Buildings for nanotechnology: A look back at the genesis of a new building type

Hal Amick, Vice President, Colin Gordon & Associates, San Bruno, CA, USA

ABSTRACT

Nanotechnology research is the newest entry into the dynamic field of advanced technology. The buildings required to carry out this work may be dramatically different from those used for other areas of advanced technology. Virtually all of these facilities impose stringent environmental criteria upon the workplace, in such areas as vibration, temperature control, fume exhaust, and electromagnetic interference. However, nanotechnology is requiring new combinations of building needs – some of them seemingly incompatible – and demanding much more stringent environmental performance than 'conventional' technology facilities.

This paper reviews many of the workplace environmental requirements that must be met by advanced technology buildings, explores the relatively recent genesis of the dedicated nanotechnology facility, including the newer interior environmental requirements, and addresses some of the construction implications. It also presents a 'snapshot' of the facilities that were under design and construction in March 2003, most of which are either recently completed or nearing completion.

Introduction

Buildings have been built to meet the needs of technology for quite some time. Laboratories have made up a continually evolving building type for many decades. The trend toward 'modern' laboratories perhaps dates back to the 1950s. Cleanroom facilities have been built specifically for the semiconductor industry for a quarter century. The newest challenge facing the designers of buildings for advanced technology are those to be used for nanotechnology research. There are many aspects of those buildings that are borrowed from previous design models. Their unique features are generally the marriage of several seemingly incompatible sets of requirements and the need to force interdisciplinary innovation.

This paper explores the genesis of buildings for nanotechnology within the larger set of buildings for advanced technology. What is new about them? What is 'borrowed?' What is the state of the building type?

In order to establish a context for the discussion that follows, let us examine the difference between 'conventional' buildings and those intended to house advanced technology (AT). Within the AT subset, we find that design practices have been somewhat divided between the needs of conventional laboratories and those associated with the semiconductor industry. Buildings for nanotechnology are, in general, forced to 'marry' the two philosophies, such that researchers from areas as diverse as biotechnology, medicine and materials science work side by side with people from the semiconductor community, often in cleanrooms. Goldstein and Yellin (2004) explore some of the facilities performance issues associated with these buildings.

It can be said that nanotechnology facilities are neither fab nor lab – they are hybrids. Virtually all of them have cleanrooms, but these cleanrooms often make up a small fraction of the overall space. In some cases, spaces are required with positive pressurization, while others in the same building require negative pressurization. Some cannot mix airflow, because of incompatible airborne molecular 'contaminants'.

The most striking example of this incompatibility is that existing between the semiconductor cleanroom in a facility and the nanobiological cleanroom in that same facility. The viables in the bio-cleanroom must have a somewhat saline environment, which leads to airborne saline. In the semiconductor cleanroom, airborne saline would be a harmful contaminant. Thus, the bio cleanroom and the fabrication cleanroom cannot co-exist, even though they are both required to fabricate a single product, such as DNA on a chip. Traffic between the two must be carefully controlled, involving gowning changes and scrubdown. They must be physically separated, but have a controlled interface so that the product can be passed back and forth without having to be exposed to other contaminants.

The primary design aspect that separates buildings for technology from conventional buildings is the requirement for sophisticated work environments. These designs typically involve detailed interaction between architects and the various engineering disciplines involved. Once the designs are prepared, there may be specific and unusual requirements placed upon the builders. Some of the specific environmental issues facing the designers and builders will be explored, along with a few of the approaches that have been considered.

What is nanotechnology?

Nanotechnology is generally defined as R&D dealing with particles and systems with dimensions between 1 and 100 nanometers (nm). It interpolates between molecular or pico scale (where dimensions historically have been expressed in Angstroms) and what we commonly call microscale (where dimensions are expressed in micrometers). Although conductors and other features of computer chips have historically been at microscale, this is changing.

Some rules of science (such as electromagnetism) vary considerably between molecular and microscales, and in some cases, the transition from one set of rules to the other is not completely understood. These discontinuities are the focus of much of the basic research in nanotechnology.

The ultimate goals of nanotechnology research often involve creation of new materials and may address novel applications, such as drug-delivery systems, handheld diagnostic systems (such as mass spectrometers) to be used against terrorism, or 'smart' fabrics for clothing to respond to the needs of the body or environment.

Nanotechnology assumes that instruments must position a probe within an accuracy of a few nanometers. They must measure very small quantities (such as nanonewtons of force). They must fabricate objects perhaps only a few molecules thick and a few square nanometers in area. The instruments used to visualize or manipulate at this scale are among the most sensitive in technology. Electron microscopy, for example, is about to cross a threshold once considered unreachable: imaging and fabrication at a scale of less than one angstrom. Therefore, the thermal variations must be small enough that an object does not change sizes by more than a few nanometers or the probe's control system would place the probe at the wrong location. The electromagnetic fields must be so stable that electrical signals can be measured in terms of nanoamperes and nanovolts.

Some spaces require acoustics comparable to those of a recording studio. Tiny airborne particles may have dimensions up to the thousands of nanometers, so contamination control – particulate and chemical – must meet demanding tolerances. Vibrations must be two to three orders of magnitude less than the threshold of perception. All these requirements must be met in a facility with as much as 100 times the power consumption by mechanical systems – and over 50 times the air movement – of a conventional building. All these features translate into very demanding design requirements. The level of care required to design and fabricate a clean space may extend to all the other environmental concerns, such as electrical quality, electromagnetic interference, or low levels of acoustic noise.

Technology buildings

Nanotechnology has been said to offer potential benefits as revolutionary as the space program of the 1960s, the advent of computers, or even the Industrial Revolution. Funding for nanotechnology research is now in the billions of dollars (US), and growing rapidly.

The sophisticated working environments required for nano-technology facilities pose big challenges to their designers and constructors. The workplace environmental requirements may include temperature and humidity control, air cleanliness (i.e. particulate and chemical contamination), biohazard containment, limits on electromagnetic fields, special electrical power conditioning, and vibration and noise control. Many of these constraints have been applicable to advanced technology buildings for many years, but the nanotechnology is challenging commonly accepted limitations on what designers can provide, either in the form of increasingly stringent demands or as a need to 'marry' two or more seemingly incompatible sets of environmental requirements.

Most of the special design aspects associated with nanotechnology have evolved from the special needs of working at exceedingly small scales. In some respects, these facilities are new applications of design and construction practices developed for semiconductor production facilities and sophisticated research laboratories.

Semiconductor facilities and cleanrooms

Nanotechnologists are quick to point out that in the vast majority of cases, their field is not focused upon fostering progress for the semiconductor industry, but almost all nanotechnology facilities have (or will have) cleanrooms and semiconductor-style production capability. This is because the most sophisticated ability to manufacture multiple copies of objects of exquisitely small scale has evolved in the semiconductor industry and requires these facilities.

Semiconductor production generally involves building up electronic circuits on wafers of silicon. The circuits consist of small and very thin layers of materials of different types that are deposited and etched away in a repetitive process that may take some time. The most common components are conductors and transistors. The conductors are currently a few tenths of a micrometer (μm) wide. Miniaturization is a function of how small the lines and other features can be made. Complexity is governed by the miniaturization and the number of layers that can be fabricated. Precision and repeatability are of paramount importance.

Cleanrooms are a relatively recent phenomenon, compared to laboratories. Their genesis actually predates the computer industry, because the earliest cleanrooms were developed for the space program and NASA. The requirements have evolved considerably for semiconductor applications, but the concepts were established independently during the infancy of the semiconductor era.

Cleanrooms provide large environments that are as free of airborne contaminants as might be required by a particular process. They are characterized by 'Clean Class' designations in an applicable international standard that define the allowable quantities of contaminants per unit volume. (A distinction may be made between cleanrooms for the semiconductor industry and those for the pharmaceutical industry, but the former is more relevant to nanotechnology.) Cleanrooms are possible only through rigorous application of special practices that must be considered during design and construction, and on throughout the life of the facility.

Perhaps the three most important factors are airflow and filtration, 'clean protocol' construction, and protection of the cleanroom environment from its worst source of damaging contaminants: the people who work in it.

Air cleanliness is by far the most important aspect in a cleanroom, but in specific parts of a semiconductor facility there may also be limits imposed upon some combination of molecular contaminants, humidity, vibration, airborne sound, electromagnetic and radio frequency interference (EMI and RFI), and temperature.

One of the primary objectives of semiconductor production is throughput, producing as many chips as possible that meet particular quality goals. The common measure of quality is yield, which is the fraction of the chips produced that meet their specifications. Yield and the number of wafer starts per unit time are the two means by which productivity is measured. The facility layout and the equipment being used govern wafer starts. The primary factor affecting yield is the quality of the environment. A seemingly small change in air particle count or other contaminant can have a dramatic effect on yield. This, in turn, affects profitability in a production facility.

Research laboratories

In a research facility, there may be less emphasis placed on yield. Research facilities – even those involved with semiconductors – are fundamentally different from production facilities. They are intended to facilitate the answering of questions, not maximize production. In many cases, the questions involve processes that are sensitive to the environment. Unwanted fluctuations in that environment can lead to electronic noise or systematic error in readings, which in turn can lead to erroneous results. If more than one of a particular item is being fabricated, it may make no practical difference if the yield is 30% or 90%.

Environmental requirements for laboratories are not established by consensus standard as they are for cleanrooms. The reason for this is simple – there is too much variation in needs for this to be feasible. There may be vast differences between laboratories for physics, chemistry, biotechnology, metrology (measurement science), materials science, and medicine. Some of the equipment is the same for several different types of facilities (mass spectrometers and electron microscopes, for example), but the actual experimental areas may be dramatically different in layout and environmental requirements.

Is there a 'typical' nanotechnology facility?

At this time, the private sector has been somewhat involved in nanotechnology, but mainly oriented toward product development. This includes major corporations, such as IBM and Corning. In most cases, they have been making use of quality space that they already have, and focusing on product development in their existing areas of research. Pure research tends to occur mostly in the public sector, with representation from both the government and academic worlds.

In the US, we find that the federal government has concentrated its resources on six nano facilities, five of which are being built by the Department of Energy as user facilities. The fifth belongs to a research laboratory of one of the military branches. However, with all the research funding becoming available, universities world-wide are jockeying to build facilities. This is where the design efforts are now concentrated, and will continue to be for the near term.

University facilities fall into two categories. First, there are those universities that have established programs – with established faculty – oriented toward nanotechnology. These tend to be in engineering, material science, chemistry, and physics. These institutions tend to have very specific objectives for their new facilities, built around the research strengths already present there.

The second category is what I've started calling the 'build it and they will come' type of facility. These are being planned by universities that don't necessarily have an existing strength directly relevant to nanotechnology, but that wish to have a high-quality research space with which to lure potential faculty and researchers. It is not unusual nowadays for a young researcher to select an employer based upon the quality of the research space offered. Indeed, a few major universities occasionally lure senior faculty away from other major schools with an offer of better space than he or she currently has.

The distinction between these two groups is very important to designers. Simply stated, the first group generally knows what it wants and needs; the second group probably does not. In some cases, the people in the first group know too well what they want. It may exceed the available resources, or the demands may be unreasonable. However, they are there to negotiate with the design team, hopefully reaching a compromise that will still meet their needs. In the second group, a design team may be faced with a demand for 'a world-class space', or some other nebulous goal. If the designers must decide between the relative importance of, say, EMI versus temperature control versus vibration control versus low acoustic noise, they may be on their own. In this case, the experience of the design team may become quite important.

One facility has emerged as a 'prototype' for many nanotechnology facilities. The Advanced Measurement Laboratory (AML) at the Maryland campus of the National Institute of Standards and Technology (NIST) was carefully designed over an extended period of time, and the process allowed for several research projects aimed at resolving design- and performance-related issues. Most of those lessons have been portable to other projects, and many in the nanotechnology world are aware of some of the desirable AML design features. In some cases, however, there can be a significant impact on the project cost, because a number of AML design features were not inexpensive. On the other hand, one of these design-research projects demonstrated that temperature control accuracy of 0.01°C could be achieved using off-the-shelf components, as reported by Soueid, et al. (2005).

Environmental requirements

Labs and fabs have always imposed more stringent environmental performance from their facilities, compared to conventional buildings, but in many respects nanotechnology facilities push the edge of the envelope.

Figure 1 shows the evolution of NIST's environmental requirements, leading to those of the AML. In several ways, the AML is much more demanding than a conventional lab or fab, particularly with regard to vibration and temperature control. However, the particulate requirements tend to be less stringent. This is typical of nanotechnology facilities in general, where cleanliness beyond ISO Class 5 (FS209 Class 100) is rarely required, since they are not driven by yield.

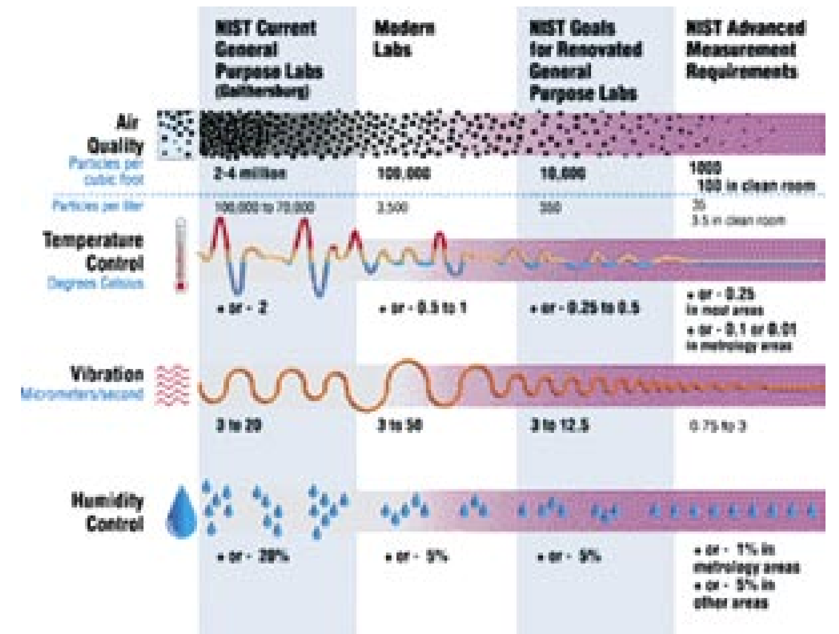


Figure 1. Evolution of NIST environmental requirements are typical of those for nanotechnology facilities (http://aml.nist.gov/information/brochure.html).

Amick, et al. (2005a) discuss the currently used vibration criteria in some detail. The ITRS Roadmap calls for a vibration criterion of VC-D (6.3 µm/s) for the foreseeable future, though a significant fraction of fabs are being designed to meet VC-E (3.2 µm/s) or an intermediate criterion of 4.5 µm/s. On the other hand, most nanotechnology facilities are being designed to meet either VC-E or NIST-A, the latter being significantly more stringent than VC-E at frequencies less than 20 Hz. Only about half of the sites for nanotechnology facilities have met NIST-A, though all of them have met VC-E.

Vitale (2005) presented an overview of the limits on electromagnetic interference (EMI) and radio frequency interference (RFI) in spaces for nanotechnology. Electromagnetic interference occurs when time-varying AC magnetic fields induce circulating currents and voltages in unshielded electronic equipment. It may be manifested as visible screen jitter in displays, hum in analog telephone/audio equipment, and data errors in magnetic media or digital signal cables. Generally, the minimum EMI threshold is 5–10 milligauss (mG) in unshielded electronic equipment, especially CRT color computer monitors and analog signal cables. Scientific instruments of the sort used in fabs and conventional research are typically susceptible to 1 mG. Field emission TEMs and SEMs used for imaging in nanotechnology and other molecular-level imaging are susceptible down to 0.3 mG, with future tools requiring levels as low as 0.01 mG. In additional to EMI limits at low frequencies, some work imposes limits at radio frequencies (RFI). In some cases, this can only be controlled by shielding.

Noise levels of NC-50 to NC-60 are common in cleanrooms, with tools themselves sometimes bringing the noise levels to NC-70. It is very difficult (and expensive) to design a cleanroom with noise levels of NC-45 or less. However, imaging equipment of the sort discussed at the end of the preceding paragraph demands very quiet environments, typically NC-25 to NC-30 or better. Clearly, advanced imaging is not practical in a cleanroom.

TABLE 1: SOME OF THE NANOTECHNOLOGY RESEARCH FACILITIES UNDER DESIGN IN MAY 2003

Facility	Owner	Location	Architect	Size, ft^2	Construction Budget
Center for Nanophase Materials Sciences (CNMS)	Oak Ridge National Laboratory	Oak Ridge, TN USA	M+W Zander	GSF: 80,000 Cleanroom: 10,000 Gen'l Lab: 16,000 Office: 54,000	$18 million
Center for Nanoscale Materials (CNM)	Argonne National Laboratory	Argonne, IL USA	M+W Zander	GSF: 92,600 Cleanroom: 13 400 Gen'l Lab: 12,800 Office: 14,500	$27 million (US)
Molecular Foundry	Lawrence Berkeley National Laboratory	Berkeley, CA USA	SmithGroup	GSF: 98,000 Cleanroom: 5,800 Gen'l Lab: 28,200	$43.5 million
Center for Integrated Nanotechnologies (CINT)	Sandia National Laboratories	Albuquerque, NM, USA	HDR Architecture	GSF: 93,000 Cleanroom: 9,000 Gen'l Lab: 16,000 Office: 40,000	$21.5 million
Center for Functional Nanomaterials	Brookhaven National Laboratory	Upton, NY, USA	HDR Architecture	GSF: 85,000 Cleanroom: 3,200 Gen'l Lab: 29,000 Office: 24,500	$25 million
National Institute for Nanotechnology (NINT)	University of Alberta & National Research Council	Edmonton, Alberta, Canada	Cohos-Evamy	GSF: 173,000 Cleanroom: 17,700 Lab+Office: 31,200	$40M (Canadian) $26M (US)
Birck Nanotechnology Center	Purdue University	West Lafayette, IN, USA	HDR Architecture	GSF: 200,000 Cleanroom: 14,000 Gen'l Lab: 19,000 Office: 20,000	$43 million
California Nanosystems Institute, UCLA	UCLA	Los Angeles, CA USA	Rafael Viñoly	GSF: 184,000 Cleanroom: none Lab+Office: 116,000	$92.3 million
California Nanosystems Institute, UCSB	University of California, Santa Barbara	Santa Barbara, CA, USA	Altoon & Porter	GSF: 111,000 Cleanroom: 7,000 Gen'l Lab: 30,000	$39 million
National Nano Fab Center	Korean Advanced Institute for Science and Technology (KAIST)	Taejon, South Korea	H&TC (Korea) IDC (USA)	GSF: 152,000 Cleanroom: 43,200	$25 million (US)
Nanotechnology Facility One	University of South Florida	Tampa, FL USA	HDR Architecture	GSF: 10,000 Cleanroom: 5,000	$3 million

Temperature requirements tend to be the most difficult to define. Strictly speaking, the concern lies with thermal expansion and contraction of the product, but variations in room temperature are attenuated by the thermal 'inertia' and insulation provided by the research equipment in which it rests. However, NIST researchers and some other metrologists believe that room-temperature variations greater than ±0.01°C can be troublesome in some circumstances. This can pose challenges for the temperature-control system of a room, because the sensors and software must be configured to accommodate the spatial and/or temporal characteristics associated with the criterion. Soueid, et al. (2005) discuss how the NIST AML provides portable temperature control sensors that may be suspended at the location requiring the greatest temperature stability.

In some cases it has been deemed necessary to use what might be called 'extreme measures' to improve building environments. NIST elected to place the AML metrology wings entirely underground, in order to place the vibration-sensitive floor at a depth where the surface vibrations would be greatly attenuated. This also improved thermal stability by eliminating the exposure to weather variations. The designs of two nanotechnology facilities have followed this lead.

Collaborative focus

Virtually all nanotechnology research is interdisciplinary and collaborative, much more so than most other areas of R&D. If nothing else, specialty researchers generally must collaborate with semiconductor fabrication specialists. However, the mix doesn't end there. Development of novel materials may involve materials scientists, physicists, chemists and polymer scientists. Development of complex processes for drug delivery or 'lab-on-a-chip' systems require the collaboration of semiconductor and electrical engineering people as well as researchers in pharmaceuticals, biotechnology, medicine (both human and veterinary), virologists, and so forth.

Designers of nanotechnology facilities are now being asked to include "collaborative spaces" that tend to foster unofficial gathering in relaxed settings. This goes way beyond conventional conference spaces. Some facilities have had coffee bars. Most have had lounges with marker boards. They are usually visually inviting places, and many architects put them 'on the way to somewhere,' so that researchers are forced to cross paths on their way to labs or offices.

Prof. Clifford Pollack of Cornell has coined the term 'intellectual collisions' to characterize this process. Cornell's Duffield Hall was one of the first dedicated nanotechnology facilities, and it was clear at that time that collaboration had to be helped by the designers, and researchers could not be allowed to become reclusive.

Snapshot of May 2003

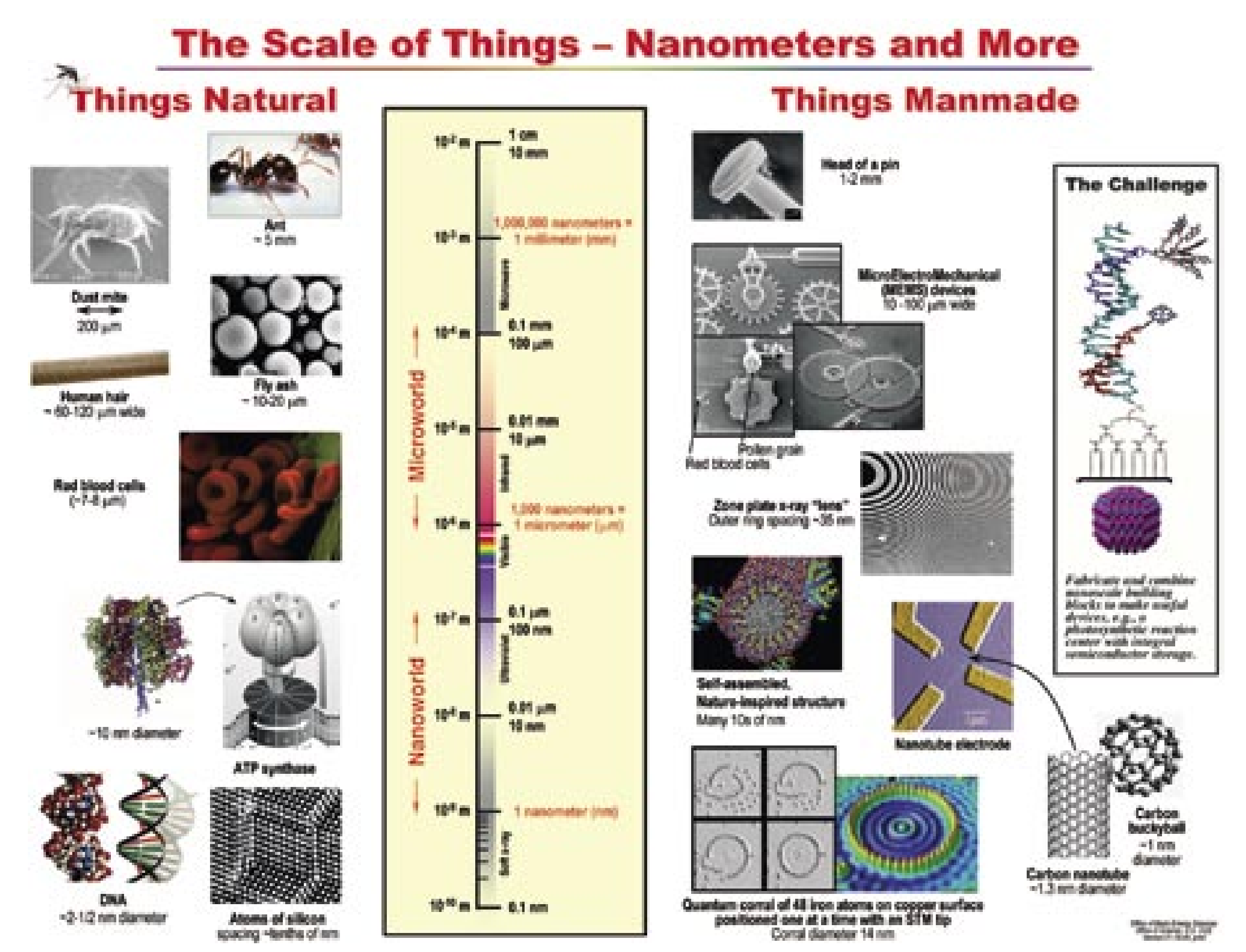
In May 2003, I attempted to track down every dedicated nanotechnology facility being designed or constructed in North America, as well as some overseas. Although the scene has changed somewhat, with all the U.S. Department of Energy facilities now under construction, it is informative to look at the cross section at that time.

At that time, half a dozen dedicated nanotechnology facilities were under construction throughout the world, or had recently been completed. These include buildings at Cornell and Northwestern Universities in the United States and University College, London in the United Kingdom, a large cleanroom at the National Nanotechnology Development Laboratory in Taiwan, and a somewhat smaller facility at the Naval Research Laboratory in Washington, D.C. The construction costs for these facilities range from $12 million to $60 million (US).

Table 1 lists details for most of the facilities under design at that time. The data are from a combination of public sources (such as project websites) and the owners or design teams. This

TABLE 2: SOME NANOTECHNOLOGY RESEARCH FACILITIES UNDER CONSTRUCTION IN MAY 2003

Facility	Owner	Location	Architect	Size, ft^2	Construction Budget	Completion
Duffield Hall	Cornell University	Ithaca, NY USA	ZGF	GSF: 150 900 Cleanroom: 25 800 Gen'l Lab: 25 600 Office: 17 000	$42 million	2003
Nano Science Laboratory	Naval Research Laboratory	Washington, DC USA	Gannett Fleming	GSF: 10 000 Cleanroom: 5000 Gen'l Lab: 5000 Office: none	$14.2 million	2003
London Centre for Nanotechnology (LCN)	University College London, Imperial College	London England	Feilden Clegg Bradley	N/A	N/A	N/A
Nanotechnology Cleanroom	National Nano-technology Development Laboratory	Hsinchu Taiwan	J. J. Pan	N/A	N/A	2004
Centre for Nano-fabrication and Molecular Self-Assembly	Northwestern University	Evanston, IL USA	ZGF	GSF: 86 800 Cleanroom: 170 Gen'l Lab: 21 100 Office: 15 700	$26 million	2002
NanoFab II Albany Nanotech Centre	University at Albany – SUNY	Albany, NY USA	CDM	GSF: 220 000	$200 million	N/A



Office of Basic Energy Sciences, Office of Science, U.S. DOE

Figure 2. How small is small? Representative sizes of things natural and manmade.

collection represents a total of 1.3 million gross square feet (130,000 m^2), a relatively small number in the context of industrial cleanroom, but a very large total area for a single genre of public-sector research facilities. This group has 125,000 ft^2 (12,500 m^2) of cleanroom space, about the same area of office space, and almost twice the area of general laboratory space. The aggregate cost of is about \$360 million (US), for a unit cost of about \$360/gross square foot. All of these facilities are now under construction or recently completed.

Table 2 lists most of the facilities under construction at that time. The construction budgets for the facilities for which costs are available are about \$280 million (US). Roughly two thirds of this total was associated with the huge Albany Nanotech, a collaboration between the State University of New York and Sematech.

Since that time, design work has started on dedicated facilities at Brookhaven National Laboratory, Georgia Tech, University of Florida, Cal Tech, University of Waterloo, and University of Oregon. Several other multipurpose facilities have dedicated research space to nanotechnology research. Universities taking this approach include Berkeley, University of Southern California, Duke University and University of Louisville.

Where is the design process going?

At a recent conference in San Diego, California (USA) a group of architects met in a roundtable to discuss the future of the design process for nanotechnology facilities. This group represented the design teams of about 90% of the nanotechnology facilities in North America, and ranged from large firms to small, and included firms that had designed as many as three facilities, and as few as one. The group reached several conclusions:

- The type of facilities we're discussing will not go away, though we may stop calling them 'nanotechnology' facilities. The technologies will be absorbed into other disciplines (such as materials science or electrical engineering), and we will stop making the distinction. However, a growing fraction of technology facilities will require advanced environments.
- The federal government will most likely not design more dedicated nanotechnology facilities beyond the six now completed or under construction. However, some of the lessons learned may apply to upcoming design projects, such as the 'Genomes to Life' (GTL) facilities.
- A growing number of universities will build nanotechnology facilities (or facilities by other names but with the same capabilities) in order to remain competitive. Not all of the top-tier schools have new facilities yet, but we will see a growing number of second-tier and third-tier schools making investments, though the facilities may be somewhat scaled back in scope and budget from those currently under construction.
- It is important for the design professions to contribute to a common 'body of knowledge' regarding the design of technical facilities. This will create a resource for smaller architects

or specialty designers who have the opportunity to become involved with one of these facilities, but do not have the experience.

At the same conference, a group of specialty consultants discussed the shortcomings presently being faced by the consulting community. The greatest concern was with the lack of measurement standards in the technical disciplines. Cleanrooms are the area of least concern; contaminant classification is a very mature field. On the other hand, EMI and temperature have virtually no standardization with regard to evaluation. If a user states that temperature stability of ±0.01°C, what does this really mean? Does it refer to spatial gradient? Time variation? If so, over what period? Once the problem – and its form of post-construction evaluation – are adequately defined, the control systems may be relatively straightforward to design. However, if they are not defined, the designer may provide something quite different from what the user was expecting.

The specialty consultants were strongly in favor of something they called 'standardization,' because it would improve communication and would lead to consistent evaluation processes. On the other hand, the architects were opposed to something they called 'standardization,' because it would stifle creativity. Clearly, more work is needed with regard to the terminology used to define the design process itself.

The Institute of Environmental Sciences and Technology (IEST), which has been actively involved in maintaining cleanroom standards in the US, has committed to support these efforts to bring some uniformity to the process (and will attempt not to stifle creativity). Tutorials and technical sessions in the next two IEST gatherings have already been scheduled, and a Working Group for nanotechnology facilities was formally established at the winter meeting in Chicago.

Conclusion

Research and fabrication at the nanometer scale will most likely lead to another industrial revolution. It will likely impact everything we do. Before that time, however, it will begin to affect a wide variety of building types within the technology sector. This will require that designers broaden their experience base, and owners will have to learn more about specialized space. These spaces cannot be designed by 'garden-variety' architects and engineers. The experience base can and should grow, but it must be a planned process and involve a dissemination of information.

It is also important to develop a standard terminology and standard methodologies for characterizing room and building environments. The disciplines working with many of the technology building environments find themselves at the point encountered by cleanroom designers in the 1960s. We know, for example, what a degree Celsius is, but what is meant by stability or accuracy of a degree Celsius? What role is played by averaging time or frequency bandwidth in vibration and acoustic measurements? How do we document and define these, allowing communication between users, designers and builders.

Clearly, the design professionals face a near-term challenge, but if we follow the lead of the contamination control community, order can be brought to the chaos that can arise. If we meet the challenge, we can embrace nanotechnology in the most economical manner possible.

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ABOUT THE AUTHOR

Hal Amick is Vice President of Colin Gordon & Associates, a California-based consultancy. He holds M.S., M.Eng., and Ph.D. degrees in civil engineering and structural dynamics from Berkeley, and he has been involved since 1985 with design and assessment of vibration-sensitive facilities for technology. He has been lead vibration consultant for the NIST Advanced Measurement Laboratory since its design began in 1993, and is team leader for CGA's work with nanotechnology facilities. As such, he has been involved with over a dozen dedicated nanotechnology facilities in the US and abroad. He is a registered civil engineer.

A list of his publications may be found at www.colingordon.com.

ENQUIRIES

Hal Amick, PhD, PE
Vice President
Colin Gordon & Associates
883 Sneath Lane, Suite 150
San Bruno
CA 94066
USA

Tel: +1 (650) 358-9577
Fax: +1 (650) 358-9430
E-mail: hal.amick@colingordon.com
Website: www.colingordon.com