Report to the National Science Foundation on

The Workshop for a Future Nanotechnology Infrastructure Support Program

Held August 18-19, 2014 at the Westin Arlington Gateway Hotel, Arlington, VA

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Introduction

The National Nanotechnology Initiative (NNI) 2014 Strategic Plan emphasizes that it is essential for the United States to sustain a dynamic infrastructure and toolset to advance nanotechnology. The National Science Foundation is in the process of planning a future nanotechnology infrastructure support program that will succeed the National Nanotechnology Infrastructure Network (NNIN). Over the past decade, NNIN facilities have supported users from academia, small and large companies, and government with open access to leading-edge fabrication and characterization tools, instrumentation, and expertise within all disciplines of nanoscale science, engineering, and technology. The Foundation did not go forward with an award in the competition that closed earlier this year for a Next Generation NNIN. NSF then sought input from the science and engineering community on a possible successor program through a Dear Colleague Letter (DCL 14-68) released on May 2, 2014, and received responses from over 90 faculty, student, company, and entrepreneur individuals.

As the next step in the planning process, The Nanoelectronics Research Initiative (NRI) of the Semiconductor Research Corporation (SRC) proposed to organize an NSF Workshop for a Future Nanotechnology Infrastructure Support program. The workshop was held on August 18-19, 2014 at the Westin Arlington Gateway Hotel in Arlington, VA. Key portions of the Workshop were made available to remote participants via web conferencing. Dr. Thomas Theis (IBM Research, on assignment to Semiconductor Research Corporation as Executive Director, SRC Nanoelectronics Research Initiative) led the effort. Prof. Mark Tuominen (University of Massachusetts, Amherst) served as co-chair with Dr. Theis.

The workshop convened recognized national experts to develop a vision of how a future nanotechnology infrastructure support program could be structured and what the key needs for the broad user communities are likely to be over the coming decade. The Workshop discussions benefited from many of the thoughtful community responses to the DCL.

This report outlines the needs, the opportunities, and the vision for a future Nanotechnology Infrastructure Support program, as developed by workshop participants. It is provided to NSF to assist in planning future programs for nanotechnology infrastructure development.

Commission to Workshop Participants

The goal of the workshop was to develop and articulate a vision for a Future Nanotechnology Infrastructure Support program that advances science, technology and education by enabling the research and technical development communities to bring key opportunities of nanotechnology to fruition. Workshop participants were charged with the following primary objectives:

1. Identify the key goals of a nanotechnology infrastructure program and recommend ways that these goals can be best achieved.
2. Identify the key needs of the user community and how these needs are expected to evolve over the next ten years
3. Develop recommendations for the organization and coordination of facilities within the program, and recommend an appropriate selection process and selection criteria.
4. Identify the opportunities inherent in a nanotechnology infrastructure program for supporting education and outreach activities and study of the societal and ethical implications of nanotechnology, including issues of environment, health, and safety.

Workshop Agenda and Methodology

The workshop began with introductory remarks by NSF leaders and the workshop Chairs, and self-introductions by workshop participants. Dr. Theis then outlined the Commission to workshop participants. In order to ensure that all panelists were familiar with the current NSF-funded nanotechnology infrastructure support program, Cornell University Prof. Sandip Tiwari, a former director of the National Nanofabrication Infrastructure Network (NNIN) gave an overview of the funding model, metrics, and best practices of NNIN. For completeness, Prof. Emilio Mendez, SUNY Stony Brook and Director of the Center for Functional Nanomaterials at Brookhaven National Laboratory, gave an overview of the Department of Energy's Nanoscale Science Research Centers (NSRCs), including their mission and practices. The NSRCs are comprehensive User facilities available to the national and international communities to advance scientific and technical knowledge in nanoscale science."

The key methodology employed for the remainder of the workshop is evident from the Workshop Agenda. (See the Appendix.) Panelists were charged with answering two broad topical questions:

Topic 1: What are the key goals of a future nanotechnology infrastructure support program, and how should it be structured to achieve these goals?

Topic 2: What are the key needs of the user community, and how will these needs evolve over the next ten years?

Each major topic was elaborated and clarified by a list of sub-topical questions which were presented to all workshop panelists**.** Panelists were asked to suggest additional sub-topical questions to be addressed, and suggested additional questions were noted. Panelists were then divided into two breakout groups of equal size. Group 1 was charged with discussion of Topic 1, while Group 2 was charged with discussion of Topic 2. After each group had extensively discussed and developed consensus answers to the various questions under its assigned topic, the two groups took a break and then switched topics and continued their discussions. The next day, all workshop participants were brought together and representatives of each breakout group presented a concise summary of their group's conclusions regarding each Topic. After questions and discussion, the conclusions of each breakout group were presented side-by-side and examined and discussed by all. Conclusions under both Topic 1 and Topic 2 were found to generally agree or to represent complementary points of view. A number of clarifying questions were asked and discussed, but no major disagreements were noted between the conclusions of the two independent breakout groups.

The questions discussed by the breakout groups and the resulting consensus answers and related recommendations to NSF are found in the following section of this report.

Questions Posed to Workshop Participants and Key Conclusions from the Breakout Discussions

__Topic 1:__ What are the key goals of a future nanotechnology infrastructure support program, and how should it be structured to achieve these goals?

What are the most critical characteristics of a nanotechnology infrastructure support program, and what are possible options to the design of such a program?

Critical characteristics:

- The program should provide simple, broad, cost-effective access to a wide range of nanofabrication and associated characterization tools. The access should include thorough training and opportunities for students to learn and use the techniques and tools.
- Each facility or site should be built upon excellent local user research expertise, have superb staff dedicated to supporting both internal and external users, and enable users to plan and carry out experiments with a rapid cycle time. Site technical staff should be chosen with an understanding of the essential education, outreach, and workforce enhancement mission.
- The NSF should give strong consideration to sites that have strong regional influence – sites that can engage other local sites with specific expertise, such as already-funded centers (ERC, STC, MRSEC, etc.), other schools, community colleges, and K-12 outreach.
- Each site should include significant education, outreach and training activities that build on the research focus of the site. Examples include student training, cross-disciplinary workshops and industry professional development.
- It is important that the program be able to seed new ideas, respond to unanticipated discoveries (beyond 2015), and revise techniques and equipment to respond to exciting opportunities, thereby enabling progress into new frontiers.

Options for design of the program:

- Workshop participants expressed a preference for a federation of individually selected sites, rather than a group of sites that competed for selection as a team. Such a program could bring forth the best and timeliest capabilities that the U.S. has to offer. Effective network coordination, regardless of how the individual sites are selected, will provide synergistic value to the overall infrastructure program.
- RECOMMENDATION: Since this is a very different approach to the team-based competition that has characterized the previous network, if sites are to compete individually, NSF should provide clear guidelines in the solicitation on the expectations for each site. These include some discussion of how site effectiveness will be assessed and how user rates should be justified. Note that metrics for evaluating work force development and education activities should be distinct from metrics for evaluating research activities. Although NSF should

provide guidelines for the solicitation, the actual metrics should ultimately be developed and refined by the organizations forming the federation.

- RECOMMENDATION: The NSF should consider a hybrid program model that includes not only sites with widely used micro- and nanofabrication capabilities, but also some sites offering critical, highly specialized tools and processes, and supporting important emerging applications. The latter may be found at locations unable to provide the former. The careful selection of a few more-specialized sites could be a mechanism to promote:
    - Rapid evolution of aggregated capabilities through inclusion of emerging teams with critical and promising ideas in fabrication technology or in applications of that technology.
    - Broader capabilities through inclusion of complementary and increasingly important domains of fabrication such as bio-directed assembly of nanostructures, wet processing for biological and medical applications, atmospheric pressure gas-phase synthesis of nanoparticles, engineered nanomaterials, heterogeneous integration, nanoscale 3D printing, high-throughput processing techniques, and other possibilities.
    - Specialized support for important emerging disciplines or applications, such as the geological and environmental sciences.
    - Access to unique, valuable, and specialized characterization techniques linked to fabrication methods, perhaps provided as a service or by remote operation.
    - A broader geographic distribution of centers, although this should not be a primary criterion for selection. (See also the discussion following the question below, *"How important is a broad geographic distribution of facilities?"*)
- It is suggested that NSF hold streamlined annual reviews for each site to monitor progress and assist in development. More detailed reviews would be associated with the 5-year renewal.

What is the unique role that NSF can play in serving users from universities, small colleges, industry, including small companies and entrepreneurs, and government?

- The unique role of the NSF Nanotechnology Infrastructure Program is to facilitate broad access to nanofabrication and nanoscience facilities that many cannot otherwise afford.
- The facilities exist at academic institutions, thereby enabling easy access to academic users from institutions ranging from Research-I universities to community colleges. This environment also serves users from companies, some of whom are local and many who work closely with academic users, building productive interactions between industry, faculty, and students.
- The NSF program provides advanced capabilities to a very large user base – not only experts. The federation of future infrastructure sites should utilize the well-recognized brand of the NSF to do more to market the capabilities to new users. The federation of infrastructure sites should host a portal website, regularly

updated, so prospective users can easily find relevant capabilities and expertise. There would be an additional benefit for prospective users if this portal could also more broadly integrate or serve as a gateway to similar information from other potentially relevant sites, such as the DOE and NIST nanocenters, the National Nanomanufacturing Network, and the nanoHUB .

- NSF should require workforce development activities as part of the solicitation, but leave it up to proposers how this is best achieved. The educational programs that promise to have most success and build on the strengths of the site should be supported. Note that workforce development goes beyond activities such as outreach to community colleges. For example, training of students to use the tools and capabilities of the infrastructure is a *very* important part of workforce development. Overall, the panel suggests that the NSF reevaluate the 15% flat allocation for education and consider whether this is too large a commitment from very limited funds.

How should university user facilities be selected?

- Workshop participants expressed a preference for selection of individual sites, rather than selection of multi-site teams, but since this is a different approach to the team-based competition that has characterized the previous network, more guidance to the community is needed in preparing proposals (e.g. X proposals funded at roughly $Y/year will ultimately be selected).
- The NSF should first solicit white papers to limit the number of full proposals that are eventually submitted. In order to ensure the highest-quality proposals and best use of proposers' efforts, NSF should establish clear criteria for a competitive proposal. Strong proposals would demonstrate a track record in several of the following areas:
    1. Understanding and serving the needs of both internal and external users
    2. Managing a shared user facility.
    3. Having a rich local (in-house) research community connected to the facility.
    4. Having a site accessible to a broad user base.
    5. Having experience in process integration (or strong commitment to learn).
    6. Having broad capabilities in nanofabrication and/or deep expertise in a complementary focused fabrication domain (such as nanomanufacturing, bio-directed synthesis and assembly, engineered nanomaterials synthesis, heterogeneous integration, nanoscale 3D printing, etc.) and/or specialized capability to support an emerging application domain (such as geological sciences, environmental sciences, energy and environmental technologies, life sciences and medicine, etc.).
    7. Providing excellent and efficient workforce development and outreach activities.
- A proposal could focus on capabilities in a specific thematic area (even involving multiple partner sites). If a proposing site presents a timely critical idea, but

lacks sufficient experience, NSF could encourage pursuit of a planning or seed grant to allow demonstration of the idea. Successfully demonstrated ideas could be become part of the infrastructure program.

- RECOMMENDATION: NSF should consider two-track funding: one level of funding for experienced teams (single or multiple sites) running a facility with comprehensive capabilities; and another level for emerging teams with critical new ideas (target equipment or technology, for example wet/bio) and are judged to have good prospects.

Should there be a facility or organization that coordinates user services across the various other facilities. If so, how should it function, and how should it be selected?

- There needs to be some coordination across the various facilities, as it will add real value to the operations of the federated sites. Effective coordination will enable the program to be greater than the sum of its parts – a system. Participation in coordination activities should be required of all sites.
- The solicitation should give some indication on what is expected from a network coordinator and some idea of the expected network coordination budget. Sites should identify in the proposal if they want to be considered as candidates to be the coordinating site.
- The coordinating site should facilitate the administrative functions of coordination and lead the other centers in building consensus regarding common goals and plans. Common goals would include development of people and capabilities through site-to-site interactions, dissemination of best practices, growth of the user base, development and collection of efficient and fair metrics for assessment, external visibility, development of high quality educational outreach materials, and more.
- RECOMMENDATION: After selection of individual sites, the federation of selected sites should confer and subsequently recommend to NSF one (or more) choices of a suitable network coordinator or coordination team. NSF would make the final decision.
- The coordination activity should include a portal website: to assist users in finding the most suitable site and contact; to serve the user and PI community through communications about capabilities, access and special events and opportunities; to collect data and simplify reporting, reviews and assessment; to provide information to educate the user community as well as the general public.
- Methods for common evaluation should be employed when possible to demonstrate collective impact. The coordinating site should lead the development and facilitate the administration of common goals and metrics by the federated sites.
- The IGERT model of coordination is an attractive model that the NSF should consider: the IGERT website promotes all of the IGERTs, helps students find an IGERT that is a good fit, shares best practices, and helps to promote the IGERT program as a whole. The mandatory IGERT leader's meetings promoted valuable learning, coordination, and connections between people. Other models

for coordination include NSF ERCs (annual meetings, website, best practices manual), DOE nanocenters and user facilities (user meetings), DOE EFRC (newsletters, annual meetings).

Should each user facility be part of a rich research culture at its site? Should the coordinating facility or organization be similarly connected?

- Each user facility should be part of a rich research culture. Proposers should be encouraged to show the depth of their research culture, as it is critical to the success of their site, especially in the area where the site is concentrating.
- The coordinating facility should be a practitioner -- one of the selected infrastructure sites. In addition, the coordinating site will require dedicated staff to support a high-quality operation, including, for example, staff with some subject matter expertise, digital librarianship expertise, and information technology expertise for the website portal.

How important is a broad geographic distribution of facilities?

- Both geographic distribution and size of facilities should be considered explicitly by review panel(s) and NSF.
- Geographic location is important, but not essential; proposing sites should highlight how they support a rich regional user base.
- Broad accessibility is an important asset and strong proposals will discuss the accessibility of the site. Accessibility is a more important and practical criterion for selection than geographic location, since distance traveled by users of the facility is less important than the time, cost, and effort of getting to the facility by any preferred means of transportation.

Should some smaller facilities be selected, based for example on geographic location or competency in a specialized area?

- Geographic location and competency in a specialized area should be considered, but research depth and accessibility should also be considered.
- Smaller facilities may be attractive for their specialized capabilities or strength in emerging application areas.

What are the relations to nanotechnology infrastructure available from other sources? Should coordination be sought with NIST and DOE nanoscale facilities, and how would such coordination be enabled?

- A strong proposal should demonstrate how its site complements and perhaps connects to other local resources (business incubators, prototype & manufacturing facilities, community colleges, etc.).
- Proposals for infrastructure sites may consider possible synergies with other facilities, including those funded by DOE, NIST, and NSF. The solicitation should

ask proposers to consider other existing infrastructure and how these existing capabilities can be leveraged.

- The coordinating site should take a lead in coordination of efforts with NIST, DOE, etc.
- A portal website developed and maintained by the coordinating site could provide useful comparisons. At a minimum, a simple table could be displayed, listing characteristics of the DOE, NSF and NIST facilities: how they work, what capabilities they have, where they are located and opportunities for funding.

***Topic 2*: What are the key needs of the user community, and how will these needs evolve over the next ten years?**

What key capabilities in user facilities are needed? How diverse should these capabilities be?

Key capabilities of the federated sites

- Many of the federated sites will provide excellent clean rooms equipped with the common tools and processes for fabrication and characterization developed by and for the microelectronics industry. The tools will include standard lithographic tools, including electron beam lithography, for patterning over large areas with nanoscale precision, standard deposition and etching tools and processes for metals, semiconductors, and insulators, and appropriate characterization tools for feedback control of fabrication processes. The success of this basic micro- and nanofabrication platform is evident: universities continue to start and then support the requisite (expensive) facilities because they meet the needs of a growing, multidisciplinary user community.
- Support for biological, geological and environmental nanoscience and technology may demand unique characterization tools and fabrication processes that do not require a clean room environment.
- The federated sites will, by specialization at selected sites, collectively offer diverse fabrication and characterization capabilities (see below) to support a wider range of disciplinary studies and exploration and development of a broader scope of potential applications of nanotechnology than can be supported by the above-described common tools and processes.
- The federated sites will collectively offer the services of staff with excellent communication and education skills, a deep knowledge of process integration, and expertise in less-well-represented disciplines. Each site will draw from a deep well of disciplinary expertise and research culture at its home institution, so that the federated sites can *in toto* offer truly world-class capability to guide prospective users in solving their problems.
- The federated sites will, by geographic distribution and by mission, be collectively capable of serving a large and diversified base of users, including PIs and students from other universities, researchers from large and small companies, and entrepreneurs.

Diversity of capabilities:

- Emerging opportunities in heterogeneous materials may demand addition of new tools for nanoscale printing, milling, or stamping of 3D structures, perhaps on flexible substrates and over large areas.
- Applications in life sciences and environmental studies may benefit from one or more facilities strongly supporting soft material fabrication techniques and 'wet' operations, including characterization steps. Separate rooms or facilities may be required for 'hard' and 'soft' fabrication steps. Single step, gas phase synthesis routes to produce well-characterized nanomaterials may also be an important support facility for these applications.

- Applications in areas such as energy conversion and storage may benefit from the capability in one or more facilities to experiment with roll-to-roll fabrication processes.
- Given foreseeable funding constraints, the cost of leading edge tools, and the primary mission for the envisioned infrastructure, characterization tools should be aimed primarily at feedback control of fabrication processes. In other words, most characterization should be an integral part of the core fabrication mission. However, support for some disciplines may demand unique characterization tools and other capabilities.
  RECOMMENDATION**:** NSF should *not* support investment under this new infrastructure program in capabilities (such as aberration-corrected electron microscopy) that are very expensive and available from other sources.
  RECOMMENDATION: NSF *should* support the acquisition of newly developed and *affordable* fabrication tools that may catalyze new discoveries and development. For example, consider new tools and instruments for nanoscale 3D patterning and printing (e.g., Nanoscribe, Swiss Litho) or biomimetic patterning, for fabrication of new materials and structures, and for broader integration capabilities.

Evolution of needs and capabilities:

- The infrastructure should be flexible enough to respond to new opportunities *as they emerge.* Capabilities may evolve over the next ten years in at least two ways:
  1. Adding new and emerging capabilities to 'basic' nodes – capabilities which are of interest to users and which appear ready for shared use.
  2. Creating specialized nodes to explore and lead the new direction.
- To accommodate emerging needs such as the assembly of functionally heterogeneous nanoelectronic systems, or emerging opportunities, such as the fabrication possibilities offered by synthetic biology, facilities should strive to
  1. Understand what new tools sets might be needed.
  2. Understand the knowledge base and methods needed.
  3. Focus on involving talented staff with appropriate expertise – personnel with a full understanding of a particular discipline and broad ability to communicate with and train others.

What are the most promising new research opportunities that could be enabled by such capabilities?

- Some very promising research opportunities include:
  - Formation of new heterogeneous materials, engineered at the nanoscale to integrate formerly disparate electronic, photonic, mechanical, and thermal properties, for functions such as energy conversion and storage, dissipation of heat, precision sensing and local actuation. The broad potential applications include healthcare and medicine, and environmental monitoring and remediation.
  - Demonstration of new architectures for nano-electromechanical systems (NEMS) including integration of such heterogeneous materials.

- Bio-inspired materials, including self-healing, responsive materials and nano-bio hybrid materials.
  - Structures and devices supporting research in the life sciences and bio-medical applications.
  - Sensors for environmental science and monitoring.
  - Nanomaterials, such as catalysts for environmental remediation; and other environmental technologies.
  - New, more energy-efficient devices and circuits for communication, storage and processing of digital information, including spintronic devices, photonic devices, and devices for quantum information processing.
  - Devices and circuits for new information processing architectures such as neuromorphic computing.

How do we establish interdisciplinary methods that will enable users to explore new integration processes for tomorrow's complex nanosystems?

- Leverage the knowledge of a community of users with expertise in the integration of diverse materials
- Adopt a diverse infrastructure model: some sites need to have broad and deep integration experience and willingness to educate other member sites. Other sites may offer niche expertise with little or no integration experience. All must be willing to learn from each other.

How can we be more inclusive of less-well-represented user communities in biosciences, geosciences, and environmental sciences, and of emerging technology platforms evolving from nanoscale science and engineering?

- Try to achieve a multi-site profile that includes staff with deep knowledge of process integration and staff with expertise in less-well-represented disciplines. This will require concomitant research depth at the appropriate institutions. *People with expertise are at least as important as the tool sets.*
- Extend infrastructure capabilities by hiring and developing staff with expertise in identifying alternative resources for specific needs (e.g. imaging techniques for biological applications, specialized fabrication processes for biomedical and environmental applications).
- Develop and publicize clear plans to make facilities available to users in new and emerging application areas.

What are the unmet needs for state-of-the-art tools including computational models and tools?

- Some examples of unmet needs for state-of-the-art fabrication tools include emerging tools for nanoscale 3D printing and patterning, and tools that enable the advancement of roll-to-roll processing and other high speed processes

envisioned for nanomanufacturing.
- Given foreseeable funding, the program should *not* support development or purchase of the most expensive “state-of-the-art” tools for fabrication and characterization. Purchase or development of computational models and tools should be aimed at fabrication processes and characterization. Tools for modeling material properties or device characteristics should be provided by users, perhaps through Nanohub or by partnering with computation centers.

What are the barriers to user access, such as geographic proximity, user fees, travel, etc.?

- Access should be a top priority. The infrastructure program provides a valuable service to the nation, so making facilities and training as accessible as possible, to as many users as possible, should be an overarching goal. Improving "access" means increasing the number of external academic and industrial people coming to be trained and accomplish projects. Further, it means having satisfied customers.
- The biggest barrier to access may be lack of knowledge by potential users of what is available and how to gain access. User workshops at infrastructure sites effectively lower this barrier. It is therefore recommended that NSF build incentives into the program to encourage hosting and user participation in workshops. Anecdotal evidence, as well as the distribution of travel distances for users of various facilities, suggests that poor accessibility becomes a significant impediment when the travel distance necessitates overnight lodging and associated costs. Thus, it is desirable that the basic micro- and nanofabrication platform be strategically replicated geographically. Travel distance may be a less important issue when the provided capability is unique and highly valuable to a subset of potential users.
- User fees were not mentioned as a significant roadblock by workshop panelists or by respondents to NSF’s call for public comment.

What is the importance of such a program to student education, training, and outreach?

- In his workshop presentation, Prof. Sandip Tiwari made the point that over 4800 graduate students have used NNIN, suggesting that NNIN supported roughly a quarter of all the engineering and science Ph.D. degrees minted during its operation. NSF should aim for similar or greater impact from the new infrastructure program.
- The infrastructure program greatly improves job prospects for students, building highly relevant skills and preparing them to “speak the language” when they walk onto the job. Even the necessary user training is a vital educational effort and one that can be extended to community colleges. The program therefore has a profound influence on workforce development.
- Outreach activities should be closely related to each site’s core mission, whether

administered by the site itself or by a national coordinating site.

- RECOMMENDATIONS:
  - Exploit the diversity of the envisioned multi-site infrastructure, allowing sites the flexibility to propose and develop different education programs (e.g., RET, REU), but requiring all to participate in workforce development and outreach in some form.
  - Hire appropriate staff to support students in education and workforce development.

Should there be a coordinated education program? Should there be a coordinated society and ethics program?

- There should be a coordinated education program. It will help in the dissemination of best practices, curriculum development, data collection and recruitment.
- RECOMMENDATION: Make one person, associated with the coordinating site, responsible for assessment and coordination of educational efforts across all of the federated sites. Leverage the multi-site infrastructure through modules shared between sites, so that staff at each site can become familiar with the material and conduct appropriate outreach activities and promote research opportunities in societal implications and ethics.
- Some workshop participants felt that while discussions of societal impact tend toward discussions of toxicity and environmental impact, the infrastructure program may provide broad opportunities for social science research because of the special, if not unique, collaborative and convergent academic, commercial and governmental participants, agendas, and interests. How do these practitioners work together, and how does the 21st century innovation ecosystem really work?

What are the recommended best practices, and what performance metrics are needed? What staff expertise will be crucial in satisfying user needs?

- Recommended best practices and staffing include:
  - Provide strong incentives to staff to focus on “external” users, particularly prospective and new users.
  - Strive to recruit and retain staff with a broad understanding of nanofabrication, good communication skills, and grounding in a relevant discipline or area of expertise
  - Consistently administer and focus on the results of user surveys, safety training and the process for bringing in new users.
- A general approach to metrics that may be helpful is to carefully and accurately determine what "success looks like" for all key stakeholders, then develop and deploy those metrics (and only those metrics) that correspond to real success.
- Each site should establish key metrics for their facility that include, but extend beyond mere satisfaction. While consistently administered surveys are one tool,

they should not be the only mechanism used to generate data. The types of information solicited should reflect the many variables relevant to the theme of each site as well as the consensus over best practices in the field.

- Some easily obtained and meaningful metrics for the federated sites (and used by NNIN) include the sum of annual user fees and its ratio to annual NSF funding, the number of new users per year, the distribution of distances these users traveled to gain site access, and the distribution of these users among academia, small companies, large companies, etc. Many more metrics can be listed. Consultation regarding metrics with NNIN participants, with their extensive knowledge base, is recommended.
- In general, NSF should encourage creative approaches to new metrics, and reward sites that develop metrics that are particularly effective.

Summary of Workshop Conclusions

The focus of the current nanotechnology infrastructure support program, NNIN, is providing support for nanofabrication. It has successfully leveraged tools developed primarily by the semiconductor industry to enable research in an extremely wide range of disciplines. Workshop contributors generally agreed that the program has imparted valuable job-specific skills to students, supported vital research in various disciplines of science and engineering, and has enabled hundreds of entrepreneurs, start-ups, and small companies to explore new product ideas. It has substantially leveraged its funding, to make enormous contributions to national industrial competitiveness.

The diffusion of lithographic patterning and related subtractive and additive manufacturing processes from the semiconductor industry, the continued rapid progress in chemical synthetic processes operating on macromolecular scales and above, and the increasing hybridization of these approaches is continually expanding the range of what can be fabricated and ultimately manufactured. Therefore, any Future Nanotechnology Infrastructure Support program should continue to offer access to standard semiconductor and thin film fabrication and characterization tools and processes, as well as more specialized tools that address the needs of established user communities in application areas such as energy, environment, life sciences and geo-sciences. *In addition, the program should have institutional mechanisms and the flexibility to quickly embrace and integrate new and emerging approaches to fabrication and characterization.*

The program should provide simple, broad, cost effective access to a wide range of nanofabrication and associated characterization tools as well as additional more specialized capabilities. The access should include thorough training and opportunities for students. Each facility should be an integral part of a rich local research culture. Each site should have superb staff dedicated to supporting external users, and enable users to plan and carry out experiments with a rapid cycle time. Site technical staff should be chosen with an understanding of the essential education/outreach and workforce enhancement mission. Outreach and education at each site should be tailored by the site to its core mission, but coordination of the education program across sites will aid in dissemination of best practices, curriculum development, and more.

The NSF should give strong consideration to sites that have strong regional influence, engaging other local sites with specific expertise, such as already funded centers (ERC, STC, MRSEC, etc.), other schools, community colleges, and K-12 outreach. Each site should include significant education, outreach and training activities that are synergistic with the research focus of the site. Examples include student training, cross-disciplinary workshops and industry professional development.

It is important that the program be able to seed new ideas, respond to unanticipated developments (beyond 2015), and revise techniques and equipment to respond to exciting opportunities, thereby enabling new frontiers. This is one reason why workshop participants expressed a preference for a federation of individually selected sites, rather than a group of sites that competed for selection as a team. While many of the federated sites will provide excellent clean rooms equipped with the common tools and processes for fabrication and characterization, NSF is urged to consider a hybrid program model that also includes some sites offering critical, highly specialized tools and processes, and supporting important emerging disciplines or applications. The complimentary capabilities of such an infrastructure would broaden the community of potential users and help to seed new capabilities in emerging areas of research and application.

Workshop participants felt strongly that if sites are selected individually, NSF should provide clear guidelines in the solicitation on expectations, such as how user rates should be justified, and how site effectiveness will be assessed. Although NSF should provide guidelines for the solicitation, the actual metrics should ultimately be developed and refined by the organizations forming the federation.

Effective coordination across sites, regardless of how the individual sites are selected, will provide value to the overall infrastructure program. Ideally, the coordinating facility should be a practitioner -- one of the selected infrastructure sites. The coordinating site or team should facilitate the administrative functions of coordination and lead the other centers in building consensus regarding common goals and plans – development of people and capabilities through site-to-site interactions, dissemination of best practices, metrics for assessment, a portal website, coordination of efforts with complimentary facilities such as those provided by NIST and DOE, and more. To promote teamwork, the newly selected sites should recommend to NSF a suitable coordinating site, although NSF should make the final decision.

Workshop participants generally agreed that such a program, properly managed, can rapidly integrate the best and timeliest capabilities in nanofabrication and characterization that the U.S. has to offer, and continue to expand the impact of the technology in diverse disciplines and in the development of new products.