

NSTC COMMITTEE ON TECHNOLOGY  
SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

**National Nanotechnology Initiative Signature Initiative:**

***Sustainable Nanomanufacturing – Creating the Industries of the Future***

**Final Draft, July 2010**

Collaborating Agencies<sup>1</sup>: NIST, NSF, DOE, EPA, IC, NIH, NIOSH, OSHA, USDA/ Forest Service

**National Need Addressed**

This interagency initiative will establish manufacturing technologies for economical and sustainable integration of nanoscale building blocks into complex, large-scale systems.

A decade of research under the National Nanotechnology Initiative has led to remarkable discoveries of nanoscale materials with unique properties, laboratory demonstrations of a range of innovative nanoscale devices, and introduction of a limited number of nanotechnology-based products into the marketplace. For this investment to become the basis for high-value industries, methods must be established to efficiently assemble products that integrate together billions of nanoscale devices with disparate functions. Current manufacturing methods such as those used in the semiconductor industry will not be economical at these scales; radically new approaches are needed. Moreover, for such products to be ubiquitous in the nation's future economy without causing long-term negative environmental or health impacts, these new approaches and the resulting products must be inherently sustainable by design.

A long-term vision for nanomanufacturing is to create flexible, “bottom-up” or “top-down/bottom-up” continuous assembly methods that can be used to construct elaborate systems of complex nanodevices. Moreover, these systems by design will reduce the overall environmental and health impacts over their full life cycle; for example, by minimizing any release of harmful nanomaterials or substances, and reducing energy consumption. To create the foundation for achieving this vision, over the next decade this initiative will first establish sustainable industrial-scale manufacturing of functional systems with relatively limited complexity based on manufactured nanoparticles with designed properties. The organized assemblies of nanoparticles manufactured here will be designed to control and manipulate information, thermal energy, and electromagnetic radiation. The systems to be manufactured will include disruptive technologies for high-speed communication and computation, solar energy harvesting, waste heat management and recovery, and energy storage. The methods developed

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<sup>1</sup> Please note that “collaborating agencies” is meant in the broadest sense and does not necessarily imply that agencies provide additional funds or incur obligation to do so. Agencies leading this effort and responsible for carrying out key aspects of these initiatives are underlined.

will be immediately extendable to more complex components and systems as future nanodevices mature.

### **Technical Program**

Although the flexibility inherent in nanomaterials offers broad possibilities for future manufactured products, to move beyond one-off nanofabrication demonstrations the following three requirements which must be addressed to enable sustainable nanomanufacturing:

- Production must be scalable up to the required throughput and yield;
- The generation, manipulation, and organization of nanostructures must be accomplished in a precise, controlled, and sustainable manner as demonstrated by full life cycle analysis; and
- All nanotechnology-based products must perform to specification over their expected lifetimes without the release of harmful nanomaterials or other toxic substances into the environment.

Two thrust areas in materials design and measurement technology will support product, tool, and process design informed by and adhering to the overall constraints of safety, sustainability, and scalability. The first thrust area focuses on scalable design of nanosystems and their manufacturing processes. The second thrust area drives new metrology for manufacturing nanoscale materials, components, and devices. Much of the work performed in these two thrust areas will provide data suitable for performing life-cycle analyses of the materials and devices being produced. These will enable rational choices of the most energy- and material-efficient processes and products to be made.

#### ***Thrust 1: Design of scalable and sustainable nanomaterials, components, devices, and processes***

Nanomanufacturing relies on scaling up production from the laboratory demonstration level to true industrial volume production. This challenge must be addressed, in part, through nanomaterial, component, and device design that identifies and eliminates the fundamental limits to scaling. New scalable processes and techniques for generating and handling nanostructures safely and efficiently on an industrial scale must be developed, validated, and disseminated. Many of these techniques will have to rely on the self-assembly or directed self-assembly of nanostructures in order to cope with the vast numbers of nanocomponents needing to be integrated into complex systems. The success of this approach will depend on the careful design of individual nanostructures as well as on the development of new control methods designed to organize matter using predominantly stochastic rather than deterministic processes.

The research and development supported will specifically focus on overcoming the major technical barriers leading from the laboratory to the production line, including the following:

- Novel processes and techniques for scalable and sustainable manufacturing of *known* beneficial nanoscale materials, components, or devices, with preference given to energy- and material-efficient processes applicable to broad classes of nanomaterials, components, and devices;

- Novel beneficial nanomaterial components and devices produced by *known* scalable and *sustainable* manufacturing processes and techniques, such as cellulosic nanomaterials;
- Fundamentals of nanomaterial, component, device, and/or nanomanufacturing process design *specifically* focused on scalability and efficient use of materials and energy for sustainability; and
- Interactions of nanomaterials, components and devices with nanomanufacturing processes and of finished products with the environment focused on EH&S.

### **Successful Outcomes (Thrust 1)**

The metrics for success of this initiative are given by the milestones and timeframes shown below. These broad sets of milestones serve as guidelines for each agency's contribution. Initial focus areas will include manufactured products based on carbon-based nanomaterials, optical metamaterials, and cellulosic nanomaterials.

- 2-year – Formation of industry/academic/government consortia coordinating research on manufacturing methods and metrology for high-performance nanomaterials.
- 4-year – Demonstration of material systems and processes for nanomanufacturing that are scalable, sustainable, efficient, and safe.
- 8-year – With industrial partners, identification of such materials and processes appropriate for production, followed by technology transfer and/or technology adoption by US manufacturers.

### ***Thrust 2: Nanomanufacturing measurement technologies***

The accuracy, precision, and reproducibility with which a structure can be manufactured are dictated in large part by the available metrology (i.e., “if it can't be measured, it can't be manufactured”). Measurement systems and standards have enabled industry to produce reliable goods and promote successful businesses and a healthy economy through high-quality process development. Nonetheless, the ability to tune and maintain nanoscale assembly processes is severely limited by the lack of truly nanoscale, real-time, in-line characterization techniques. The metrology tools required to quickly, inexpensively, and accurately characterize products at the relevant scales of one to hundreds of nanometers have yet to be developed. Existing methods are time-consuming, expensive, and require high-tech infrastructure and high skill levels to perform. For example, a clean-room laboratory infrastructure and advanced expertise are required to perform electron or atomic force microscopy and complex specimen preparation. Often, one must resort to macroscopic, and thus indirect, measurements of functionality that omit crucial information about the causal chain of process, structure, and function. In-line, rapid, and inexpensive nanoscale metrology techniques must be developed to enable and maintain complex, multi-step assembly processes in which a large number of variables have to be optimized and controlled.

The research and development supported will specifically focus on overcoming the major technical barriers leading from the laboratory to the production line, including the following:

- Novel measurement techniques that enable information about nanoscale material composition and behavior to be obtained at high speed;
- Process control methods that can utilize the information provided by high-speed measurement techniques to maintain process stability and guarantee product composition/consistency; and
- Development of methodologies that enable accurate measurement of nanomaterial evolution and transport during product manufacturing and use, and across the material lifecycle.

## **Successful Outcomes (Thrust 2)**

The metrics for success of this initiative are given by the milestones and timeframes shown below. These broad sets of milestones serve as guidelines for each agency's contribution.

- 2-year – Formation of industry/academic/government consortium focused on metrology for high-throughput roll-to-roll nanomanufacturing.
- 4-year – Demonstration of a suite of generic measurement systems that are fast, robust, standardized/traceable, and operate in real-time/in-line; for example, a system for monitoring a production roll-to-roll process continuously without stopping the process, with thickness measurements precise to 1 nm in 100 nm, and defect detection and classification down to 100 nm x 100 nm at a throughput of 10 m<sup>2</sup>/s.
- 8-year – Development and benchmarking of measurement systems and methodologies with industrial partners to allow transfer of measurement technology.

## **Agency Roles and Contributions**

The challenges of realizing a sustainable nanomanufacturing economy are significant, and our goals can only be met through a concerted interagency effort that addresses scientific and technological challenges spanning several disciplines.

Some of the most impressive examples of self-assembled complexity and functionality bridging nano- to macro-scales are in the biological world, and a critical challenge is to understand the basic principles that govern assembly in this realm (where NSF and NIH play key roles in this initiative), so that they can be adapted and applied to the high-throughput creation and integration of nanostructures (i.e., roles played by NSF, DOE, and NIST in this initiative). Similarly, basic scientific questions about the interplay of thermodynamics and kinetics in nanoscale assembly processes must be addressed to understand the fundamental physical limits of scalability and manufacturing error rates at nanometer scales (NSF, NIST, and DOE roles).

True nanomanufacturing, as distinct from one-off demonstrations, will require characterization and standardization that enable the use of nanomaterials and components as building blocks in quality-controlled industrial processes (NIST role). Environmental, health, and safety considerations must be integrated at all levels of research and development through regulation and through basic research into the toxicity, long-term environmental impacts, and exposures of new, active nanomaterials (EPA, NIH, NIOSH, and OSHA roles). Finally, the sustainability of

manufacturing processes must be thoroughly understood from both scientific and practical standpoints (NIST, NSF, DOE, and EPA roles).

**Table 1. Agency Contributions by Thrust Area**

Thrust Area	NIST	NSF	EPA	NIH	DOE	OSHA & NIOSH
1. Design of scalable and sustainable nanomaterials, components, devices, and processes	•	•	•	•	•	•
2. Nanomanufacturing measurement technologies	•	•		•		•

- **NIST:** Develop data, standards and best practices metrology procedures and tools for quantifying the relevant characteristics of nanomaterials, structures and nanomanufacturing processes. (*Thrust Areas 1 and 2*)
- **NSF:** Develop fundamental science further to enable converting nanofabrication and nanoscale assembly processes into nanomanufacturing. (*Thrust Areas 1, and 2*)
- **EPA:** Develop the research, requirements, rules, and procedures for the safe and low-impact handling and use of nanomaterials across the lifecycle in collaboration with OSHA and NIOSH. (*Thrust Area 1*)
- **OSHA and NIOSH:** Develop the research, requirements, rules, and procedures for safe occupational handling and accurate occupational exposure measurement of nanomaterials across the life cycle in collaboration with EPA. (*Thrust Area 1 and 2*)
- **NIH:** Develop fundamental science further to harness assembly in the biological world for nanomanufacturing without toxicity or harmful environmental effects. (*Thrust Areas 1 and 2*)
- **DOE:** Develop the processes and materials that enable energy efficiency in nanomanufacturing. (*Thrust Areas 1 and 2*)
- **USDA and Forest Service:** Develop manufacturing technology, characterization techniques, life cycle and sustainability data, applications research and stimulate the organization of multi-industry consortium on using cellulose nanomaterials technology. (*Thrust Area 1*).

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