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Advancements in Nanotechnology Open Opportunities for Environmental Sciences

By Clifford (Bud) Frith

Nanoscience and *nanotechnology* are the new buzzwords for the next generation of research, development, engineering, operations, marketing, and distribution. It is estimated that investments in nanotechnology will exceed $10 billion globally this year alone.

"Nano" means very, very small with measurements recorded using the nanometer (nm), or one-billionth of a meter. The nanoscale for measurement and communicating is at the level of the atom or molecule. Ten hydrogen atoms in a row, for instance, equal approximately one nanometer. The average diameter of a human hair is 50,000 nm.

The environmental sciences have standardized terms using the prefix "micro," based on the micrometer, or one millionth of a meter. Applications in the semiconductor, computer, aerospace, biotech, and pharmaceutical industries define the level of expertise at the nanometer level. However, these processes are considered top down. Microelectromechanical systems (MEMS), semiconductor circuits, and biotech products approach the nanoscale but are not started at the atomic or molecular level.

The nanosciences focus on producing solutions, products, components, devices, systems, and processes from the ground up, starting with the basics of matter. This technology involves the nanomanipulation and nanoanalysis of the atom and molecule building blocks at the nanometer scale. Specialists have defined nanoscience as processes in the 1–100 nm range.

Nanotechnology is a new frontier will drastically alter our lives. This article will review the state of the art, including new facilities and requirements.

Impact on Environmental Sciences

The impact of nanotechnology applications on the environmental sciences will pose major challenges over the coming decades. Monitors, probes, sensors, and other instruments will be needed with smaller physical dimensions. Fabrication techniques may require new processes with better contamination controls. Personnel will still be the major contributing factor for contamination. Unit processes will require better documentation, higher testing levels, and improved data storage and retrieval. Processes may need sophisticated environmental chambers, equipment, and services not previously required. Research, development, and engineering will demand more disciplined activities, education, and funding to establish criteria for environmental monitoring and controls.

Suppliers will need to upgrade their facilities, equipment, processes, testing, quality, and personnel for nanotech applications. Biological sciences may be required in areas not previously part of the operation and processes. This means testing and control for living organisms, both hazardous and nonhazardous. Waste recovery and disposal may need a new set of criteria requiring specialists on the operations and management team.

In the face of these challenges, the environmental sciences will be a major contributor to the success of nanotechnology, building on developments that have already been achieved. For example, temperature, relative humidity, motion, shock, vibration, electrostatics, cleanliness, and purity are defined for the microfabrication processes. The ability to resolve issues with regard to the environment has been valuable for organizations supporting microtechnologies. Now the nanotechnology challenges and opportunities will be tested for the 21st century.

Nanotechnology Roots

The Information Revolution of the second half of the 20th century significantly changed our way of life, business operations, and ability to communicate and transfer information globally. This revolution required new methods of manufacturing and technologies not considered 30 years earlier.

The original idea for building nanostructures from the ground up dates back to 1959, when cleanrooms were initially designed, constructed, and operated for the beginning of the space program. Dr. Richard Feynman, a scientist with the California Institute of Technology, presented the concept at a meeting in California of the American Physical Society. Now considered the "father of nanotechnology," Feynman gave a keynote address titled, "There's Plenty of Room at the Bottom."

In that same year, the US Air Force (USAF) released the first published document for the design and operating criteria for cleanrooms (Air Force Technical Order 00-25-203). This document was used globally for aerospace and microelectronic applications until the publication of Federal Standard 209. The Air Force Tech Order established the lower level for particle control at 0.3 μm, or 300 nm. This particle size was derived from the airborne filter rating specification using dioctyl phthalate (DOP) particles, approximately 0.3 μm. However, the monitoring test used in actual cleanrooms, either at design or operating conditions, was a method used for counting blood cells in hospital labs, in which the air sample was impinged into filtered water and then put on a microscope slide for enumeration. This methodology was borrowed from the US Public Health Service for monitoring industrial health conditions in coal mines, which have significantly different concentrations of airborne particles than cleanrooms. Moreover, the particle resolution level of the light microscope technique was insufficient for detection at the 0.3 μm standard. Likewise, the methods for observing and manipulating atoms and molecules were only concepts in 1959.

Microstructures developed over the past 10 years at the submicrometer scale are defined as MEMS. Figure 1 compares a MEMS device to blood cells, approximately 5 μm, and a grain of pollen, approximately 8 μm. These are not true nanotech devices. They are developed using proven manufacturing methods and require larger materials as the starting point. The properties and specifications are well-defined and measured to meet the standards of material sciences.

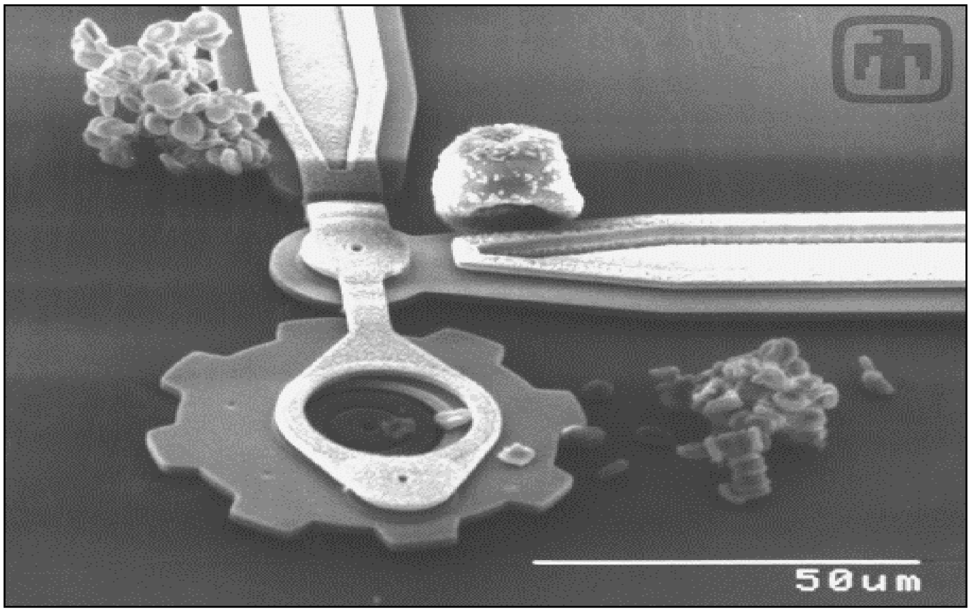

Figure 1—MEMS device compared to red blood cells (courtesy Sandia National Laboratories).

Nanoscience in its earliest forms might well predate the ideas of Dr. Feynman. The chemical and plastics industries clearly understood the technology of atoms and molecules, but their applications were not developed for microstructures until semiconductor processes were refined. The medical sciences have used living virus cells as a reference point for decades and could have applied the nanoscale. Two researchers at IBM Corporation's Almaden Research Center in 1989 were the first to record manipulation of atoms to create a nanostructure. Using a scanning probe microscope (SPM) developed by IBM, the researchers manipulated 35 Xenon atoms to produce the IBM logo and presented their results. At this dimension, 190,000 logos would fit in the area of a pinpoint. Figure 2 shows the Xenon atoms on a nickel substrate. This example is recorded as the first nanoscience exhibit and started the nanotechnology revolution.

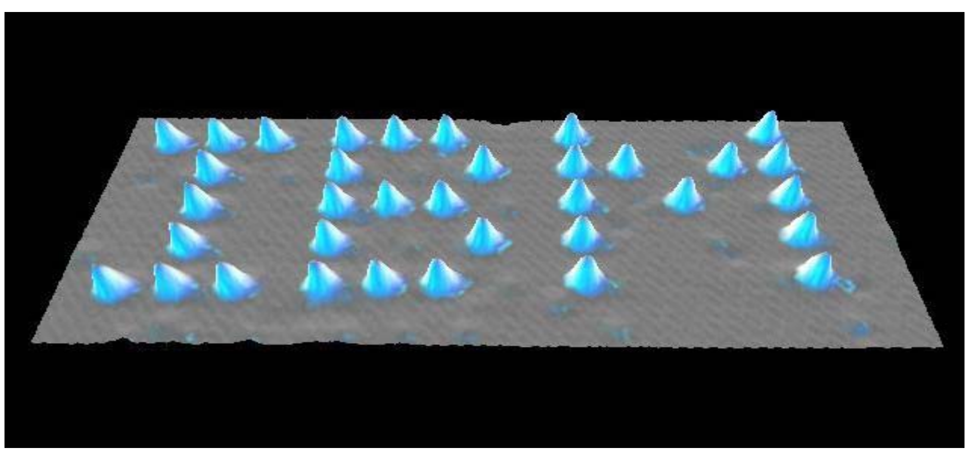

Figure 2— Xenon atoms representing IBM logo (courtesy IBM Corporation).

Figure 3 illustrates our current understanding of the nano-micro measurements for semi-conductors and medical applications. The Intel transistor is compared to the influenza virus cultured by the US Centers for Disease Control.

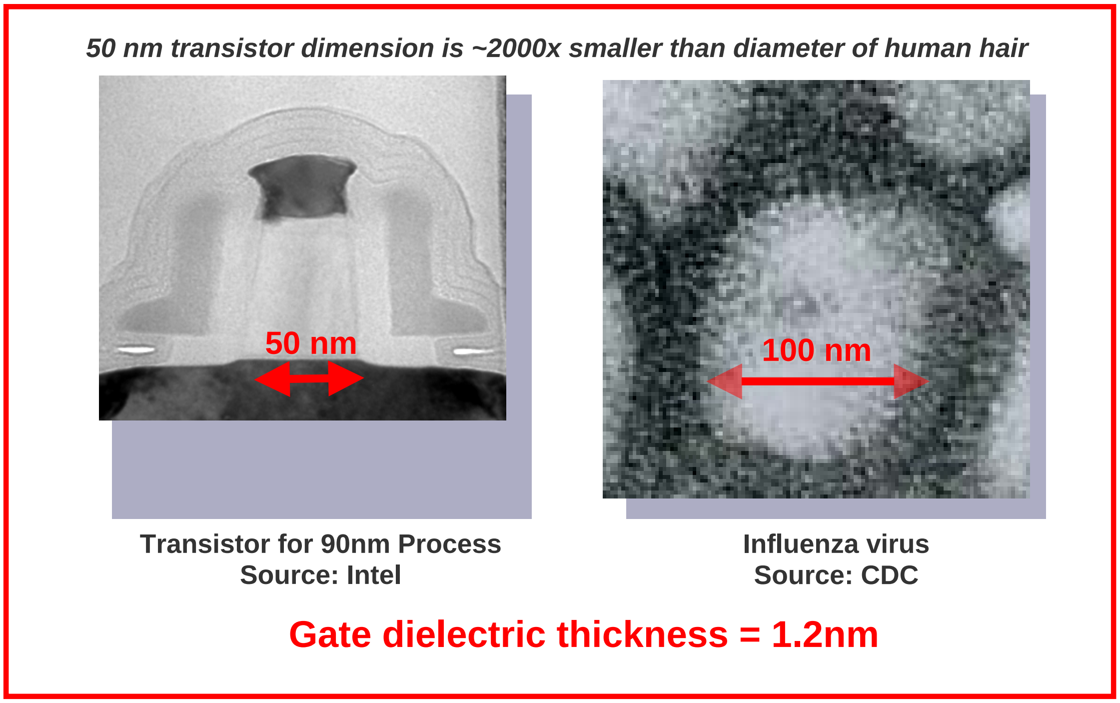

Figure 3—Nanoscience in semiconductor and medical industries (courtesy Intel Corporation, US Centers for Disease Control).

New Opportunities

The significance of starting processes from the bottom up is that the properties of the resulting nanomaterials exhibit different characteristics from those of standard materials used today. New nanomaterials are reported to be thousands of times stronger and much more flexible because the specialists have many different elements to combine and manipulate. Computers will be many times faster and storage capacity almost unlimited. Components and systems will be better, more reliable, and more cost effective. The solutions to today's medical problems, diseases, and recovery from injuries will be improved greatly.

NASA and the transportation industry report nanotechnology as possibly the best breakthrough since the early days of the Wright brothers' first flights. The National Nanotechnology Initiative has labeled this "The Next Industrial Revolution" and focuses attention on almost every field of science in its strategic plan. Nanotechnology will require a new way of thinking for the future and the economic and societal impact will change lives globally for the better.

In 2003, President Bush signed into law the Nanotechnology Research and Development Act (Public Law 108-153) with a $1 billion budget for 2004. Twenty-two government agencies are participating through a National Nanotechnology Coordinating Office. Revenue exceeding $1 trillion in 2012 and employment of more than one million people have been projected for the United States. The other industrial nations are projecting at least three-quarters of this revenue by 2010.

Estimated 2005 investments in nanotechnology applications by companies, academic centers, and governments will exceed $10 billion, with 40% in North America and the remaining 60% divided equally between Asia and Europe. Major global companies such as IBM, NEC Corporation, Hewlett-Packard Company, Samsung Group, and General Electric Company have committed significant resources to jump-start the new initiative with aggregate investments exceeding $4 billion. Thirteen US academic centers are either operational or starting construction in 2005 with outlays exceeding $200 million each. Ziegel's Nanotechnology Index includes 15 publicly traded companies. The US Patent and Trademark Office has established a nanotechnology cross-reference digest as a first step in designating nanotechnology as a major new classification. This will be big business worldwide and it is anticipated that average annual revenue growth will triple the next two years.

Nanotechnology research focuses on understanding the optical, chemical, electrical, magnetic, and mechanical properties of the atomic and molecular nanostructures. Scientists and engineers from many disciplines and almost every industry, government, and academic organization are participating. Computer, medical, biotech, pharmaceutical, communications, microelectronics, chemical, aerospace, automotive, defense, and energy applications will benefit. Observation, measurement, and manipulation tools are a major requirement and represent a very large investment to enter the nanotechnology businesses. It is projected that high-end scientific instrument industry revenues will double in the next two to three years. Controlled environments and adequate monitoring of all solids, liquids, and gases employed will see a resurgence of business opportunities. New research and development budgets are required to support the growth anticipated for nanotechnology.

New Tools

For observing, measuring, and manipulating the building blocks of the new materials, laboratories and development suites will be more robotic and have more stringent requirements than most current cleanroom facilities. Figure 4 illustrates the manipulation of iron and cobalt atoms on a copper substrate to form a nano quantum corral.

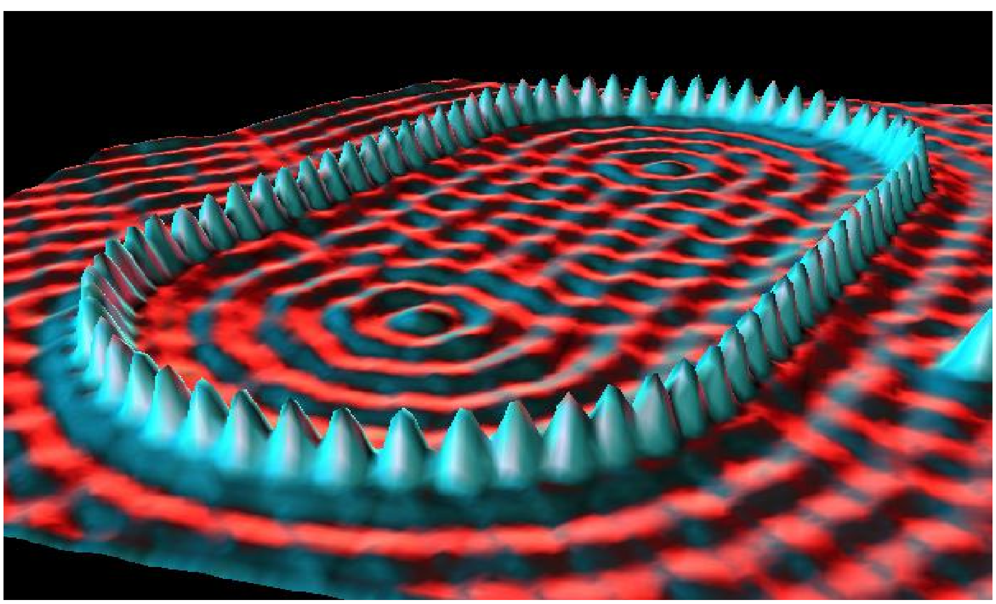

Figure 4—Iron and cobalt atoms on a copper substrate form a nano quantum corral.

Standard equipment will include automated research and testing tools such as scanning electron microscopes (SEMs), scanning probe microscopes (SPMs), scanning tunneling microscopes (STMs), atomic force microscopes (AFMs), and magnetic force microscopes (MFMs). This equipment can be used for nanolithography, E-Beam lithography and scanning probe techniques. Electrochemistry, spectroscopy, and surface chemistry instruments will be improved to meet the nanoscale. Environmental monitoring and control devices for pure air, gases, and liquids will be assembled to the process tools, making particle counters and other monitoring instruments an integral part of the process control protocol. The specifications for micro-monitors will advance and provide excellent business opportunities for environmental companies. As a "bleeding-edge" example, scientists at the University of North Carolina have developed the NanoManipulator, a tool to move and probe atoms and molecules with the aid of a computer. This equipment is commercially available.

Polymerization, crystal growth, and nano-reduction techniques are part of the ground up strategy at the nanoscale level. Physical vapor synthesis (PVS), a process that heats materials so hot that they vaporize, creates nanoparticles under controlled conditions of temperature and pressure as the materials cool. Molecular beam epitaxy uses atom-level coatings precisely layered to change the material surface. Properties at the surface are changed and have unique characteristics created through these nanoprocesses.

Nanoscience development processes are very expensive and time consuming. Personnel will need new skills for developing prototypes, performing quality functions, and defining performance specifications. The selection and training of a new workforce with the advancement of the sciences and tools has plenty of upside potential for the next generation. Education is critical to keep pace with demands of new technologies. This cannot be overemphasized if the US is to be a nanotechnology leader in the competitive global economies.

Equally important will be disposal of waste products and process materials. A new government agency will be formed from existing regulatory organizations to meet requirements.

Nano Applications Status

Current semiconductor applications provide clear-cut examples of how speed and computing power have increased over the past five decades. In a position statement more than 40 years ago, Dr. Gordon Moore, one of the founders of Intel, predicted exponential increases in the number of transistors per square inch on integrated circuits. His predictions, now known as Moore's Law stating that computing power will double every 18 months, have held true. The first computer required a complete facility and a kilobit processor. This article was prepared on a laptop with gigabit speed and gigabit storage capacity. The first molecular-scale circuit, which did not use silicon, was named the 2001 Breakthrough of the Year by the American Association for the Advancement of Science. Light-emitting diodes (LED), a standard part of any electronics package, have been scaled down to nanoLEDs and are being used for TV and computer screens. More advanced than liquid crystal displays (LCD), these new nanoLED products will soon replace most older components with a higher quality and lower price. Samsung is marketing flat panel displays using carbon nanotubes. Motorola is looking to partner with a manufacturing and distribution company for its new prototype screen to replace cathode ray tubes (CRTs). The improved quality and cost reduction for producing these TV screens will soon have a major economic impact on standard CRT displays. Data storage devices using current manufacturing techniques have reached the limitations of physics and chemistry. Nanotechnology will be the only way to continue the ability to pack more and more data into smaller and smaller devices.

HP has invested large sums of money into research and development for the next generation of computers. In cooperation with the University of California, Los Angeles (UCLA), Hewlett-Packard has patented a logic gate (switch) using a single molecule. This “molecular wire crossbar memory system” could revolutionize storage technology. IBM’s project “Millipede” has been reported to eliminate the current spinning disk by using thousands of nanoprobes. These nanoprobes make tiny holes in the polymer surface and the same nanoprobes can read the data stored. Currently, magnetic disk drives have a capacity of 35 gigabits per square inch. With these nanoprobes, it is estimated that densities exceeding one terabit per square inch of data storage is possible—an increase of over 28× in capacity. IBM also has reported that carbon nanotube transistors can carry twice the current of experimental silicon prototypes.

Pharmaceutical and biotechnology industries understand the implications of nanotechnology because molecules are their building blocks. Scientists have suggested that more than half of the biopharmaceuticals produced by 2015 will use nanotechnology processes. However, their R&D processes will need support from the material sciences and instrument manufacturers to advance their applications.

Medical applications include squeezing larger molecules into smaller passages to get drug treatment to the proper location and rebuilding tissue after surgery or an injury. Biocidal nanoparticles are impregnated into dressings that can be used in treatments not previously possible. Nanocrystal-based quantum dots from the semiconductor industry are being used to detect biological targets and analyze pathways to tumor cells.

Energy and transportation applications are using nanoscience to improve petroleum production efficiencies with zeolites or nanosieves. Nanoparticle coatings are currently being supplied for shielding ultraviolet radiation and providing superior scratch resistance on auto components. Prototype fuel cells have been tested using advanced nanotechnology materials. Membranes for separating hydrogen in a fuel cell application use nanostructured materials. The efficiency of improved fuels versus petroleum-powered units will have a major impact on the transportation industry. Battery materials using nanotubes will become standard for rechargeable products and significantly increase the life and quality of the power.

Clothing made with fabrics using nanofibers and nanoparticles will provide superior stain resistance and will not fade in the harshest of chemical cleaning. Cloth material with excellent flexibility and strength may replace heavier metal applications. Wear-resistant fabrics for hazardous applications are being developed and manufactured with nanofibers and should appear in distribution channels in 2005.

The aerospace industry is experimenting with new super materials that are 150 times stronger than steel, yet only 25% of the weight. These materials will increase the payloads of each space exploration mission and also increase space travel distances from the space station. Nanoparticles can be used in lubricant applications at much higher temperatures and the USAF has released lubricant contracts to major suppliers. US Navy ships are being coated with nanoparticles to reduce drag, increase speed, and prevent corrosion from saltwater. Solar cell efficiencies have been increased in prototype units using nanotechnologies. Defense and homeland security applications for nanotechnology will shift budget priorities over the next three years. Many start-up companies are competing for these defense funds as they have high priority within the current administration’s strategic plans.

Facilities and Personnel

Thirteen nanotech centers at academic institutions are currently scheduled across the country. Cornell, Rice, and Northwestern Universities have operating facilities. Purdue University is in the final stage of constructing a facility. These facilities are funded by federal, state, private, and industry commitments. Internationally, Japan has three major universities developing facilities. China and Israel have completed the first phase in their nanotechnology centers. Several other countries are close behind.

The challenge for each center, in addition to raising funds, is determining its strategic focus. Northwestern's focus is bio and chemical sensors. Cornell has the Center for Nanoscale Systems in Information Technology. Two of the three Japanese universities are focused on basic material science.

Industry will be partnering with the academic centers as well as assigning priorities to existing internal groups. IBM, HP, and NEC have designated facilities. Many small startup companies have emerged, both venture-funded and with industry partners. Biotech businesses have been successful the past 10 years in partnering with large pharmaceutical and biopharmaceutical companies. The small companies usually perform research, develop the products, and start the clinical trials. Then the large partners continue the process for US Food and Drug Administration approval and introduce the product and applications through their global marketing organizations. Since the normal schedule is 8 to 10 years for biopharmaceutical product release with final regulatory approval, the small companies survive with funding from these partnerships. A similar plan for new nanotechnology businesses makes sense because such ventures require significant investments only large companies can provide.

One of the biggest challenges for planning facilities in the university nanotechnology center is determining what processes may be used by the many nanotechnology applications over three to four years. (See page 75 for a report on the new Birck Nanotechnology Center at Purdue University.) Cleanrooms are assumed as a starting point, but the specifications change constantly as new information is collected about processes and applications. Additionally, what may be nonbiological space this year may be designated biological in the future. Changing from positive- to negative-pressure operations seems simple, but the initial costs are very high if part of the design specification. Semiconductor process design and operating criteria are easy to define for a facility, but the nanosciences may require additional personnel restrictions not yet encountered. Outgassing of materials and equipment at the lower nano level and online instrumentation to detect such changes is not a minor issue. Human body conditions are being considered as the processes may need a higher level of personnel control. Isolation chambers are mandatory but some processes will require human interface to determine the best methods to meet the stringent requirements. Vibration and electrostatic discharge (ESD) have new specifications not previously considered in design. An engineering firm with specialists trained in the newer design, measurements, and construction for nanotechnology facilities should be retained at the site-selection stage.

Supplier qualifications will need new standards. Many semiconductor and aerospace contractors will state their credentials from current microtechnology experience. However, purity, transport, and documentation must meet new requirement levels for process materials. Training of service and support personnel and security are additional needs. Storage, aging, and disposal of process materials are considerations for nanotechnology centers and their suppliers. The move to nanotechnology capabilities may require revising human resources manuals. Retraining existing personnel at all levels and education concerning nanotechnology for new employees is critical.

A highly educated and skilled workforce is an essential part of the planning and execution strategies for successful nanotechnology businesses.

International standards for cleanliness of facilities, processes, and materials will require revision and a new generation of personnel must accept this challenge. Hundreds of professional societies, including IEST, must cooperate in the tasks of defining and developing new standards for testing and control. A new phase of environmental sciences is on the horizon, certain to be an economic challenge but very rewarding for successful organizations. Starting from the ground up, atom by atom and molecule by molecule, the environmental sciences industry is positioned to take a leading role in the Nanotechnology Revolution.

Clifford (Bud) Frith, a consultant to technology companies, has been involved in environmental testing and control for more than four decades and currently is focusing his efforts in biotechnology and nanotechnology. A graduate of the Virginia Military Institute, Frith was a pioneer in the early days of designing, monitoring, and operating cleanrooms for NASA and the USAF. After his military service, he spent 14 years on the technical and senior management staff at Millipore Corp. Frith has held positions as vice president of Vaponics, Inc.; founder, director, and CEO of Anatel Corp. and DataTrax Corp; and general manager of the Filtration and Separations Global Business Unit at Osmonics, Inc. He has published more than 60 technical papers and chapters in technical books, is an international lecturer, and holds two patents. Frith is a Senior Member of IEST and a Technical Editor of the Journal of the IEST.