, Displays, Lighting
- **Sensors:** Biological, Chemical, Multiplexed
- **Structural:** High-Strength, Light-Weighting, Packaging
- **Biomedical:** Implants, Tissue Scaffolds, Diagnostics, Therapeutics, Probes
- **Sheets/Wires:** Fibers, Cables, Filters, Membranes, Textiles, Paper

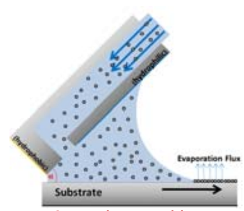
Scale-up Methods



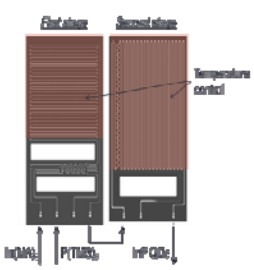
R2R Printed NPs *(Chang, Oregon State)*



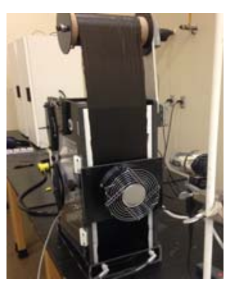
3D Printing *(Chen, UC-San Diego)*



Convective Deposition
(Gilchrist, Lehigh)

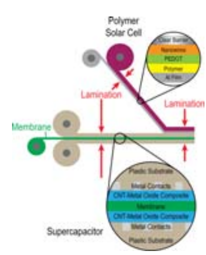


Microreactor for QDs
(Jensen, MIT)



R2R Bucky Paper
(Liang, Florida State)

Parallel Antennae Array
(Xu, Purdue)



R2R supercapacitor
(You, UNC)

SNM Projects Relevant to Sustainability

Tools and Methodologies

- **Designing and Integrating LCA Methods for Nanomanufacturing Scale-up** – *Jacqueline Isaacs, Northeastern*
  - Use the *life cycle assessment (LCA)* methodology to address the ethical, legal, and societal impacts in decision-making as nanomanufacturing scales to commercial production

Technologies for Sustainability

- **Scalable Continuous Production of Aligned Carbon Nanotube and Nanoporous Membranes** – *Chinedum Osuji, Yale*
  - Investigate scalable methods for fabricating vertically aligned carbon nanotube and nanoporous membranes for applications in *analytical separation and water purification*
- **Continuous, Large-Scale Nanocomposite Production Via Micellular Electrospray** – *Jessica Winter, Ohio State*
  - Combine electrospray with self-assembly to produce nanocomposites for biomedical imaging and pharmaceutical separations, *integrate EHS considerations into process design*
- **Scalable and Sustainable Hydrothermal Manufacturing of Nano-array based Low Temperature Diesel Oxidation Catalysts** – *Pu-Xian Gao, U of Connecticut*
  - Study hydrothermal manufacturing technique for continuous, scalable and sustainable synthesis of low operating temperature diesel oxidation catalysts for automotive industry, with direct impact on fuel economy, energy and *environmental sustainability*
- **Scalable Manufacturing of Nanostructured Membranes for Fracking Wastewater Treatment** – *Daeyeon Lee, U of Pennsylvania*
  - Use combination of nanostructured amphiphobic membranes, nanoimprinted anti-fouling membranes, and nanocomposite membranes that have enhanced selectivity and permeability *for fracking wastewater treatment*
- **Roll-to-Roll Manufacturing of Films and Laminates Based on Cellulose Nanomaterials** – *Jeffrey Youngblood, Purdue*
  - Study continuous casting methods for roll-to-roll fabrication of cellulosic nanomaterial films and laminates, supported by *sustainable and eco-friendly approaches* for surface modification and particle dispersion

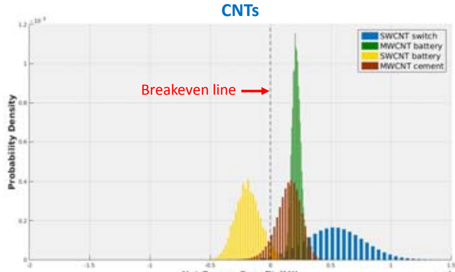
Example of SNM Research

Designing and Integrating LCA Methods for Nanomanufacturing Scale-up

PI: Jacqueline Isaacs, Northeastern University

- How can industry develop new nanotechnologies in a responsible and sustainable manner?
- How can we ensure nanomanufacturing processes and products remain safe for workers, consumers and environment?

Net energy benefits of manufacturing and use of CNTs



Distribution of Net Energy Benefits

Zhai, Isaacs, Eckelman, manuscript submitted, 2015

Assessing NM and EHS costs and trade-offs for CNT batteries

Cost breakdowns for low level of EHS at $29/battery

- Costs are 15% higher for implementation of highest levels of EHS protection
- Process yield and cycle time have greatest effects on unit cost of laptop batteries
- Annualized cost of a MWCNT-enabled computer battery is $6.20 (compared with $10.86 for conventional batteries)
- Relative cost of specific energy decreases to $0.118 /Wh for MWCNT-batteries (from $0.142 /Wh for conventional batteries)
- Development or expansion of battery recycling infrastructures that avoid exposures and releases should be considered at end-of-life

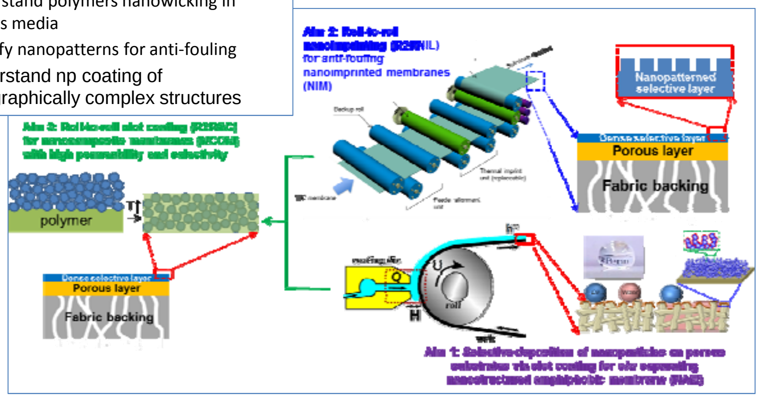
Hakimian et al, ES Nano, 2015

Example of SNM Research

Scalable Manufacturing of Nanostructured Membranes for Fracking Wastewater Treatment

PI: Daeyeon Lee, University of Pennsylvania

Research
- Understand polymers nanowicking in porous media
- Identify nanopatterns for anti-fouling
- Understand np coating of topographically complex structures

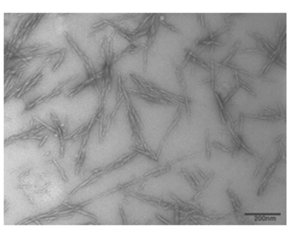


Meet one of NAE Engineering Grand Challenges— provide access to clean water

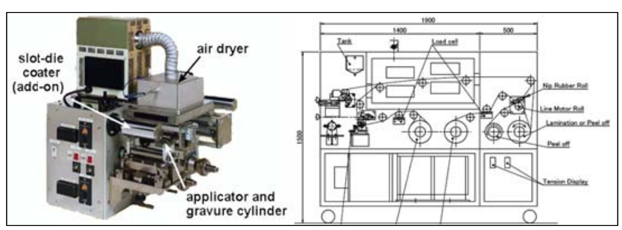
Example of SNM Research

Roll-to-Roll Manufacturing of Films and Laminates Based on Cellulose Nanomaterials

PI: Jeffrey Youngblood, Purdue



Cellulose Nanocrystals (CN)



Roll-to-Roll Processing of CN Films, Laminates and Composites

- Bio-derived nanomaterials ~50nm-5μm long and 5-50nm wide
- Extremely strong and stiff with high transparency and barrier properties
- LCA shows more sustainable than many materials and also low cost

Approach
- Solvent-less CN modification to keep sustainability
- Real-time in-line measurement of thickness, rheology and temperature and feedback
- Integrated multi-scale modelling of microstructure effects on properties

Sustainable nanotechnology-enhanced materials for packaging, cars, electronics

NNI Signature Initiative

Sustainable Nanomanufacturing: Creating Industries of the Future

Goal: Establish manufacturing technologies for economical and sustainable integration of nanoscale building blocks into complex, large-scale systems, e.g., CNTs in nanocomposites

Key requirements:

- **Scalable**
  - *Production must be scalable to the required throughput and yield*
  - Accelerate the development of industrial-scale methods for manufacture of functional nanoscale systems
- **Controllable and Sustainable**
  - *Generation, manipulation and organization of nanostructures must be accomplished in precise, controlled and sustainable manner as demonstrated by a full life-cycle analysis*
- **Safe**
  - *Nanotechnology-enabled products must perform to specification over their expected lifetimes safely*

The Signature Initiative targets production-worthy scaling of classes of sustainable materials that have the potential to affect multiple industry sectors with significant economic impact — *high-performance structural carbon-based and cellulosic nanomaterials*

Federal Agencies: DOD, DOE, EPA, IC/DNI, NASA, NIH, NIOSH, NIST, NSF, OSHA, USDA/FS

Sustainable Nanomaterials

C-based Nanomaterials

- Federal Agencies: NRO, DOD, NIST, NASA
- Benefits: Modulus, Strength, Thermal and Electrical Conductivity
- Impact: High-performance, lightweight materials for aerospace, energy and transport
- Manufacturing: Scale-up, quality control, testing, standards for commercial applications
- Measurements/metrology: For development *and* production
- *Lifetime assessment: Degradation and nanomaterial release, accelerated aging tests*
- *Life-cycle assessment: Gauge commercial readiness*

Cellulosic Nanomaterials

- Federal Agencies: USDA/FS, DOE, NIST
- Benefits: Lightweight, abundant, sustainability
- Impact: Structural, packaging, separation and membrane applications
- Research Priorities: Identify new bio-based nanomaterials, preserve biomass nanoscale properties for engineering new products and applications
- Commercialization: Identify pathways, facilitate communication across industry sectors

Strategies and solutions to mitigate process releases and worker exposure

NM and Environmental, Health and Safety (EHS)

- EHS of large-scale, volume nanomanufacturing – *potential exposure to workers during production*
- Nanomaterials and nanotechnology-enabled products and their *exposure to the general public* – a high priority
- *Assess risks* and ensure that nanomanufacturing and nanotechnology-enable products are safe in the workplace and at home
- *Current Intelligence Bulletin 65 on Occupational Exposure to Carbon Nanotubes and Nanofibers, 2013* – *quantitative risk assessment, recommended exposure limits, risk management recommendations for safe handling and use* – CNTs/CNFs
- *Focus is development and implementation of engineering control strategies and solutions that mitigate process releases and worker exposures*
  - Provide guidance to nanomanufacturing using established materials, such as CNTs and CNCs;
  - Develop prospective guidance for emerging materials, such as graphene, by *conducting hazard assessment* employing *in vitro* and *in vivo* models of exposure and response
- Collaboration with the National Toxicology Program to investigate *potential hazards* associated with exposure to cellulose nanomaterials

Federal Agencies: CPSC, NIOSH, OSHA, NIST, EPA