CNS-ASU Report #R08-0005

The Center for Nanotechnology in Society
ARIZONA STATE UNIVERSITY

Heldrich Center's Arizona Nanotechnology Workforce Report December 2008

The Workforce Needs of Companies Engaged in Nanotechnology Research in Arizona

Carl Van Horn
John J. Heldrich Center for Workforce Development
Rutgers, The State University of New Jersey

and

Aaron Fichtner
John J. Heldrich Center for Workforce Development
Rutgers, The State University of New Jersey

The Center for Nanotechnology in Society
Arizona State University

December 2008

This research was conducted as part of the Center for Nanotechnology in Society, Arizona State University (CNS-ASU). CNS-ASU research, education, and outreach activities are supported by the National Science Foundation under cooperative agreement #0531194.

REPORT SUMMARY

Nanotechnology, defined by the National Science Foundation as "research and technology development at the atomic, molecular or macromolecular levels, in the length of approximately 1 – 100 nanometer range," is widely predicted to have the potential to transform industries and scientific processes (National Science Foundation, 2000). By controlling and manipulating matter at the nanoscale, scientists are creating materials that have new properties, creating new building blocks such as carbon nanotubes, building microsensors that can be used in a variety of settings, and creating new microchips that are smaller and faster than ever before.

Nanotechnology has applications in a wide variety of scientific disciplines, including material science, electrical engineering, chemistry, physics, and biology, and as a result, has the potential to have a large impact on a broad range of industries such as biotechnology, microelectronics, and aerospace. New nanotechnology advances, however, depend on research scientists who have the skills and education necessary to work at the nanoscale. While much has been written on nanotechnology advances, the workforce and skill implications on nanotechnology are less understood, particularly in regional labor markets.

This report, based on interviews and input from more than 50 companies, educators, and other stakeholders in Phoenix and Tucson, Arizona, explores the effect that nanotechnology is having on the workforce needs of companies and educational institutions engaged in nanotechnology research in Arizona. By focusing this research on one region of the nation, researchers were able to interview a variety of individuals and stakeholders, and obtain an in-depth picture of a single labor market. Input for this study came from responses to an online inquiry, in-depth interviews with more than 25 individuals, and a progressive dialogue with educators and stakeholders in February 2008. Research was conducted in 2007 and during the winter of 2008.

<u>Findings</u>

Four key findings emerged from the research effort.

1. Given the dynamic nature of the industries and of technological advances, it is difficult for companies to anticipate their future use of nanotechnology.

> Most companies in Arizona that provided input for this study anticipated that they would increase their use of nanotechnology in the

future. They could not be specific about their future workforce needs, however.

2. Individuals interviewed report that researchers with advanced degrees in traditional disciplines possess much of the general knowledge and many of the skills necessary to learn the basics of nanotechnology research on the job.

While all acknowledged that nanotechnology research required a basic understanding of concepts at the nanoscale and of quantum effects, most individuals chose instead to stress the importance of on-the-job training for the skill and knowledge development of new research scientists. In fact, some individuals interviewed for this report said that they prefer to hire individuals with limited work experience and to provide them with informal on-the-job training through work in teams and through mentoring by senior scientists.

3. Employers consistently mention inter-disciplinary skills as an important skill for nanotechnology researchers, and an important skill deficiency.

Many nanotechnology advances involve the collaboration of researchers from different scientific disciplines. As a result, individuals working in nanotechnology research must have a basic knowledge of other scientific disciplines and be able to communicate effectively with other scientists.

4. While some employers in Arizona are concerned about the supply of workers with necessary interdisciplinary skills, others believe that the shortage of skilled workers will be temporary as educational institutions adjust to industry need.

Most companies providing input for this report concluded that their use of nanotechnology is likely to grow in coming years, increasing the demand for workers with the necessary interdisciplinary skills. Many expressed confidence that colleges and universities would make the appropriate modifications to their programs and curricula to ensure that new scientists were adequately prepared for new research opportunities.

Many individuals offered suggestions for ways in which educational institutions in Arizona could be more responsive to the needs of companies engaged in nanotechnology. Many of these suggestions centered on ways in which colleges and universities can continue to build closer connections to individuals in industry.

Focus of Future Research Efforts

In the summer and fall of 2008, researchers from the Heldrich Center will conduct additional research in the New York/New Jersey region and nationally to further explore the effect of nanotechnology on employer workforce and skill needs. In particular, research will be conducted to further explore two hypotheses generated from the research in Arizona.

> *Hypothesis 1.* Nanotechnology is having an evolutionary effect on the knowledge and skills needed of researchers.

> *Hypothesis 2.* The interdisciplinarity of nanotechnology research is having the most significant effect on knowledge and skill needs.

In the summer and fall of 2008, researchers will use case studies with biotechnology and pharmaceutical companies in New York and New Jersey to further explore the skill and workforce needs of nanotechnology research. In addition, researchers will use an online survey of educational institutions across the United States and follow-up interviews to map the nanotechnology education landscape and to explore the mechanisms by which educational institutions make decisions concerning related programs and curricula.

I. INTRODUCTION

Nanotechnology, defined as "research and technology development at the atomic, molecular or macromolecular levels, in the length of approximately 1 – 100 nanometer range," involves the control and manipulation of atoms and molecules (National Science Foundation, 2000). Scientists, working at the nanoscale, can create materials that have new properties, create new building blocks such as carbon nanotubes, build microsensors that can be used in a variety of settings, and create new microchips that are smaller and faster than ever before. Nanotechnology is not a scientific discipline and nanotechnology advances are not confined to any single industry. Instead, nanotechnology has applications in a wide variety of scientific disciplines, including material science, electrical engineering, chemistry, physics, and biology, and as a result has the potential to have a large impact on a broad range of industries such as consumer products, biotechnology, microelectronics, and aerospace.

During the past ten years, companies in a wide range of industries and university-based researchers in an ample variety of scientific disciplines have produced a rapidly increasing number of patents involving nanotechnology and written a rapidly increasing number of peer-reviewed articles on nanotechnology. In order for companies and educational researchers to fully realize the potential of nanotechnology, they must be able to hire research scientists who have the necessary skills and training to contribute to new research activities and assist in the development of new innovations. The Subcommittee on Nanoscale Science, Engineering, and Technology at the U.S. National Science and Technology Council has projected that the worldwide demand for nanotechnology workers will reach 2 million by 2015 (Roco & Bainbridge, 2001).

A number of specific research questions are suggested when considering workforce preparations to facilitate nanotechnology development. Will the demand for nanotechnology workers outpace the supply of qualified workers? What skills must researchers and scientists possess to take maximum advantage of the commercial potential of nanotechnology? What should educational institutions do in order to ensure that there is an adequate supply of researchers with the necessary nanotechnology skills?

There is some evidence that companies involved in nanotechnology research are concerned about their ability to find qualified workers with the necessary skills. In a 2004 online survey in Europe, nearly 50 percent of 720 respondents from the nanotechnology community predicted that European companies would experience a shortage of workers with appropriate nanotechnology training within the next five years. An additional 25 percent of respondents reported that European companies would have a shortage of such workers in 5 to 10 years (Malsch & Oud, 2004).

In the United States, some experts have predicted that the demand for skilled nanotechnology workers may exceed supply (Fonash, 2001). In addition, other experts have concluded that education and training may be inadequate in many regional labor markets (Pandya, 2001; Roco, 2003). More recent research suggests that these concerns may still hold true. For example, a study conducted by Lux Research (2007), found that 60 percent of the 26 companies they interviewed about their hiring plans, priorities, and preferences, reported that they had experienced a shortage of qualified nanotechnology workers. Studies such as this, combined with anecdotal evidence, have led some individuals to call for increased investment in education and training efforts in the United States to better prepare individuals to conduct nanotechnology research.

Government policy makers have recognized the need to create educational programs to train individuals for jobs in nanotechnology. The National Nanotechnology Initiative (NNI), an effort of the National Science Foundation, was launched in 2001 to promote and support the development of nanotechnology research in the United States. One of the primary missions of NNI is to ensure that the United States has a supply of qualified workers for nanotechnology and the U.S. educational institutions implement programs to build this skilled workforce (Roco, 2002). Through NNI, the U.S. government continues to fund the establishment of Research Centers and Networks of Excellence at universities and government research labs with the twin goals of encouraging nanotechnology research and education (National Nanotechnology Initiative, 2007). In addition, colleges and universities across the United States and abroad have taken steps to respond to the perceived need of companies using nanotechnology by creating new degree programs and modifying existing curricula.

II. Overview of the Report

Despite previous studies and government efforts, limited research has been conducted to explore the effect that nanotechnology is having on the skill and workforce needs of companies and educational institutions engaged in research. To better understand these issues, the John J. Heldrich Center for Workforce Development at Rutgers, The State University of New Jersey conducted a study of the workforce needs of companies and educational institutions involved in nanotechnology research in the Phoenix and Tucson metropolitan regions in Arizona. This study is part of a larger five-year study that is funded by the National Science Foundation as part of the Center for Nanotechnology in Society at Arizona State University.

By focusing the research effort on one region, researchers were able to speak with a variety of stakeholders involved in the same labor market in order to paint a more complete picture of the effect of nanotechnology on employer workforce and skill needs.

During 2007 and the winter of 2008, researchers obtained input from more than 50 companies, educators, and other stakeholders in Phoenix and Tucson, Arizona through an online inquiry, in-depth interviews with companies and stakeholders, and a progressive dialogue with educators and other stakeholders.

Online Inquiry: An online inquiry was used to collect information from employers engaged in nanotechnology research in Arizona about the effect that nanotechnology is having on their skill and workforce needs. Extensive efforts were made to encourage response to the inquiry from relevant individuals. A request to respond to the online inquiry was distributed to members of the Arizona Nanotechnology Cluster, a nonprofit organization active in promoting cross-industry cooperation and information sharing among companies involved in nanotechnology research, product development, and assembly. In 2007, there were approximately 90 members of the Arizona Nanotechnology Cluster. The Cluster hosts monthly information sharing sessions in both Tempe and Tucson and hosts an annual Nanotechnology Symposium. In addition, researchers sought the cooperation of a variety of stakeholders, including educational institutions, industry associations, and others, in identifying individuals in relevant industries in Arizona who might be interested in responding to the inquiry.

A total of 30 individuals responded to the online inquiry. The results of the online inquiry cannot be viewed as being representative of all companies and educational institutions engaged in nanotechnology research in Arizona. The results, however, when combined with other methodologies, serve to create a more complete picture of nanotechnology workforce issues in Arizona.

The 30 individuals who responded to the survey were employed by a diverse group of companies and educational institutions. Half of the respondents worked for employers with less than 25 employees. Seven of the 30 respondents worked for companies with more than 250 employees. Eight of the respondents were employed by microelectronics companies. An additional five respondents were employed by aerospace companies and one respondent was employed by a biotechnology company. The remaining 14 were employed by companies in other industries, which they did not identify. Two respondents were employed by university research centers that hire individuals to conduct nanotechnology research.

<u>In-Depth Interviews</u>: To supplement the online inquiry and to obtain more detailed information, researchers conducted more than 20 interviews with individuals engaged in nanotechnology research in Arizona. Individuals to be interviewed were identified through a variety of means. Researchers attended four separate functions of the Arizona Nanotechnology Cluster, including three monthly seminar meetings (two in Tempe, Arizona and one in Tucson, Arizona) and the 2007 Arizona Nanotechnology Symposium, and met individuals engaged in nanotechnology research. Second, researchers attended a monthly meeting of the Arizona Technology Council, a nonprofit industry association for technology companies, and also met individuals involved in nanotechnology research. Researchers also asked individuals who were interviewed to recommend additional individuals engaged in nanotechnology research. Finally, the online inquiry was used to identify individuals who completed the inquiry and were willing to be contacted for a follow-up interview.

Interviews were conducted with individuals from a variety of companies, including both small companies and large research companies. In addition, individuals were employed in all three key industries in Arizona engaged in nanotechnology research, including microelectronics, aerospace, and biotechnology.

<u>Progressive Dialogue with Educators and Stakeholders</u>: In February 2008, researchers convened a meeting of approximately 25 individuals with an interest in nanotechnology research to discuss preliminary results from the online inquiry and from the in-depth interviews. Researchers used a variety of

approaches to invite individuals to the progressive dialogue, which was held at Arizona State University. The Arizona Nanotechnology Cluster sent an email invitation to members. In addition, the Center for Nanotechnology in Society at Arizona State University invited all individuals on their email list from Arizona. Finally, Heldrich Center researchers invited all individuals who had responded to the online inquiry or who had been included in the in-depth interviews.

Participants in the progressive dialogue included faculty and graduate students from Arizona State University, staff of the Maricopa Community College system, staff from the state of Arizona and the city of Tempe, Arizona, and other interested individuals. During the dialogue, researchers presented preliminary results of the research and led a discussion of research questions generated by the online inquiry and the in-depth interviews.

III. BACKGROUND: NANOTECHNOLOGY IN ARIZONA

A review of labor market data, interviews with individuals in Arizona familiar with nanotechnology research in the region, and a review of patent and publication data complied by researchers at the Georgia Institute of Technology suggest that Arizona is a regional center for nanotechnology research, development, and commercialization, with a focus on three key industry sectors — biotechnology, aerospace, and microelectronics. While Arizona lags behind other regions of the nation in some measures of nanotechnology research, including the number of nanotechnology-related patents and articles, the state is home to companies, both large and small, engaged in nanotechnology research and two research universities with some nanotechnology research activity. The dynamic nature of nanotechnology and limitations of existing labor market data, however, make it difficult to estimate the current and future demand for scientists in nanotechnology.

A. Employment in Key Industry Sectors

The southern part of the state is home to significant employment in three key technology industries — biotechnology, aerospace, and microelectronics. Research facilities and labs in these three industries are located in the Phoenix and Tucson regions. In addition, the region is also home to production facilities in these industries as well. Each of these industries has a large presence in Arizona and has the potential for extensive work related to nanotechnology. In addition, interviews with members of Arizona's nanotechnology community indicate that these three industries cover much of the nanotechnology research in the state.

Biotechnology: Biotechnology firms engage in a wide variety of life science related activities, including the research, development, and production of pharmaceuticals and medical devices. In the biotechnology industry, nanotechnology can potentially be used to develop devices and processes that can be used to diagnose medical conditions and to more effectively treat illnesses (Abicht, Freikamp, & Schumann, 2006). Examples of nanotechnology in the biotechnology industry include the use of carbon nanotubes as highly sensitive electronic DNA detectors and the use of nanoparticles as MRI agents to help detect metastatic lesions with greater precision.

Arizona's 407 biotechnology firms play an important role in the state's economy, employing approximately 5,547 employees and supporting a large number of high-paying research and development jobs (Esher, 2005). The sector has grown in recent years as well, with five percent annual job growth between 2001 and 2003. The region also has two active industry cluster organizations, one headquartered in Phoenix and one headquartered in Tucson. The industry is concentrated in Maricopa County (Phoenix) (310 firms and 4,058 employees) with a small number of firms in Pima County (Tucson) (92 firms and 1,477 employees).

Aerospace: Aerospace firms are involved with developing, producing, and operating aircraft and aircraft support systems for both private-sector and military clients. Examples of possible use of nanotechnology in the aerospace industry include the use of nanofabricated materials to reduce size, weight, and power consumption of airplanes, missiles, and spacecrafts. In addition, nanofabricated materials can be used to develop aircraft engines that will allow for more thrust and better fuel efficiency leading to higher operating temperatures, lower engine weights, and increased rotor operating stresses.

The aerospace industry is a key component of the Arizona economy, employing more than 33,000 workers in 2003 (Esher, 2005). The number of jobs in the industry remained stable between 2001 and 2003. The industry is concentrated in Maricopa County (Phoenix) (1,417 firms and 32,000 employees) with a small number of firms in Pima County (Tucson) (120 firms and 1,063 employees. Key aerospace employers in Arizona include Boeing, General Dynamics, and Raytheon.

Microelectronics: Firms within the microelectronics industry develop and produce electronic components for both commercial and research uses. There are a variety of possible uses of nanotechnology in the microelectronics industry, including the use of nanofabricated materials such as nanostructured polymer films that feature brighter images, lighter weight, less power consumption, and wider viewing angles. In addition, nanofabricated materials can be used in chip production to improve both performance and power consumption.

The industry employs about 27,000 people in Arizona (Esher, 2005). Although employment in Arizona's microelectronics industry decreased by 31 percent from 2001 to 2003, there was an increase in industry employment in 2005. The industry is located only in Maricopa County (Phoenix) (142 firms and 26,797 employees). Key employers in the microelectronics industry in Arizona include Motorola and FreeScale.

B. Nanotechnology Research Activity

Based on analysis of nanotechnology patent and publication data compiled by researchers at the Georgia Institute of Technology, Arizona is a modest center for nanotechnology research but lags behind other metropolitan areas of the United States. According to its analysis and calculations, individuals in the Phoenix region were responsible for 334 academic publications relating to nanotechnology and 380 patents relating to nanotechnology between 1990 and 2006 (Table 1). The calculations do not include publications or patents from individuals in the Tucson metropolitan region. With 334 nanotechnology publications, Phoenix ranks tenth among U.S. metropolitan regions. Six metropolitan regions, however, have more than 500 publications during this period. With 380 patents, Phoenix ranks 17th in the number of nanotechnology patents among U.S. metropolitan regions. Eight metropolitan regions have more than 750 patents during this period, however.

C. Stakeholder Assessment of Nanotechnology Research in Arizona

Based on a review of all input gathered for this research, nanotechnology research occurs in four types of organizations in Arizona. First, Arizona is home to research facilities for a number of large national and multinational companies in the microelectronics and aerospace industry. Some of these labs are engaged in nanotechnology research. Second, both the University of Arizona and Arizona State University (national research universities) have established research centers in a variety of fields that are engaged in nanotechnology research. Third, Arizona is home to a limited number of medium-sized companies that are focusing almost entirely on nanotechnology. Finally, Arizona is home to start-up companies (often with small numbers of employees) that often have close connections to the state's educational institutions.

Table 1.
Top 20 U.S. Metropolitan Regions for Nanotechnology Research
Number of Nanotechnology Publications and Patents, 1990 - 2006

Metropolitan Region	Number of Nanotechnology Publications	Number of Nanotechnology Patents
New York	3,515	2,950
San Francisco / San Jose	2,444	3,588
Boston	805	2,322
Los Angeles	565	1,322
Washington DC / Baltimore	724	875
Philadelphia	641	1,014
Chicago	389	885
Houston	270	586
Cleveland	247	494
Minneapolis	342	838
Detroit	338	618
Albany	240	533
San Diego	217	405
Research Triangle, NC	306	293
Dallas	265	374
Pittsburgh	159	478
Phoenix	**334**	**380**
Denver	144	367
Austin	203	491
Atlanta	145	402

Source: Georgia Institute for Technology as part of the Center for Nanotechnology in Society, at Arizona State University

D. Gross Demand for Nanotechnology Workers

Since nanotechnology research takes place in a wide variety of industries and in educational institutions, there is no existing labor market data that can be used to determine the number of individuals who are working in nanotechnology research. Given the dynamic nature of the industries and of technological advances, it is difficult for companies to anticipate their future use of nanotechnology.

Companies providing input for this study anticipate further research in nanotechnology but cannot be specific. Nineteen of the 30 respondents to the online inquiry reported that they expect that their organization's use of nanotechnology would increase moderately or greatly during the next three years. Individuals interviewed for this study largely reported that their organization's use of nanotechnology would likely increase in the coming years as well. Individuals interviewed, however, were not able to, or were unwilling to, provide more specific estimates of their future workforce needs.

Many of the individuals interviewed cited a variety of reasons for this unwillingness or inability. Individuals reported that they are generally uncertain about the outcome of current and future research efforts. Particularly for smaller companies, future workforce needs would be driven by the company's success, or failure, in creating new nanotechnology innovations and in attracting venture capital to fund further research. One individual, employed in a research lab of a large company, reported that the company's management, located in another city and state, would ultimately make a decision about the location of nanotechnology research efforts. As a result, the individual was unable to make any predictions about the company's need for nanotechnology scientists in Arizona.

IV. SKILLS AND KNOWLEDGE NEEDED BY NANOTECHNOLOGY RESEARCHERS IN ARIZONA

A. General and Foundational Skill and Knowledge Needs of Nanotechnology Researchers

Despite the difficulty in estimating future demand for nanotechnology researchers, individuals were more comfortable in offering their opinions concerning the skills and knowledge required of individuals involved in nanotechnology research.

Approximately half of the respondents to the online inquiry reported that they believed that the use of nanotechnology will change the skills of workers to a moderate or great extent at their company during the next three years.

<u>General Knowledge and Skills:</u> Individuals, both through interviews and through the online inquiry, report that researchers with advanced degrees in

traditional disciplines possess much of the general knowledge and many of the skills necessary to learn the basics of nanotechnology research on the job. For example, one respondent to the online inquiry wrote that "nanotechnology is really molecular chemistry under a new name, so the necessary skills are not new, just renamed." Nanotechnology has applicability to a variety of different scientific disciplines. As a result, individuals from different disciplines often expressed a different perspective on nanotechnology. One individual interviewed for this study concluded that "nanotechnology can be understood if you have the basics of physics."

As importantly, many of the individuals interviewed for this study reported that they expect that research scientists would learn a significant amount about nanotechnology during the course of performing their jobs. Individuals with a strong background in a traditional scientific discipline, such as chemistry, physics or engineering, developed through graduate degree programs are likely to have a foundation of skills and knowledge that would allow them to learn new nanotechnology related skills and knowledge.

Given the dynamic nature of innovation in nanotechnology and the use of proprietary technology and approaches by companies, employers fully expect that new research scientists would not be fully productive for the first months of their time on the job. A research scientist at a large aerospace company in Arizona reported in an interview that the company prefers to hire individuals with graduate degrees and strong scientific skills and knowledge in their scientific discipline but who have limited work experience. The company routinely assigns newly hired research scientists to work in a team lead by senior scientists, who are in turn expected to train and mentor the employee, helping the employee to develop the skills and knowledge necessary to be successful at the company. Based on past experience, the individual reported that employees who have more experience before joining the company are often constrained by their prior experiences and less open to learning new approaches and techniques. Similar perspectives were voiced by other individuals interviewed for this report.

The importance of on-the-job training to the development of nanotechnology skills and knowledge increases the importance of skills relating to learning and knowledge acquisition. One individual interviewed reported that the ability to learn is a crucial skill for individuals working in nanotechnology research.

Foundational Skills and Knowledge: Individuals interviewed for this report acknowledged that the specific skill and knowledge requirements for new research scientists using nanotechnology vary from one industry to another and from one scientific discipline to another. One individual reported that the "specific [skill] needs depend on the specific industry." Most individuals agreed that new research scientists should have some foundational skills and knowledge relating to nanotechnology, however.

Individuals interviewed for this report conclude that new research scientists in nanotechnology should have some background exposure to the use of nanotechnology and to key concepts at the nanoscale. This includes a basic understanding of concepts at the atomic, molecular, and supramolecular levels. Individuals reported that new research scientists should have a basic understanding of quantum mechanics and quantum effects. At the nanoscale, the properties of materials can be quite different from those at a larger scale. As a number of individuals stressed in interviews, these "quantum effects" are at the center of nanotechnology. Individuals working in nanotechnology should have a basic understanding of these concepts.

An additional key component of nanotechnology is characterization, the ability to determine a nanoparticle's physical attributes, and in some cases its biological properties. A number of individuals in interviews and in the progressive dialogue stressed the importance of characterization to nanotechnology research. New research scientists should have some exposure to the basic approaches, tools, and concepts that allow for characterization.

B. Interdisciplinary Skills and Knowledge

Nanotechnology is applied in diverse fields such as biology, chemistry, medicine, and engineering, and there is strong agreement in the literature that nanotechnology has increased the need for inter-disciplinary cooperation (Roco, 2003; Abicht, Freikamp, & Schumann, 2006).

Interviews with individuals familiar with the nanotechnology related industries in Arizona indicate that future cross-sector collaborations are likely to be crucial to unlocking new nanotechnology developments. In addition, in Arizona there is currently a significant amount of cross-sector interaction among firms in the three key technology industries in the state. For example, 58 percent of aerospace firms who responded to a 2005 survey of high-technology businesses in Arizona reported that they either buy materials from, or sell materials to, microelectronics firms in Arizona. In addition, 31 percent of biotechnology firms reported a business relationship with microelectronics firms, while 13 percent of biotechnology respondents reported buying from, or selling to, aerospace firms (Esher, 2005).

Individuals providing input to this study consistently mention that this level of current and expected future interaction between industries and traditional scientific disciplines has increased the importance of interdisciplinary skills for research scientists in nanotechnology. Scientists and researchers working in nanotechnology must possess the skills, knowledge, and abilities to communicate and collaborate with scientists and researchers in other fields.

Ten of the 30 respondents to the online inquiry reported that interdisciplinary skills and knowledge were crucial for scientific research and development employees that work with nanotechnology. An additional 11 respondents reported that these skills were very important. Individuals interviewed for this study often emphasized the importance of interdisciplinary skills for nanotechnology research scientists and offered a variety of examples of ongoing collaboration among scientists from different disciplines.

For example, a senior research scientist at a large semiconductor company reported that much of company's new research in nanotechnology involves the interaction of materials engineering and electrical engineering. This collaboration has proven difficult due to the inability of scientists from the two disciplines to effectively communicate.

The senior research scientist at a large semiconductor company reported that:

> *"Inter-disciplinary skills are important: Students with a background in materials do not generally have the necessary background in electronics devices. This has created challenges within the company. The materials group did understand the application that was being developed, leading to miscommunication and delays in research development."*

A variety of individuals interviewed for this study also reported that new research scientists often do not have the interdisciplinary skills and knowledge needed to be effective nanotechnology researchers their respective companies. One individual reported that "a lack of interdisciplinary skills is the primary reason that we are having difficulty finding skilled nanotechnology research scientists."

A senior scientist of an aerospace company reported that research scientists working with nanotechnology need to be trained in more than one scientific discipline to broaden their knowledge and allow them to communicate effectively with other researchers. The individual stated that such cross-disciplinary training is important because “scientists and engineers are likely to come across things that they have not seen before, and need to have as much background as possible to help place things in a scientific, known context.”

The results of this study echo the findings of other research efforts. Over 90 percent of the 720 responses to a 2004 survey of the European nanotechnology research community reported that interdisciplinary skills were crucial or very important to workers in nanotechnology (Malsch & Oud, 2004). In addition, a recent research paper by the European Centre for the Development of Vocational Training concluded that interdisciplinary knowledge is the primary professional competency. The authors note nanotechnology developments typically involve the intersection between two or more typically distinct scientific fields, such as physics, chemistry, biology, and specific engineering fields (Abicht, Freikamp, & Schumann, 2006). For example, biologists and physicists must collaborate in the field of biophysics.

C. Safety and Health

Nanotechnology, by definition, involves working with materials that are extremely small and that may interact with each other in previously unobserved ways. Governments and researchers are beginning to focus on the possible effect of nanotechnology on the health and safety of workers. The National Institute for Occupational Safety and Health has begun research on the potential health risks to those working with nanoscale particles. Although the extent of the health risks remains unclear, precautionary measures have been recommended, including “the use of good work practices, the education and training of workers, and the use of personal protective equipment, when needed, should help reduce the potential for exposure” (National Institute for Occupational Safety and Health, 2007).

Individuals providing input to this study recognize that researchers in nanotechnology should have the knowledge and skills necessary to protect their safety and health. Half of the 30 respondents to the online inquiry reported that safety and health skills were crucial or very important to the scientific research and development employees working in nanotechnology. No individuals interviewed, however, cited safety and health as a critical skill need.

V. The Response of Educational Institutions to Nanotechnology Workforce Needs in Arizona

Some individuals providing input to this study are concerned that there is an insufficient supply of researchers in Arizona with the necessary interdisciplinary skills, general scientific skills and knowledge, and foundational nanotechnology skills. Most individuals believe, however, that the shortage of skilled workers will be temporary as educational institutions adjust to industry needs.

Only 6 of the 30 respondents to the online inquiry reported that it was difficult to find workers with the nanotechnology related skills needed for work at their company. An additional 12 of the 30 respondents reported that it was somewhat difficult to find workers with the needed nanotechnology skills. In addition, 8 of the 30 respondents reported that it was difficult to find new scientific research and development employees with the necessary nanotechnology skills.

While half of the respondents reported that there is currently a shortage of qualified personnel in Arizona for nanotechnology, one-third reported that they were unable to answer the question. Some employers are concerned about the short-term supply of researchers with necessary nanotechnology skills. One individual responding to the online inquiry reported that currently "the nanotechnology workforce is limited" in Arizona. In interviews, individuals rarely voiced concern about the supply of nanotechnology researchers in Arizona, focusing instead on the skill deficiencies of recent employees and offering related suggestions for educational institutions.

Most companies providing input for this report concluded that their use of nanotechnology is likely to grow in coming years, increasing the demand for workers with the necessary skills. Many expressed confidence, however, that colleges and universities would make the appropriate modifications to their programs and curricula to ensure that new scientists were adequately prepared for new research opportunities.

Others believe that any shortage of researchers will be temporary. A researcher at a microelectronics company reported that nanotechnology skills are "coming on board" in Arizona as educational institutions are reacting to advances in nanotechnology.

To meet industry needs and to better prepare students for nanotechnology research positions, universities in Arizona have begun to create new interdisciplinary degree programs and to establish new research centers and institutes in the areas of nanotechnology research. Arizona State University has created an interdisciplinary Ph.D. program in science and engineering manufacturing operations and has created a master's degree program in semiconductor processing and manufacturing. Both programs are interdisciplinary in nature and integrate components from various scientific disciplines. In addition, Arizona State University is in the process of creating a professional science master's degree program with a focus on nanotechnology.

Both Arizona State University and the University of Arizona have created research centers and institutes with some focus on nanotechnology (Table 2). Many of these institutes are interdisciplinary in nature, providing faculty and students from multiple scientific disciplines the opportunity to work together on common research projects. The centers and institutes provide an important learning opportunity for students. In addition, many of the centers and institutes have established relationships with individuals from industry in the state.

Table 2.
Research Centers and Institutes with a Focus on Nanotechnology at Arizona Universities

Arizona State University
BioDesign Institute
Center for Applied Nano Bio-science
Arizona Institute for Nano-Electronics (AINE)
Center for Bio-electronics and Bio-sensors
Center for Bio-optical Nanotechnology
University of Arizona
Bio5: collaborative biotechnology research institute
Semi-/Nano Fabrication Center
Advanced Semi-systems Laboratory
NanoBiomolecular Engineering, Sciences and Technology (nBEST)

Many individuals in interviews and through the online inquiry offered suggestions for ways in which educational institutions in Arizona could be more responsive to the needs of companies engaged in nanotechnology.

Adding Nanotechnology Skills and Knowledge to Existing Curricula: A number of individuals providing input suggested that universities in Arizona add nanotechnology skills and knowledge to a variety of existing graduate programs. For example, one individual suggested that chemistry programs teach students about basic nanotechnology concepts. Another individual recommended that material science and engineering programs should include nanotechnology skills and knowledge. An additional individual suggested that graduate students be given hands-on experience in the use of characterization tools that could be used to describe the physical characteristics of molecules.

Development of Interdisciplinary Skills and Knowledge: Many individuals providing input to this study identified a lack of interdisciplinary skills and knowledge among new research scientists as the primary nanotechnology related skill and workforce deficiency in Arizona. As a result, a variety of individuals suggested that universities take steps to expose students to a variety of scientific disciplines. For example, an employee of a microelectronics company stressed that colleges and universities should support the development of interdisciplinary skills by encouraging students to take courses outside of their primary scientific discipline and by providing students with research opportunities that involve the collaboration of scientists from multiple scientific disciplines.

Building Ongoing Linkages Between Industry and Education: The most common suggestions, however, centered on ways in which colleges and universities can continue to build closer connections to individuals in industry. Individuals largely agreed that technical development in the field of nanotechnology is occurring constantly and the demanded skill sets will thus be continuously changing.

For example, a senior researcher at a large aerospace company reported that the dynamic nature of nanotechnology makes it critical for graduate education to be closely aligned with developments in the nanotechnology industry. The individual suggested that universities create more opportunities for graduate students and faculty to present their research to industry scientists and to obtain feedback on their work. One individual recommended that research scientists employed by industry should be encouraged to, and given the opportunity to, teach classes at universities.

Other respondents suggested that existing internship programs should be expanded to provide students with the opportunity to gain hands-on experience; work with state-of-the art tools, infrastructure, and resources; and gain an appreciation for the skills and knowledge that they will need to succeed in nanotechnology research.

One respondent to the online inquiry suggested that companies bear some of the responsibility for ensuring that colleges and universities are adequately preparing scientists for nanotechnology research positions. The individual suggested that companies engaged in nanotechnology research should designate a staff member as a higher education liaison, responsible for ensuring ongoing interaction between research scientists at the company and researchers and faculty at colleges and universities.

VI. Conclusions and Areas for Further Research

Based on input from more than 50 individuals in Arizona involved in nanotechnology research, researchers have formed two hypotheses that will be explored in subsequent research efforts.

> *Hypothesis 1.* Nanotechnology is having an evolutionary effect on the knowledge and skills needed of researchers.

Individuals in Arizona interviewed for this study acknowledge that nanotechnology researchers must have a basic understanding of concepts at the nanoscale and of quantum effects. With this basic understanding and knowledge and with a strong graduate education in a traditional scientific discipline, individuals possess much of the general knowledge and many of the skills necessary to learn the basics of nanotechnology research on the job.

In the summer and fall of 2008, the Heldrich Center will conduct in-depth case studies with companies engaged in nanotechnology research in the biotechnology and pharmaceutical industry in New York and New Jersey. These case studies will be used to explore this hypothesis and to answer related questions.

> *Hypothesis 2.* The interdisciplinarity of nanotechnology research is having the most significant effect on knowledge and skill needs.

Many nanotechnology advances involve the collaboration of researchers from different scientific disciplines. As a result, individuals working in nanotechnology research must have a basic knowledge of other scientific disciplines and be able to communicate effectively with other scientists.

The future in-depth case studies will be used to explore the importance of interdisciplinary skills in nanotechnology research in biotechnology. Researchers will use interviews as part of the case studies to define the specific interdisciplinary skills required of researchers and attempt to characterize and define these skills. In addition, researchers will explore the extent to which nanotechnology increases the need for interdisciplinary skills. Finally, researchers will explore if companies prefer to have researchers who are cross-trained in multiple disciplines or to rely on team leaders who have the ability to coordinate and translate research from different scientific disciplines.

Response of Educational Institutions.

Colleges and universities in Arizona and other regions of the United States have begun to create or revise academic programs that are designed to prepare and retrain individuals for careers or tasks in nanotechnology research. Some of these efforts have involved the creation of new interdisciplinary programs focused on nanotechnology. Other efforts have been made to integrate nanotechnology knowledge and skills into existing academic disciplines. There is no one source for information on all the programs that have been created, however

Researchers will identify degree programs focused solely on nanotechnology in the United States and to identify academic programs that have been modified to include a significant focus on nanotechnology. The Heldrich Center will create a database of such programs based on web-based searches, a review of National Science Foundation funding to educational institutions, a web-based survey of colleges and universities, and follow-up interviews.

The interviews with academic program leaders will further explore a variety of issues including the reasons that the college or university created the program and the extent that employers were and are currently involved in the development and modification of the curriculum.

References

Abicht, L., Freikamp, H., & Schumann, U. (2006). *Identification of Skill Needs in Nanotechnology*. European Centre for the Development of Vocational Training, Office for Official Publications of the European Communities.

Esher, J. C. (2005). *High Technology Industry Clusters in Arizona: 2003 Status Report*. Industry Cluster Development Program, The University of Arizona, Office of Economic and Policy Analysis.

Fonash, Stephen J. (2001). Education and Training of the Nanotechnology Workforce. *Journal of Nanoparticle Research, 3.*

Lux Research. (2007). *Nanotech Hiring Continues to Climb* [Data File]. Retrieved from http://www.luxresearchinc.com/press/RELEASE_HiringNanotechTalent.pdf.

Malsch, I., & Oud, M. (2004). Outcome of the Open Consultation on the European Strategy for Nanotechnology. *European Nanotechnology Gateway* [Data File]. Retrieved from http://www.nanoforum.org/dateien/temp/nanosurvey6.pdf

National Institute for Occupational Safety and Health. (2007). *Progress Toward Safe Nanotechnology in the Workplace*.

National Nanotechnology Initiative. (2007). *NNI Research Centers*. Retrieved from http://www.nano.gov/html/centers/home_centers.html

National Science Foundation, National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology. (2000). *Nanotechnology Definition*. Retrieved from www.nsf.gov/crssprgm /nano/reports/omb_nifty50.jsp

Pandya, B. H. (2001). *Nanotechnology Workforce Pipeline Challenges: A Current Assessment and the Future Outlook*. New York: American Society of Mechanical Engineers.

Roco, M. C. (2003). Converging Science and Technology at the Nanoscale: Opportunities for Education and Training. *Nature Biotechnology, 21 (10)*, 1247-1249.

Roco, M. C. (2002) Nanoscale Science and Engineering Education Activities in the United States (2001-2002). *Journal of Nanoparticle Research, 4*, 271-274.

Roco, M. C., & Bainbridge, W. S. (Eds.). (2001): *Societal Implications of Nanoscience and Nanotechnology*. New York: Springer.