Cellulose Nanomaterials— A Path Towards Commercialization Workshop Report

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The Forest Service also wishes to acknowledge the contributions of the workshop participants representing industry, academia, and government. A full list of participants can be found in Appendix A.

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Executive Summary

Cellulose nanomaterials are primarily isolated from trees and other organisms; are naturally occurring polymeric materials that have demonstrated great promise for commercial applications across an array of industrial sectors; are renewable and environmentally sustainable; and have the potential to be produced in large volumes (i.e., millions of tons per year). The commercialization of cellulose nanomaterials has the capacity to create hundreds of thousands of direct and indirect jobs, particularly in rural America. The United States is currently in a good position to become a leading global source of commercial cellulose nanomaterials innovation, production, and use.

A National Challenge

Despite great market potential, commercialization of cellulose nanomaterials in the United States is moving slowly. In contrast, foreign research, development, and deployment (RD&D) of cellulose nanomaterials has received significant governmental support through investments and coordination. U.S. RD&D activities have received much less government support and instead have relied on public-private partnerships and private sector investment. Without additional action to increase government investments and coordination, the United States could miss the window of opportunity for global leadership and end up being an "also ran" that has to import cellulose nanomaterials and products made by incorporating cellulose nanomaterials. If this happens, significant economic and social benefits would be lost. Accelerated commercialization for both the production and application of cellulose nanomaterials in a wide array of products is a critical national challenge.

A Market-Driven Approach

The U.S. Department of Agriculture (USDA), in collaboration with the U.S. National Nanotechnology Initiative (NNI), organized the Cellulose Nanomaterials Commercialization Workshop held on May 20–21, 2014, in Washington, DC. This workshop brought together a wide range of experts representing industry, academia, and government in an effort to strengthen cross-sector partnerships and ensure that future RD&D efforts are informed by market needs. The workshop generated market-driven input in three areas: Opportunities for Commercialization, Barriers to Commercialization, and Research and Development (R&D) Roles and Priorities.

Opportunities for Commercialization

The workshop identified numerous commercial opportunities for cellulose nanomaterials to meet a wide range of end-use needs and to help address key policy agendas such as advanced manufacturing, accelerated technology transfer, energy efficiency, and rural economic development. Commercial applications discussed at the workshop included such diverse areas as automotive components, aerospace applications, electronics, cosmetic applications, food packaging, specialty paper, and polymer reinforcement. This potential is both a blessing and a curse for accelerating commercialization. With finite resources, the multitude of options could easily dilute focus. Hence, it is important to identify those opportunities that can provide the initial market pull to have the most robust impact, enabling initial large-scale manufacturing and paving the way for the development of other higher value applications.

Barriers to Commercialization

Within the context of the workshop, barriers to commercialization represented the key "problems" to be solved. Clarifying the problems to be solved is a precursor to identifying solutions. The workshop identified critical barriers that are slowing commercialization. These barriers included lack of collaboration among potential producers and users; coordination of efforts among government, industry, and academia; lack of characterization and standards for cellulose nanomaterials; the need for greater market pull; and the need to overcome processing technical challenges related to cellulose nanomaterials dewatering and dispersion. While significant, these barriers are not insurmountable as long as the underlying technical challenges are properly addressed. With the right focus and sufficient resources, R&D should be able to overcome these key identified barriers. Achieving the focus and the resources will require collaboration of industry, government, and research as well as prudent investment of R&D funds.

R&D Roles and Priorities

The discussion of R&D roles and priorities represented a shift in focus from key problems to "solutions." Given the market-driven orientation of the workshop, the discussion of R&D roles and priorities included both general needs and specific technical challenges that need to be addressed and provided important and valuable input to future R&D efforts. At the more general level, key themes revolved around demonstration and scale-up and improvement of the manufacturing process in order to achieve the best balance of cost and performance. In addition, collaboration between the public and private sectors is seen as having a significant role in supporting R&D. At a more specific level, the workshop discussions identified key technical barriers that will help to establish targets for R&D initiatives.

Path Forward

The workshop generated input that will be used to inform the USDA Forest Service's R&D planning for cellulose nanomaterials and future directions of the NNI's Nanomanufacturing Signature Initiative. With the market-driven focus of the workshop, the results build on and advance past efforts to explore the market potential of cellulose nanomaterial applications by identifying R&D thrusts that will help enable commercialization. From the workshop results, it is clear that, with the proper focus and resources, R&D advancements will provide a critical stimulus to accelerate commercialization of cellulose nanomaterials.

1. Introduction

Cellulose nanomaterials have demonstrated potential applications in a wide array of industrial sectors, including electronics, construction, packaging, food, energy, health care, automotive, and defense. Cellulose nanomaterials are projected to be less expensive than many other nanomaterials and, among other characteristics, tout an impressive strength-to-weight ratio (Erickson 2012, 26). The theoretical strength-to-weight performance offered by cellulose nanomaterials are unmatched by current technology (NIST 2008, 17). Furthermore, cellulose nanomaterials have proven to have major environmental benefits because they are recyclable, biodegradable, and produced from renewable resources.

The commercialization of cellulose nanomaterials in the United States has the potential to create hundreds of thousands of direct and indirect jobs and, in particular, would strongly benefit rural America (Erickson 2014, 26). In addition, the United States possesses the resources and the infrastructure to support a large cellulose nanomaterials industry. However, the commercialization process needs to be accelerated in order to get cellulose nanomaterials into applications that can create strong market pull and support the growth of the cellulose nanomaterials industry.

To accelerate the commercialization of cellulose nanomaterials, the U.S. Department of Agriculture - Forest Service (USDA-FS), in collaboration with the National Nanotechnology Initiative (NNI), held a workshop titled "Cellulose Nanomaterials – A Path Towards Commercialization" on May 20–21, 2014, at the USDA Patriot Plaza III in Washington, DC. This workshop brought together a wide range of experts representing industry, academia, and government sectors to explore opportunities for commercialization, identify technical barriers, and provide input to USDA-FS Research and Development (R&D) about potential areas of R&D needed to address the key technical barriers to commercialization. Although the workshop included technical experts, the intent was to engage a broader audience in a cross-sector dialogue and adopt a market-driven approach to ensure that future R&D efforts would be informed by market needs.

Structure of this Report

The purpose of this report is to summarize the workshop results and present the major conclusions to inform and guide USDA-FS and NNI planning and investments aimed at expediting the commercialization of cellulose nanomaterials. The next chapter presents an overview of cellulose nanomaterials: the background, the potential of the materials, and the current state of technology and applications in the United States.
Chapter 3 provides a rationale for the workshop's five panels and for the three areas of focus: commercialization opportunities, barriers and challenges, and R&D roles and priorities. Chapters 4–6 provide an overview of the major themes and some specific comments derived from participant input. Chapter 7 presents reflections on the path forward.

2. Cellulose Nanomaterials

Overview of Cellulose Nanomaterials

Cellulose nanomaterials are nanoscale materials isolated from trees, other plants, and algae or generated by bacteria and tunicates (Erickson 2014, 26). Different raw material sources, as well as different production methods, will lead to cellulose nanomaterials with differing morphology and properties, such as length, aspect ratio, branching, and crystallinity (Ireland, Jones, Moon, Wegner, and Nieh 2014, 4). With respect to commercialization, two major categories of cellulose nanomaterials have received the greatest interest: cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs). Cellulose nanocrystals and cellulose nanofibrils are obtained from wood pulp or other cellulose sources by two contrasting methods. For example, cellulose nanocrystals are produced by acid hydrolysis of wood fiber or other cellulosic materials. The process produces rod-like nanoscale materials that are 3–20 nm wide and 50–500 nm in length (Moon and Walker 2012, 34). Alternatively, cellulose nanofibrils are produced using mechanical processes with or without chemical (e.g., 2,2,6,6-tetramethylpiperidine-1-oxyl, or TEMPO) and biological (e.g., enzyme) treatments to produce fibril-like nanoscale materials. CNFs are 4–50 nm wide, longer than 500 nm in length, and can be single strands or branched (Moon and Walker 2012, 34). The range of cellulose nanomaterial morphologies and properties supports a variety of potential applications across multiple industries.

Cellulose is the most abundant organic polymer on earth. It can be found in plant cell walls together with other renewable polymers such as lignin and hemicellulose. Trees produce cellulose from atmospheric carbon dioxide and water with solar energy through photosynthesis. Products made from cellulose will store the atmospheric carbon throughout their service until the end of life.

Potential Applications

Cellulose nanomaterials could lead to many novel applications and products. All forms of cellulose nanomaterials are lightweight, strong, and stiff. CNCs possess photonic and piezoelectric properties, while CNFs can provide very stable hydrogels and aerogels. In addition, cellulose nanomaterials have low materials cost potential compared to other competing materials and, in their unmodified state, have so far shown few environmental, health, and safety (EHS) concerns (Ireland, Jones, Moon, Wegner, and Nieh 2014, 6). Currently, cellulose nanomaterials have demonstrated great potential for use in many areas, including aerogels, oil drilling additives, paints, coatings, adhesives, cement, food additives, lightweight packaging materials, paper, health care products, tissue scaffolding, lightweight vehicle armor, space technology, and automotive parts. Hence, cellulose nanomaterials have the potential to positively impact numerous industries.

An important attribute of cellulose nanomaterials is that they are derived from renewable and broadly available resources (i.e., plant, animal, bacterial, and algal biomass). They are biodegradable and bring recyclability to products that contain them. For example, CNC and CNF could be coupled with polylactic acid (PLA) to provide a fully biologically sourced and biodegradable fiber-reinforced composite, and incorporation of biodegradable cellulose nanomaterials allows for the production of recyclable electronics. Hence, cellulose nanomaterials may reduce environmental impacts by enabling post-consumer disposability and recyclability of many products. Cellulose nanomaterials sequester carbon and can be a substitute for fossil fuel-derived products in various applications. Therefore, the potential environmental benefits of producing and using cellulose nanomaterials are substantial.

Current State of Technology and Application

Up to now, the United States has invested resources to understand and develop applications of cellulose nanomaterials and has developed technologies and pilot-scale capacity to manufacture them. The United States currently possesses about 751 million acres of forests, 44% of which are managed by federal, state, or local governments (Erickson 2014, 27). The forest products industry procures wood from forests and converts it to large quantities of lumber, wood composites, pulp, and paper products. The infrastructure is already in place to support large-scale production of cellulose nanomaterials from forests (Ireland, Jones, Moon, Wegner, and Nieh 2014, 8). The current economic decline and shrinking markets for business- and publication-grade papers have created excess production capacity for facilities in several U.S. regions. Successful development of cellulose nanomaterial-enabled products would provide stressed production facilities with an emerging product that can bring them back to profitability and provide a substantial boost to rural economies.

Commercialization of cellulose nanomaterials could profoundly benefit the U.S. economy. In his opening remarks at the workshop, Thomas Kalil, Deputy Director for Technology and Innovation at the White House Office of Science and Technology Policy, pointed to a study estimating that commercializing cellulose nanomaterials for the paper industry alone could yield as many as 425,000 new direct and indirect jobs in the United States by 2020 (Erickson 2014, 26). USDA Deputy Undersecretary Arthur (Butch) Blazer also mentioned the importance of cellulosic nanomaterials to creating jobs and improving the economy in rural America in his opening remarks. Considering the numerous applications for cellulose nanomaterials in other sectors, the potential for job creation is enormous.

However, commercialization of cellulose nanomaterials in the United States has been moving slowly. Since 2009, the USDA Forest Service has invested around $20 million in cellulose nanomaterials R&D, a small fraction of the $680 million spent on cellulose nanomaterials R&D by governments worldwide (Erickson 2014, 26). In order to remain globally competitive, accelerated research, development, and commercialization of cellulose nanomaterials in the United States is imperative. Otherwise, the manufacturing of cellulose nanomaterials and cellulose nanomaterial-enabled products will be established by foreign producers, and the United States will be purchasing these materials from other countries. Establishing a large-scale production of cellulose nanomaterials in the United States is critical for creating new uses from wood—which is, in turn, vital to the future of forest management and the livelihood of landowners.

Need to Accelerate Commercialization

To respond to the very substantive and coordinated investments being made by industry, government, and academia in foreign countries, there is an urgent need for identifying and developing solutions to overcome the key technical barriers and challenges that are hindering the speed of cellulose nanomaterials commercialization in the United States. The intent of this workshop was to help address this need by identifying major barriers, analyzing the areas of greatest opportunities, and pinpointing areas where R&D could best benefit cellulose nanomaterials commercialization.

3. Workshop Structure

Introduction

Commercialization is necessary for the full potential and impact of cellulose nanomaterials to be realized. However, the translational process to commercialization is an arduous one. In order to successfully accelerate the commercialization of cellulose nanomaterials, it is important to utilize a market-based approach. This workshop was structured to consider perspectives from several industry sectors in order to identify opportunities, challenges, and research and development (R&D) priorities for commercialization.

The Commercialization Challenge

The focus of the workshop was based on the recognition of the urgency for action for our Nation to benefit from the commercialization for cellulose nanomaterials. To date, most efforts within the United States have been on foundational and proof-of-concept research—technology readiness levels (TRLs) 1–3. Significant emphasis also needs to be placed on translational R&D in order to move the technology forward into commercialization. Particular focus on the transition through what is typically referred to as the "valley of death" (TRLs 4–7) is vital. The valley of death refers to the stages at which there is a high probability that a startup technology will fail prior to achieving significant market penetration. Therefore, the most efficient and timely use of resources would be to allow market needs to guide the development of the technology going forward. This does not exclude the need to invest in additional foundational research, but all R&D, including foundational R&D, should be driven by market needs in order for cellulose nanomaterials to cross the valley of death, achieve successful and timely commercial operation, and keep the United States competitive in the global marketplace.

The U.S. National Nanotechnology Initiative (NNI) was launched in 2001. The Forest Service is one the 20 Federal departments and independent agencies participating in the NNI. Expert inputs from this FS-NNI Cellulose Nanomaterials workshop will inform Forest Service research, NNI Signature Initiatives, and other major Presidential initiatives such as the National Network for Manufacturing Innovation.

Workshop Participants

Because the commercialization challenge requires collaboration across numerous sectors, the workshop participants included more than 130 experts representing various industries, academia, and government organizations (see Appendix A). This diversity allowed for a greater understanding of the market needs and potential across a variety of industry sectors.

The Five Panel Areas

Within the workshop, there were five different panels: Federal; Large Volume User; Paper, Packaging, Food & Beverage; Specialty Applications; and Manufacturing. Additional input came in the form of discussions during facilitated breakout sessions that were held on the second day of the workshop, organized according to the same topics as the panel sessions with the exception of the Federal panel (see the workshop agenda in Appendix C). These panels and breakout sessions were designed to capture a variety of market-based perspectives from users, producers, and government. The Federal panel represented the federal government perspective. This perspective encompassed multiple broad mission areas of the government, including R&D and regulatory agencies as well as agencies that often serve as early adopters (end users) of new technology (e.g., the U.S. Department of Defense [DOD] and the National Aeronautics and Space Administration [NASA]).

The remaining four panels with their respective breakout sessions focused on a more limited market perspective. The Large Volume User; Specialty Applications; and Paper, Packaging, Food & Beverage panels were designed to represent the end-user perspective. The Specialty Applications panel focused on high-end uses, an area where functionality is more important than price. Alternatively, the Large Volume User panel focused more on the scale of production and price reduction. The Paper, Packaging, Food & Beverage panel represented a significant sector with large volume that is further along than some other sectors in the commercialization process. Understanding these different user perspectives is crucial for creating market pull for the material, opening up pathways to commercialization, and prioritizing R&D efforts. Finally, the Manufacturing panel represented the producers, those interested in making the material. Hence, the five panels enabled the workshop to view cellulose nanomaterials markets from a variety of angles along the value chain.

Opportunities, Barriers & Challenges, and R&D Roles & Priorities

In order to tackle the commercialization issue with a market-based approach, the workshop prompted the participants to first think about potential opportunities for the commercialization of cellulose nanomaterials, then to acknowledge the challenges and barriers to commercialization relative to the identified market opportunities, and finally to identify what can be done to address those barriers, particularly the role of R&D. In this way, the workshop was able to investigate a large number of ideas from a market-driven perspective.

The following three chapters summarize the participants' responses in regards to these three concepts (commercial opportunities, technical challenges, and R&D priorities). Their input was derived both from open discussions during the panel sessions and breakouts and from worksheets that were handed out during the sessions in order to capture input from individuals who did not speak during the discussions. This ensured that all possible feedback was gathered from participants.

In some cases, participants offered input that was very specific to their panel area; however, there were also some significant themes frequently referenced at multiple panels. The next three chapters address both the reoccurring key themes and the panel-specific comments for each of the three concept areas.

4. Commercial Opportunities

Introduction

A market-based approach begins by looking at the potential applications that could create commercial opportunities. In essence, the identification of commercial opportunities helps define the end state toward which commercialization efforts are aiming.

Nanotechnology is the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. At this scale, materials can exhibit unusual physical, chemical, and biological properties.

Key Themes

The most common themes to emerge across the panels and breakout sessions regarding the commercial opportunities for cellulose nanomaterials included the following application areas: Automotive, Aerospace, Construction, Electronics, Cosmetics, Coatings and Paint, Food Packaging, Paperboard and Packaging, Specialty Paper, and Composites and Polymer Reinforcement. Specifically, stakeholders at the workshop focused on the following:

- **Automotive Applications/Markets**: Market opportunities include cellulose nanomaterial-enabled composites and surface coatings to be incorporated into the body components and interiors of automobiles. For automobile body components, the market is based on the potential of cellulose nanomaterial composites and materials to reduce weight without reducing strength. For interiors, the benefit of cellulose nanomaterials is in improving surface resistance to abrasions, improving appearance, allowing tunable appearance, and light-weighting. The application of cellulose nanomaterials also improves the recyclability of automobile components and increases the portion of the automobile that is made from sustainable materials.
- **Aerospace Applications/Markets**: Market opportunities within the aerospace market are similar to those of the automotive market. Cellulose nanomaterial-enabled components may be incorporated into aircraft and satellites. For aircraft, the applications could include interior panels, trays, and seats. For satellites, the application is for wiring and housing materials. The market opportunity is based on cellulose nanomaterials' potential impact on light-weighting as well as on improving dimensional stability and even thermal resistance of materials.
- **Construction Applications/Markets**: Market opportunities include use of cellulose nanomaterial-enabled composites, surface coatings, and additives in wallboard, wood-based structural components, insulation, and cement or concrete. For wallboard and other structural components, the opportunity would be based on the ability of cellulose nanomaterials to improve strength-to-weight ratios and add water resistance. For insulation, cellulose nanomaterial aerogels would provide a thinner and more breathable insulation material. Cellulose nanomaterials may also be used to reinforce cement to increase toughness and durability.

- **Electronics**: Market opportunities in the electronics industry include the potential for cellulose nanomaterial-enabled composites and materials to be used as substrates in flexible electronics, in housings, and even in some electronic components. This market opportunity is enhanced by the ability of cellulose nanomaterials to enable a more sustainable and environmentally friendly disposal of used or obsolete products, either through recycling or improved biodegradability.

- **Cosmetics Applications/Markets**: Market opportunities in cosmetics include use of cellulose nanomaterial additives as emulsifiers, hydrating agents, or rheology modifiers. The market opportunity benefits from the non-toxic and nonallergenic nature of cellulose nanomaterials.

- **Coatings/Paint**: Market opportunities include the use of cellulose nanomaterials as additives to improve the properties of paints and coatings such as varnishes and urethanes. This market opportunity is based on the ability of cellulose nanomaterials to serve as rheology modifiers to affect viscosity and application characteristics such as dripping, splattering, sagging, and coverage. Cellulose nanomaterials can also improve finish durability and provide ultra-violet light (UV) protection.

- **Food Packaging**: Market opportunities in food packaging include the use of cellulose nanomaterial coatings and materials as barriers and/or as sensors. This opportunity benefits from the ability of cellulose nanomaterial packaging to provide a vapor barrier that improves freshness and reduces odor. In addition, cellulose nanomaterials possess piezoelectric properties and can be surface-modified to act as a sensor to indicate the condition of the packaged contents (e.g., spoiled).

- **Paperboard/Packaging**: Market opportunities include use of cellulose nanomaterials in coatings or as fillers in paperboard manufacturing. The opportunity comes from the potential of cellulose nanomaterials to improve strength-to-weight ratios and allow for lighter-weight end products. As coatings, cellulose nanomaterials can improve the dry and wet strength of paperboard.

- **Specialty Paper**: Market opportunities include use of cellulose nanomaterials in surface applications and fillers. The use of cellulose nanomaterials can improve the product's surface properties such as smoothness and printability. Cellulose nanomaterials also can improve strength and reduce the basis weight (grammage) of the finished product. The use of cellulose nanomaterials may also reduce production costs.

- **Composites/Polymer Reinforcement**: Market opportunities exist for cellulose nanomaterials to serve as composite or polymer reinforcements. In this market, the cellulose nanomaterials provide a range of possible value-adding characteristics, including improved strength, light-weighting, shape memory, and water absorbency. Cellulose nanomaterials can substitute for petroleum-based additives and thus increase the sustainability of composite materials. Cellulose nanomaterials also can improve the biodegradability of the material. Cellulose nanomaterials have the potential to enable the development of new composite materials with new value-added properties.

- **Others of note**: Other market opportunities include the *oil and gas industry,* where cellulose nanomaterials could be used in both drilling and in oil spillage cleanup; the *food products industry,* where cellulose nanomaterials could serve as a fillers; and *health care,* where cellulose nanomaterials could be used for tissue scaffolding, wound healing, or as a delivery mechanism for medication.

Beyond these common themes, each panel discussion generated a number of additional ideas and comments about the commercial applications and market opportunities for cellulose nanomaterials. These are presented in Table 1 on the next page.

Current State of the Dialogue

One of the most important insights derived from both the dialogue at the workshop sessions and the questionnaire input was the breadth of possible applications and commercial opportunities. Cellulose nanomaterials have the potential to add value to a wide variety of products across a wide range of industries. They have the potential to displace non-renewable materials with ones that have a sustainable source and are more environmentally friendly. While this vast potential is encouraging, it also creates an impediment to commercialization. In the introduction to this section, opportunities were said to define the end state for commercialization efforts. Defining the destination should help focus the journey; however, the breadth of potential applications for cellulose nanomaterials presents multiple end states and thus makes it difficult to establish focus. The lack of a focus can dilute the effectiveness of commercialization efforts and can cause resources to be spread too thin. To mitigate this lack of focus caused by the breadth of applications identified, it is important to look for issues, needs, and themes that are held in common across the various applications identified. The following two chapters outline a number of these common needs identified by the workshop participants.

Table 1: Panel-Specific Comments on Commercial Opportunities

Federal Panel Discussion	Large Volume User Panel Discussion	Paper, Packaging, Food & Beverage Panel Discussion	Specialty Applications Panel Discussion	Manufacturing Panel Discussion
▪ Energy storage systems ▪ Size-exclusion filters ▪ High-temperature applications in elastomers ▪ Period cellular structural materials and structural ballistic glasses ▪ Cosmeceuticals—cosmetics with pharmaceutical or medical benefits, such as improved moisturizers ▪ Rheology modification for high-temperature applications ▪ Sensors and biosensors ▪ Security printing ▪ High-performance functional materials ▪ Hygiene products	▪ Renewable materials for meeting sustainability standards ▪ Environmentally "safe" actuators ▪ Personal care products that require low toxicity and that are renewable ▪ Low-cost reinforcements as fillers or fibers ▪ Additive in drilling fluids for the oil and gas industry ▪ Hydrogels ▪ Aerogels ▪ Absorbents/diapers ▪ Laminate and sheet applications ▪ Viscosity modifiers ▪ CNC use in 3-D printing ▪ CNF in commodity products, but CNC likely in specialty products	▪ Food additives to stabilize emulsions, modify viscosity, and enable tunable texture ▪ Cholesterol-lowering food additives as in bacterial cellulose and potentially enhancing taste ▪ Thixotropic additives ▪ Fiber-based packaging ▪ Tamperproof packaging ▪ Light-weighting in carbonated bottles ▪ Reinforced polyethylene terephthalate (PET) composites for bottles (i.e., cellulose nanomaterial reinforcement) ▪ Rheological modifiers for processing and appearance ▪ Biodegradable packaging ▪ Insulation materials for food and beverage ▪ Embedded sensors	▪ Reinforcing hydrophobic systems ▪ Biological scaffolding as used in tissue engineering ▪ Dielectrics in ultra-capacitors ▪ Sensors based on piezoelectric properties of cellulose nanomaterials—fluorescent and dosimetric detection ▪ Absorbency of cellulose nanomaterials for use in personal care products ▪ Health monitoring based on flexible electronics ▪ Functional materials harnessing dielectric and piezoelectric properties ▪ Scratch-resistant coatings ▪ Functionalized cellulose for EMI shielding ▪ Renewable energy storage—large-surface-area capacitors, batteries with high power density ▪ Oil-absorbing gels ▪ Nano/hydrogel foams	▪ Electronic substrates for integrated circuits, etc. ▪ Oil and gas recovery; increasing oil-spill clean-up efficiency ▪ Aerogel insulation for buildings ▪ Wound healing applications such as wound healing membranes ▪ Replacement for petroleum-based products ▪ Smart structural materials that combine piezoelectric properties with good mechanical strength ▪ Adhesives ▪ Water treatment ▪ Medical/pharma

5. Challenges and Barriers

Introduction

In addition to identifying opportunities, stakeholders participating in the workshop considered the barriers and technical challenges to commercialization of cellulose nanomaterials. The challenges and barriers represent the "problems" to be solved in the commercialization of cellulose nanomaterials. The challenges and barriers provide a more concrete context for looking at the potential role of and priorities for R&D.

Key Themes

The major themes to emerge across the panels were similar to those identified in the R&D section: the need for characterization and standards, production and processing methods; the need for better understanding of potential impact on environmental, health, and safety (EHS) issues; the need for market pull and cost/benefit analysis; and the challenge of dewatering cellulose nanomaterials; and technical readiness. Specifically, workshop participants identified the following technical challenges facing commercialization of cellulose nanomaterials:

- **Need for Characterization and Standards**: In order for a new material to be adopted for use, it must be well understood and end users must have confidence that the material is the same from one batch to the next. There is a need to better characterize cellulose nanomaterials with respect to their structure, surface properties, and performance. Development of new characterization methods, especially with respect to *in situ* measurements, may be required. Standard methods and materials also need to be developed to enable reproducibility and comparison with existing materials. End users need to be able to run cost/benefit comparisons of cellulose nanomaterials with respect to existing materials and calculate the return on investment (ROI) for switching to cellulose nanomaterials.

According to The Technological Association of the Pulp and Paper Industry (TAPPI), scientists at the ITT Rayonier Eastern Research Division discovered microfibrillated cellulose (known as cellulose nanofibril today) by running a 3% slurry of chopped pulp fibers through a milk homogenizer. As ITT Rayonier gave free license to its patents to pulp customers, research organizations in Europe, Canada, Japan, and the United States continued to research CNC and CNF for a broad range of applications.

- **Production and Processing Methods**: Commercialization is inhibited by the lack of processing and production methods and know-how for ensuring uniform, reliable, and cost-effective production of cellulose nanomaterials, especially at large volumes. This is both a scale-up and a process control issue. Commercialization of cellulose nanomaterials into large volume markets will require order-of-magnitude increases in production capacity to ensure supply and lower costs. This level of production capacity has not been demonstrated, nor is large-scale process equipment available. There is also a need for better process control capability to ensure quality, including nanoscale measurement and manipulation capabilities. A more streamlined and uniform production process would lower the cost of manufacturing cellulose nanomaterials and make them more competitive in the market.

- **Need for More Complete EHS Information**: Limited EHS information creates a significant barrier to commercialization because any uncertainty regarding material safety and the pending regulatory environment presents risk for early movers across all industries. Currently, there are limited data available regarding the EHS impact of cellulose nanomaterials, especially in the food, medical, and pharmaceutical industries.

- **Need for Market Pull and Cost/Benefit Performance**: As noted earlier, cellulose nanomaterials have potential applications in a wide range of areas, but there is no single need that is driving their commercial development. Stakeholders suggested several reasons, including lack of awareness of the material and its properties and a need for better market understanding. Commercialization will require market pull in order to incentivize manufacturers, yet there is no perceptible demand for cellulose nanomaterials at the moment. In addition, many potential users will require large quantities of material with well-defined properties at a known cost beyond near-term production capabilities. Producers currently do not have reliable information about the cost structure of the materials. Ultimately, a robust discussion between researchers, producers, and potential customers regarding what cellulose nanomaterials can do, what industry needs, and the cost/benefit ratio associated with each needs to be conducted. Public-private partnerships can play a significant role in facilitating this information exchange.

- **Challenge of Dewatering/Drying**: One of the most significant technical challenges identified is the dewatering of cellulose nanomaterials into a dry and usable form for incorporation into other materials. The lack of an energy-efficient, cost-effective drying process inhibits commercialization of cellulose nanomaterials, particularly for non-aqueous applications. Cellulose nanomaterials in low-concentration aqueous suspensions raise resource and transportation costs, which make them less viable commercially.

- **Technology Readiness**: Technology readiness is a major challenge in the adoption of cellulose nanomaterials. One obstacle in developing a market for cellulose nanomaterials is the lack of information on the basic properties of different types of cellulose nanomaterials, as noted in the characterization and standards discussion. There is also a lack of understanding of the performance of cellulose nanomaterials in their application environment. Furthermore, work is needed to improve the understanding of the surface properties of cellulose nanomaterials, including how to functionalize surfaces appropriately to improve their compatibility with matrix resins in composites and with aqueous and non-aqueous solvents. The need for thermal stability in manufacturing processes involving thermoplastic polymers (e.g., nylon and PET) is another example of a performance challenge in an application environment.

Beyond these common themes, the panel discussions and breakout sessions generated a number of additional ideas and comments about the technical barriers to commercialization. These are presented in Table 2 on the next page. It should be noted that participants were asked to consider more general barriers to commercialization and identify the most significant ones for each market area. The results confirmed some of the key differences between the markets. For example, price/economics was identified as the most significant barrier in large volume applications but was behind material functionality, technology readiness, market awareness, and market acceptance for the specialty products area. For manufacturing and production of cellulose nanomaterials, price and material functionality were the most significant issues.

Summary of Challenges and Barriers

The broad themes of the challenges identified by the stakeholders are indicative of their knowledge of the cellulose nanomaterials industry. The stakeholder input from the viewpoint of potential cellulose nanomaterials users included both technical and more general market-level challenges similar to those associated with most nascent technology industries. While their comments were helpful in identifying the most important themes and in giving a good sense of priority, it is clear that more detailed discussions within the USDA Forest Service and the National Nanotechnology Initiative (NNI) are needed to take this input and convert it into specific activities and actions. By working with its formal and informal partners, the USDA Forest Service is well positioned to accomplish this, especially from a science and technology perspective, with its participation in the NNI; its interactions with other federal departments and agencies; its involvement in public-private partnerships such as P^{3}Nano; its interactions with industry through entities such as the Agenda 2020 Technology Alliance; and its interactions with academia.

Table 2: Panel-Specific Comments on Barriers

Federal Panel Discussion	Large Volume User Panel Discussion	Paper, Packaging, Food & Beverage Panel Discussion	Specialty Applications Panel Discussion	Manufacturing Panel Discussion
▪ Cellulose nanomaterials have limitations (e.g., thermal stability) that prevent simple substitutional comparison with other nanomaterials. ▪ High-performance composites. Achieving the performance potential of DW materials in a composite is then the critical technical challenge. ▪ Lack of know-how in using these materials in macro-structural elements ▪ For polymer-fiber composites, the barrier is the water absorption of the cellulose fibers. ▪ Dispersion of cellulose nanomaterials in different applications/compatibility ▪ Need a focused program of work ▪ Availability of materials for startups ▪ Availability of materials at a cost-effective level ▪ Funding for small businesses to get ideas of R&D into production ▪ Level of funding in the United States vs. the rest of the world ▪ High-margin exorbitant pricing of cellulose nanomaterials; pricing index ▪ Process/purification, recovery drying ▪ Materials property database	▪ Having the correct surface chemistry for non-aqueous applications ▪ Dispersion is key for strength. ▪ Understanding and controlling self-assembly of cellulose nanomaterials ▪ Lack of demonstration of macrostructures ▪ Retaining the benefits of cellulose nanomaterial reinforcement in composites ▪ Putting cellulose nanomaterials in engineered polymers such as nylons ▪ Sustainability/lifetime of materials ▪ Recyclability ▪ Lack of focus in R&D efforts ▪ Removal of contaminants ▪ Availability of feedstock ▪ Need for production cost analysis or price point for a specific application to work toward ▪ Interface stability ▪ Structure/property relationships ▪ Scale-up of acid hydrolysis method with respect to cost and disposal ▪ Reliability/reproducibility	▪ Ability of the product to be combined with other materials ▪ The use of enzyme-immobilized cellulose nanomaterials for use in food packaging to improve anti-spoiling properties ▪ Stability and integrity of cellulose nanomaterials in packaging material ▪ Irreversible bonding of CNF upon drying ▪ Lack of application-focused R&D, including antibacterial, freshness, and exploring new uses ▪ How the materials may impact flavor ▪ Food—application work ▪ Barrier film performance under wet conditions/hydrophobicity ▪ Functionalizing the cellulose nanomaterials to be hydrophobic ▪ Applications of CNF/CNC in/on paper/packaging—retention coatings (on coating or size process) ▪ The ability to coat CNC or CNF effectively on paper (very low solids/high viscosity); application methods ▪ Product form and surface chemistry are important for polymeric packaging. ▪ Controlling interface between PET/polymer and cellulose nanomaterials ▪ Surface energy measurements for public databases ▪ Regulatory and consumer acceptance	▪ Technical challenges are to interface this technology with applications including biomedical point of care, etc. ▪ Providing CNC/CNF in a dry, re-dispersible form that can be handled by the end users ▪ Low-cost hydrophobic treatment to incorporate in hydrophobic polymers ▪ Dealing with the hydrophobicity of cellulose nanomaterials ▪ Compatibility with non-aqueous resin systems ▪ Improving surface compatibility with suitable resins to attain high strength/modulus; need to demonstrate ↑ stiffness/weight ratio ▪ CNC or CNF surface modification for combining with polymers ▪ High-gloss finish ▪ Dispersion in a broad range of materials ▪ Can CNC/CNF be used in PET polymer as an additive? ▪ What is the effect of CNC/CNF on haze/color of clear PET polymer? ▪ Impact on PET recycling will need to be assessed. ▪ Lack of feedstock and consistent supply for manufacturing ▪ Barriers to entry in established markets (autos, aircraft, and electronics)	▪ Lack of characterization of size and shape ▪ Compatibility with resin in composites ▪ Microelectronics—both electronic and cellulose nanomaterial substrate ▪ Lack of product development—medical/etc. ▪ Hydrophobizing/surface modification ▪ Lack of feedstock and consistent supply for manufacturing ▪ Regulatory uncertainty ▪ Process and quality control for large volume applications ▪ Functionalization ▪ Large-scale vs. distributed production ▪ Drying/redispersion ▪ Need for Materials Safety Data Sheets ▪ Throughput ▪ Desired specifications

6. R&D Roles and Priorities

Introduction

Whereas challenges and barriers represent the problems to be solved in the commercialization of cellulose nanomaterials, the R&D roles and priorities represent potential solutions.

Key Themes

The most common themes to emerge across the panels and breakouts regarding the role of R&D in future cellulose nanomaterial activities included the following: environmental, health, and safety (EHS) research; collaboration; demonstration and scale-up; process and manufacturing innovation; drying and dewatering; characterization and development of standards; dispersion; performance cost/benefit demonstration; and application innovation. Specific points of discussion by stakeholders at the workshop for each of these themes are summarized below:

- **EHS Research**: Additional research is required to understand the potential implications of cellulose nanomaterials on human health and the environment across the product lifecycle. Research foci should include as-manufactured materials as well as those with modification or functionalization that may change their toxicology. As scientific understanding of the EHS behavior of cellulose nanomaterials matures, standards in the EHS area and Materials Safety Data Sheets (MSDSs) should be developed to ensure environmental protection and human safety.

- **Collaboration**: Participants identified collaboration as a key need to accelerate commercialization of cellulose nanomaterials. Public-private partnerships help facilitate communication and leverage resources. Cross-sector dialogues help to inform users about the material properties and functionalities of cellulose nanomaterials and at the same time help researchers understand the properties and functionalities they need to expand in order to meet user needs. Partnerships and collaboration are essential to hone processing technologies, facilitate application innovation, and create more consistent funding opportunities for cellulose nanomaterials.

- **Demonstration and Scale-up**: To move beyond pilot-scale production requires demonstration and scale-up projects to develop the manufacturing processes to produce cellulose nanomaterials at full scale with the desired properties. Characterization and quality control instrumentation and techniques need to be developed to ensure consistent material production. Future demonstration and scale-up projects will involve the production of more complex materials or structures, such as composites, where cellulose nanomaterials are an additive.

- **Process and Manufacturing Innovation**: R&D is needed to develop innovations in process control to make consistent materials, reduce overall energy use to lower costs, vertically integrate manufacturing, and generally reduce production costs to achieve a price point that fosters broader market application and penetration.

- **Drying/Dewatering**: One of the most significant challenges identified, which impacts all potential application areas, is the need to remove the water from the cellulose nanomaterials to reduce shipping cost and enable compatibility with solvent-based systems. Research is needed to focus on how to remove the water from the system efficiently without destroying the nanoscale material properties or resulting in agglomeration.
- **Characterization/Development of Standards**: Further research is needed to fully characterize the structure and performance of cellulose nanomaterials, including both CNCs and CNFs as well as their surface-modified forms. Standard materials and methods need to be developed to ensure material properties are consistent. As understanding matures, materials performance sheets should be developed to communicate attributes with potential end users.
- **Dispersion**: R&D is needed to develop understanding and methods to enable dispersion of cellulose nanomaterials in the desired matrix material. The required surface modification may be matrix and/or application-specific and would benefit from strong interaction between the research community and end users.
- **Performance Cost/Benefit Demonstration and Analysis**: The advances in the research areas identified above should be utilized to develop cost/benefit demonstration and analysis. Market-specific research would help identify price targets for materials producers and enable calculation of return on investment. Performance-based analysis from advances in characterization and standards will enable end users to analyze the benefits of substituting cellulose nanomaterials for existing materials.
- **Application Innovation**: R&D could further commercialization by exploring high-value functional properties of cellulose nanomaterials and developing new applications for the materials. This type of translational R&D would be application-driven and focused on leveraging the functional properties of cellulose nanomaterials to discover new, value-added uses and expand understanding of the unique contribution that cellulose nanomaterials can provide in different applications. This area of research would require a more precise understanding and control of functional properties of cellulose nanomaterials. Initiatives could include the funding of a prototyping center, feasibility studies in collaboration with potential customers, and initial testing of new product performance for market sustainability.

Beyond these common themes, each panel discussion generated a number of additional ideas and comments about the role that R&D could play. These are presented in Table 3 on the next page.

Summary of R&D Priorities

The stakeholder comments included both technical and market-related research needs. Significant technical research priorities that will impact all potential application areas included dewatering, dispersion, characterization of properties and performance, standards, and EHS behavior.

Table 3: Panel Specific Ideas/Comments on R&D

Federal Panel Discussion	Large Volume User Panel Discussion	Paper, Packaging, Food & Beverage Panel Discussion	Specialty Applications Panel Discussion	Manufacturing Panel Discussion
▪ Wood fiber reinforcement ▪ Develop low-cost, effective hydrophobization treatment for high-surface-area cellulose nanomaterials ▪ Fund cellulose nanomaterial research on sensor development ▪ Need to explore how trees/plants can be manipulated to produce designer nanomaterials versus what nature provides ▪ Government-funded prototyping center available on for-fee basis	▪ Dispersion technologies ▪ Improve high-temperature performance ▪ Interfacing and stabilizing ▪ Large-scale manufacturing must be preceded by funding research for small pilot manufacturing. ▪ All these large-volume applications need non-precompetitive industry-based research and market development. ▪ Research data for durability, biodegradability, performance with varying humidity and temperature	▪ Looking at the immobilization of enzymes on cellulose nanomaterials and applying this to packaging for antimicrobial properties ▪ Control of hydrogen bonding, drying, and dewatering ▪ Control over water absorption on CNF/CNC surface; tuning hydrophilicity and oleophilicity ▪ Enabling coating of the low-concentration CNC/CNF without warping/shrinking the paper board product ▪ Controlling interface and stability through chemical modification/functionalization ▪ Food preservation to replace questionable chemicals ▪ Multivitamins, bread conditioners, and emulsifiers ▪ LCA is needed to justify CNC/CNF-enabled products ▪ Understanding interactions between cellulose nanomaterials and foods	▪ CNC or CNF without losing "nano" properties ▪ Comparison of CNC, CNF, and CF (cellulose filaments) ▪ Fund R&D for medical sensors used for point-of-care diagnostics ▪ Growth and manufacture of material ▪ Stability of material under temperature and water environments ▪ Technology advancement to prevent agglomeration of nanoparticles when dried. This limits strength performance in composites. ▪ Taking something hydrophilic and putting into hydrophobic applications will have some cost—is this a show stopper? ▪ Exploiting piezoelectric and optical properties ▪ Properties as a function of crystal structure, size, purity, aspect ratio, and structure ▪ Public outreach	▪ Disperse cellulose nanomaterial particles in resins ▪ New methods for generating CNC/CNF to provide greater stability ▪ Processing method that avoids water (stream, solvent) ▪ Surface adhesion between resin and cellulose nanomaterial particle ▪ Surface chemistry support for surface modification ▪ Surface modification of cellulose nanomaterials to improve adhesion ▪ Flexibility to adjust or adopt recommendations ▪ Funding to scale up products or of cellulose nanomaterial sheets for a wide range of applications ▪ Program to provide funding to companies that can move rapidly to market ▪ To produce nanotechnology-enabled products with effective cost

7. Path Forward

This workshop builds on past efforts to explore the market potential of cellulose nanomaterials applications and enable commercialization through R&D advancement. The specific focus of the workshop was to use a market-based approach to draw out input from a wide range of stakeholders and facilitate a collaborative dialogue across government, academia, and industry. The results of the workshop will be used to inform Forest Service R&D planning for cellulose nanomaterials and the broader National Nanotechnology Initiative (NNI) nanomanufacturing R&D activities.

In this regard, two points are worth noting. The first is in regard to the economics of cellulose nanomaterials. The theme of cost and cost structure came up repeatedly during the workshop dialogue. It is clear that more work needs to be done in this regard, especially given that uncertainty around the economics of cellulose nanomaterials impedes commercialization. However, it is also important to recognize that there are significant indicators for the economic viability of cellulose nanomaterials. In other words, it is reasonable for commercialization efforts to move forward with the expectation that cellulose nanomaterials will end up being abundant and affordable.

Second, the workshop dialogue raised the issue of awareness. In spite of all the efforts to this point, there remains a significant lack of awareness about what cellulose nanomaterials are, how they may be used, and the benefits that they can provide. In other words, awareness remains a significant barrier to commercialization. While awareness is not directly a technical R&D issue, the Forest Service and the NNI recognize that they have an important role to play in this regard. Going forward, the cellulose nanomaterials research agenda should include promoting market awareness of cellulose nanomaterials.

Appendix A. List of Participants

First Name	Last Name	Organization
Omar	Ali	Herty AMDC - Georgia Southern University
Jun	Amano	Konica Minolta Laboratory USA
Howard	Andres	Energetics Incorporated
Jewel	Beamon	National Nanotechnology Coordination Office
Yvonne	Beltzer	Freelance Journalist
Dean	Benjamin	NewPage Corp.
Cristina	Bilbao-Sainz	U.S. Department of Agriculture
Michael	Bilodeau	University of Maine
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Steven	Bloembergen	EcoSynthetix Corporation
Jean	Bouchard	FPInnovations
Rolf	Butters	National Institute of Standards Technology
Michell	Cahill	GL&V USA, Inc.
Richard	Canady	ILSI Research Foundation
Chris	Cannizzaro	U.S. Department of State
Altaf	Carim	Office of Science and Technology Policy
Bernard	Cathala	NANTES (France)
Hongda	Chen	U.S. Department of Agriculture, Forest Service
Bor-Sen	Chiou	U.S. Department of Agriculture
Fan-Li	Chou	U.S. Department of Agriculture
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Jed	Costanza	U.S. Food and Drug Administration
Daniel	Coughlin	ITECS
John	Cowie	Cowie & Company LLC
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Braz	Demuner	Fibria Celulose S.A.
D. Andrew	Dill	University of Georgia
Paul	Durocher	Sappi Fine Paper
Travis	Earles	Lockheed Martin
Adrienne	Eastlake	National Institute for Occupational Safety and Health
Cliff	Eberle	Oak Ridge National Laboratory

First Name	Last Name	Organization
J. Vincent	Edwards	Agricultural Research Service, Southern Regional Research Service
Britt	Erickson	Chemical & Engineering News
Martin	Fairbank	Resolute Forest Products
Celia	Feldpausch	Brazil Industries Coalition
Aaron	Forster	National Institute of Standards and Technology
Lisa	Friedersdorf	National Nanotechnology Coordination Office
Anne	Galyean	University of North Carolina at Chapel Hill
Charles	Gause	AxNano, LLC
Charles	Geraci	National Institute for Occupational Safety and Health
Marc	Gerrer	GL&V USA, Inc.
Jeffrey	Gilman	National Institute of Standards and Technology
Michael	Goergen	P³Nano
Gopal	Goyal	International Paper
David	Haldane	Innovatech Engineering
Fred	Hansen	Energetics Incorporated
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Mary	Kombolias	United States Government Printing Office
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Joyce	Lin	U.S. Food and Drug Administration
Joanne	Littlefair	U.S. Department of Commerce
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Martha	Marrapese	Keller and Heckman LLP

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Gloria	Oporto	West Virginia University
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Nicholas	Panaro	Leidos Biomedical Research
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Michael	Pannell	Occupational Safety and Health Administration
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Fritz	Paulsen	KapStone Paper & Packaging
Susan	Pell	American Association for the Advancement of Science
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Michael	Postek	National Institute of Standards and Technology
Girish	Ramakrishnan	Stony Brook University
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Orlando	Rojas	North Carolina State University
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Alan	Rudie	USDA Forest Products Laboratory
Sangmeshwar	Sangmule	Inland Label
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Gary	Senatore	Occupational Safety and Health Administration
Lewis	Shackford	GL&V USA, Inc.

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Amy	Shalom	USDA APHIS
Paul	Shapiro	U.S. Environmental Protection Agency
Jo Anne	Shatkin	Vireo Advisors, LLC
Dev	Shenoy	U.S. Department of Energy
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Meisha	Shofner	Georgia Institute of Technology
Manoj	Shukla	Army Engineer Research and Development Center
John	Simonsen	Oregon State University
David	Skuse	IMERYS
James	Snyder	Army Research Laboratory
Edward	Socci	PepsiCo
Qiong	Song	State University of New York, College of Environmental Science and Forestry
Erik	Svedberg	The National Academies
Daniel	Sweeney	Emergent Properties, LLC
Mehdi	Tajvidi	University of Maine
Yannick	Tamm	Energetics Incorporated
Clayton	Teague	Consultant
Treye	Thomas	Consumer Product Safety Commission
Jesyca	Turner	Innovatech Engineering
Nick	Viggiani	Rensselaer Polytechnic Institute
Jesko	von Windheim	Duke University
Greg	Weatherman	AeroSolver
Theodore	Wegner	U.S. Department of Agriculture, Forest Service
Cynthia	West	U.S. Department of Agriculture, National Institute of Food and Agriculture
Lloyd	Whitman	National Nanotechnology Coordination Office
Gloria	Wiens	Advanced Manufacturing National Program Office (AMNPO)
Hongli	Zhu	University of Maryland College Park

Appendix B. Workshop Organizers

Title	First Name	Last Name	Organization	Position
Dr.	World L.S.	Nieh**	USDA Forest Service, Washington Office	National Program Lead, Forest Products
Dr.	Lisa	Friedersdorf**	National Nanotechnology Coordination Office	Deputy Director
Dr.	Hongda	Chen	USDA National Institute for Food and Agriculture	National Program Leader, Bioprocess Engineering/Nanotechnology
Mr.	Michael	Goergen	U.S. Endowment for Forestry and Communities	Director, P^3Nano
Mr.	Sean	Ireland	Verson Paper Corp.	Manager, New Technologies and Market Ventures
Dr.	Sandeep	Kalkarni	PepsiCo	Technical Manager
Dr.	Michael	Meador	NASA Game Changing Development Program	Nanotechnology Project, Manager
Dr.	Theodore H.	Wegner	USDA Forest Service, Forest Products Laboratory	Assistant Director

** Co-Chair

Appendix C. Workshop Agenda

Cellulose Nanomaterials – A Path Towards Commercialization

May 20 -21, 2014

USDA Conference and Training Center,
Washington D.C.

Workshop Agenda

Tuesday, May 20, 2014	
8:00 am – 8:30 am	**Registration** Breakfast and Coffee
8:30 am - 8:45 am	**Welcoming Remarks** Mr. Arthur "Butch" Blazer, Deputy Under Secretary for Natural Resources and Environment, USDA
8:45 am – 9:15 am	**Opening Remarks – Day 1** Mr. Thomas Kalil, Deputy Director for Technology and Innovation, OSTP
9:15 am – 9:45 am	**Cellulose Nanomaterials – Technical State of the Art** Dr. Robert Moon, Materials Research Engineer, Forest Products Laboratory and IPST at Ga Tech
9:45 am – 10:00 am	**Charge to the Workshop** Dr. World Nieh, National Program Lead, Forest Products, USDA Forest Service
10:00 – 10:20 am	**Break**
10:20 am – 12:00 pm	**Federal Panel** Dr. Cynthia West, Associate Deputy Chief for R&D, USDA Forest Service Mr. Thomas Kalil, Deputy Director for Technology and Innovation, OSTP Dr. Dev Shenoy, Chief Engineer, AMO, EERE, DOE Dr. Michael Meador, Nanotechnology Program Manager, Game Changing Technology, NASA Glenn Research Center Dr. Charles Geraci, Coordinator, Nanotechnology Research Center, National Institute for Occupational Safety and Health Each Panelist will speak for 10 minutes followed by a facilitated Q&A and Open discussion

12 pm – 1:30 pm	**Lunch** Keynote: Revitalizing American Manufacturing Putting "&" Back into R&D Dr. Sridhar Kota, Herrick Professor of Engineering, Mechanical Engineering, University of Michigan
1:30 pm – 3:00 pm	**Large Volume User Panel** Mr. Travis Earles, Senior Manager, Advanced Materials & Nanotechnology Initiatives, Lockheed Martin Dr. Soydan Ozcan, Staff Scientist, Oak Ridge National Laboratory Dr. Orlando Rojas, Professor, Departments of Forest Biomaterials and Chemical & Biomolecular Engineering, North Carolina State University Each Panelist will speak for 10 minutes followed by a facilitated Q&A and Open discussion
3:00 pm – 3:20 pm	Break
3:20 pm – 4:50 pm	**Paper, Packaging, Food and Beverage Panel** Ms. Beth Cormier, Vice President for R&D and Technology, SAPPI Paper Dr. Ed Socci, Director of Beverage Packaging, PepsiCo Advanced Research Dr. Bernard Cathala, Group Leader of Nanostructured Assemblies and Deputy Director of the Biopolymer, Interaction and Assembly Unit, National Agronomical Research Institute, Nantes, France Each Panelist will speak for 10 minutes followed by a facilitated Q&A and Open discussion
4:50 pm – 5:00 pm	**Closing Remarks of the Day** Mr. Sean Ireland, Manager of New Technologies and Market Ventures, Verso Paper
5:00 pm	**Adjourn**

Wednesday, May 21, 2014				
8:00 am – 8:30 am	**Registration** Breakfast and Coffee			
8:30 am – 8:45 am	**Recap of Day 1 and Expectations for Day 2** Dr. Lisa Friedersdorf, Senior Scientist, NNCO			
8:45 am – 9:00 am	**Opening Remarks – Day 2** Dr. Altaf Carim, Assistant Director for Nanotechnology, OSTP			
9:00 am – 10:30 am	**Specialty Applications Panel** Dr. Zhenqiang "Jack" Ma, University of Wisconsin Dr. Cliff Eberle, Technical Development Manager, Carbon and Composites, ORNL Dr. Brian O'Connor, Program Manager – Environment, FPInnovations Each Panelist will speak for 10 minutes followed by a facilitated Q&A and Open discussion			
10:30 am – 10:45 am	**Break**			
10:45 am – 12:15 pm	**Challenges and Opportunities in Manufacturing Panel** Dr. Kim Nelson, Vice President for Government Affairs, API Mr. Jean Moreau, CEO, CelluForce Mr. Mike Bilodeau, Director, Process Development Center, University of Maine Mr. Yoram Shkedi, CEO, Melodea Each Panelist will speak for 10 minutes followed by a facilitated Q&A and Open discussion			
12:15 pm – 1:20 pm	**Lunch** Introduction to P³Nano Mr. Michael Goergen, Director, P³Nano			
1:20 pm – 1:30 pm	**Reconvene session, charge for breakout (Fred Hanson, Energetics)**			
1:30 pm – 3:30 pm Four breakouts in the same room	**Breakout 1: Large Volume Users**	**Breakout 2: Paper, Packaging and Food**	**Breakout 3: Specialty Applications**	**Breakout 4: Challenges and Opportunities in Manufacturing**
3:30 pm - 3:45 pm	Break			
3:45 pm – 4:30 pm	**Breakout Reports and Discussion** Dr. World Nieh, USDA Forest Service and Mr. Fred Hansen, Energetics			
4:30 pm – 4:45 pm	**Closing Remarks** Dr. Ted Wegner, Assistant Director, USDA Forest Service, Forest Products Laboratory			
4:45 pm	**Adjourn**			

Appendix D. Additional Resources

Workshop

1. Cellulose Nanomaterials: A Path Towards Commercialization Workshop. [Online] June 2014. www.nano.gov/ncworkshop.

National Nanotechnology Initiative

2. National Nanotechnology Initiative. [Online] www.nano.gov.

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19. **Fang, Zhiqiang, et al.** Novel nanostructured paper with ultrahigh transparency and ultrahigh haze for solar cells. *Nano Letters.* 2014, Vol. 14, 2, pp. 765–773.

20. **Pu, Yunqiao, et al.** Investigation into nanocellulosic versus acacia reinforced acrylic films. *Composites Part B: Engineering.* April 2007, Vol. 38, 3, pp. 360–366.

21. **Saito, Tsuguyuki, et al.** Individualization of nano-sized plant cellulose fibrils by direct surface carboxylation using TEMPO catalyst under neutral conditions. *Biomacromolecules.* 2009, Vol. 10, 7, pp. 1992–1996.

22. **Zhou, Yinhua, et al.** Recyclable organic solar cells on cellulose nanocrystal substrates. *Scientific Reports.* March 2013, 3:1536.

23. **Roco, Mihail C.** Environmentally responsible development of nanotechnology. *Environmental Science & Technology.* March 1, 2005, Vol. 39, 5, pp. 106A–112A.

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Appendix E. References

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