Presented at "Buildings for Nanoscale Research and Beyond," a SPIE Conference
31 July 2005 – 1 August 2005, San Diego, CA

Addressing the environmental challenges of the NIST Advanced Measurement Laboratory

Ahmad Soueid*[a], Hal Amick[b], Theodore Zsirai[a]
[a]HDR Architecture Inc., 1101 King Street, Suite 400, Alexandria, VA USA 22314
[b]Colin Gordon & Associates, 883 Sneath Lane, Suite 150, San Bruno, CA USA 94066

ABSTRACT

The recently built Advanced Measurement Laboratory at the National Institute of Standards and Technology (NIST) provides a great step forward for that organization with regard to its research environments. Vibration and temperature control were among the most critical concerns expressed by the researchers, and considerable attention was given to meeting their objectives. Critical laboratory environments called for vibration to be controlled to amplitudes no greater than 25nm rms displacement and 3.1 μm/s, and as much less than that as feasible. Some of the spaces required thermal stability controlled to within +/- 0.01° C. The design phase involved research projects examining ways in which those goals might best be achieved. The critical rooms met or exceeded the temperature and vibration control requirements. Some spaces were found to have displacement amplitude on the order of 10 nm, velocity amplitude of 1 μm/s, and acceleration of 19 μg, all well below the design goals, making this one of the world's finest research spaces.

Keywords: vibration control, temperature stability, humidity control, metrology laboratories, laboratory design, nanotechnology

1. INTRODUCTION

Completed in 2004, the Advanced Measurement Laboratory (AML) at the National Institute of Standards and Technology (NIST) campus in Gaithersburg, MD, was awarded "High Honors" in the *R&D Magazine* 2005 Lab of the Year competition. Behind this simple statement lies a planning, design, and construction effort that began in the 1980s. The AML provides NIST researchers with lab environments of the highest caliber.

If simply viewed as another government laboratory, its cost may seem high; neither the facility nor the design effort itself was inexpensive. However, the payback is ongoing, taking the form of design technology that is portable to the nanotechnology facilities of today. The design teams for nanotechnology facilities have available to them information and design tools that would have been too expensive for any single nanotechnology project to bear.

This paper discusses some of the features of the AML that make it unique among laboratories, and some of the "design research" that allowed the ambitious goals set forth by NIST to be met without a construction cost that might have been disastrous.

2. THE MISSION OF THE AML

The mandate of NIST is to provide the country's leadership in measurement science and standards, and to represent the U.S. internationally in that arena. It is important that NIST scientists stay competitive with standards bodies in other countries as well as stay abreast of advancement in technology. As the world of technology heads from the "micro" scale toward the "nano" and molecular scales, the building environment in which the work is carried out takes on a singular importance.

---

* Ahmad.Soueid@HDRinc.com; phone 1 703 518-8552; fax 1 703 683-6146; www.HDRinc.com

The lab buildings on their Gaithersburg campus simply were not capable of meeting cutting-edge requirements. Given the need to gauge distances in increments tinier than the radius of an atom or the capacity to determine the size of an electrical current by tabulating, one by one, the number of electrons flowing by, such a laboratory requires unprecedented levels of environmental stability.

NIST scientists and engineers must be able to locate and manipulate single atoms on a surface; detect ultratrace amounts of chemical agents; and measure the many optical, physical, and quantum properties of components for telecommunications devices, semiconductor chips, and magnetic recording devices. However, deteriorating conditions in NIST's older lab facilities were limiting the quality, accuracy, and productivity of many of these efforts. When the AML became ready for use by Gaithersburg researchers in 2004, it dramatically improved NIST's ability to provide U.S. industry and science with the best measurements and standards in the world.

This facility, completed in late 2004, added a total of 49,860 m^2 (511,070 ft^2) to NIST's Gaithersburg campus. The construction cost of $174 million resulted in a unit cost of \$3,500/m^2 (\$325/ft^2). It consists of two single-floor metrology wings completely below grade, two single-floor instrument laboratory wings at grade, and one above-grade ISO Class 5 (FS209 Class 100) clean room wing.

2.1. The challenge from NIST

The two-part challenge from NIST was to (1) provide the researchers with a big leap forward with regard to research space, which they had needed for quite some time; and (2) provide a means by which NIST could maintain its place as a leader in measurement science.

When working at the scale of the atom, the slightest variations in environmental conditions – a hundredth of a degree change in temperature, vibrations from local traffic, a flutter in electrical current – can plunge the results of the most carefully designed experiment into ambiguity. These demands include high levels of accuracy in environmental and design criteria.

Addressing so many criteria simultaneously can pose a challenge in its own right. Many of these design challenges had been individually achieved at similar facilities around the world but none has integrated such a combination of environmental criteria into a single facility as the AML was expected to do. Implementation of these criteria may lead to what the design team termed "conflicting criteria."

Two examples may serve to illustrate the potential conflicts:

- In attempting to control air cleanliness and temperature control, massive volumes of air are required; the AML moves over 2,500,000 cubic feet of air per minute (CFM). The movement of such volumes of air, along with the mechanical equipment needed (five times the amount required for a biomedical research lab), would result in a greater potential for acoustical noise and mechanical vibration interferences.
- Regulating the temperature of the floor was one of the means by which temperature stability was achieved. In attempting to control slab temperatures, two options existed: hydronics (liquid) and electric. With the use of a hydronic system the movement of fluids resulted in vibration. Alternately, the use of electric heating elements in the slabs created electromagnetic fields.

The design team—made up of design professionals and consultants—did not feel it was appropriate to resolve conflicting criteria within the design team alone. To this end, a team structure was established early in the project which made available to the design team a formal Technical Advisory Group (TAG) made up of key researchers and support staff who might be candidates for the new facility. The TAG group acted as a liaison between the designers and the NIST research community. In essence, the design team had to teach the TAG group members a certain amount of design, and the TAG group taught the designers a certain amount of science. This facilitated discussions that sometimes went for several hours on some of the minutiae of a project of this magnitude. When conflicting criteria arose, the conflicts and potential resolutions were defined to the TAG group—sometimes in exquisite detail—and then the TAG group members would carry the discussions back to the appropriate members of the research community. Generally, the TAG group members would carry back the responses to the design team. (Occasionally, the potentially affected scientists would come to speak on their own behalf.) In several instances, this process went through several iterations, which might spread a discussion and decision out over several months.

2.2 "Data-gathering" and the "experimental" design approach

The areas of greatest concern to the NIST researchers were vibration and thermal stability. To meet their goal of a great leap forward, it was necessary to adequately define the status quo, both within NIST and outside. The bulk of this paper will focus on vibration and temperature, with some minor excursions into other environmental parameters.

Many of the world's finest metrology laboratories were visited and their designs closely scrutinized. To advance the lessons learned from other similar projects, design concepts developed for the AML were tested in several full scale mockups. Most notably, a Vibration Isolation Research Project (VIRP) was carried out to test design concepts for vibration isolation and a Temperature Control Research Project (TCRP) was executed to test the high-accuracy temperature control laboratories. Such mockups proved invaluable for NIST researchers and the A/E team as well as potential manufacturers of equipment to be installed at the AML. Lessons learned from these mockups were incorporated into the design of the building long before construction started.

3. VIBRATION CONTROL

Vibration concerns in the AML project went through a significant evolution over the life of the project. When the NIST researchers were examining their requirements in the mid- to late-1980s in preparation for a formal programming effort, it appeared to the researchers that the most sensitive processes were those in which the vibrations were best controlled by limiting displacement. A criterion which may be quantified as an rms displacement amplitude of 1 microinch (25 nm) was initially proposed by NIST. The vibration consultant suggested that NIST might also wish to consider the requirements of other research instruments, particularly those associated with advanced semiconductor fabrication.

The hybrid criterion now known as NIST-A emerged from these discussions. It was a marriage of the original NIST displacement criterion of 25 nm and the popular criterion VC-E (rms velocity 6.25 μm/s) from the semiconductor industry.[1,2] These two criteria take on the same amplitude at approximately 20 Hz, so the displacement portion limits vibrations at frequencies less than 20 Hz, and the velocity portion applies to vibrations at higher frequencies.

3.1 Vibration surveys

Considerable effort was devoted to reaching these goals, including one of the most exhaustive site vibration surveys ever undertaken. The program included the usual ambient measurements at the four corners and center of the proposed footprint, but they were taken over a continuous period of 24 hours. The data were examined in half-hour segments in terms of overall velocity amplitude (with frequencies limited to those between 1 and 100 Hz), and statistical centile spectra.[3] The statistical distribution curves of individual frequencies were used for purposes of comparisons.

Two sites were considered. One was near the main entrance to the NIST campus, in a position of high visibility. The other was at the opposite end of the campus, where many visitors would be unaware of its presence. There were many reasons for preferring the site near the entrance. Its prominence near the entrance would allow a strong architectural statement that would visually represent the leap forward being made by the agency. However, the vibration environment was deemed more important than making an architectural statement, and the less visible site was chosen. (The vibration environment at both sites met NIST-A a majority of the time, but when represented statistically, it was demonstrated that the remote site met it a larger fraction of the time.)

It is not uncommon to obtain vibration measurements at one or more locations of existing equipment in order to validate vibration criteria or to form a basis of comparison for assessment of a new location. NIST took this to new heights, asking the design team to evaluate dozens of representative spaces in almost every building on both campuses (Gaithersburg, MD and Boulder, CO). The result was surprising: the majority of NIST labs *already* met NIST-A. This was a good thing, but created a bit of a quandary. If one objective was to improve on what NIST had at the time, how would this be achieved? The goal was modified in two ways:

1. Examine measures necessary to improve on the already excellent vibration environment presented by the selected site, without creating a new criterion; and
2. Examine, in particular, whether it was feasible to vibration-isolate a room-sized space such that the space met a "better-than-NIST-A" vibration criterion (eventually deemed "NIST-A1").

The first goal was addressed in many ways throughout the design process by employing "conservatism for its own sake." The second goal was the objective of the Vibration Isolation Research Project (VIRP), the topic of the following section.

3.2 Vibration isolation research project (VIRP)

It is customary in many areas of research to perform experiments on optical tables—stiff tabletops supported on airspring legs. These systems provide significant vibration attenuation at frequencies above about 4 Hz. However, during brainstorming sessions, the design team and the TAG group encountered several settings in which a high degree of vibration isolation was desired, but the use of a conventional optical bench was problematical:

- *Long and complex beam paths.* Several types of experiments involve laser beam configurations which cannot be easily fit on a 1.2m x 2.4m optical tables. Two (or even three) optical tables may be required, but then the use of vibration isolation is out of the question, because the beam alignment between two tables is subject to the differential motion of the two tables. Historically, multi-table experiments have been performed with deflated or rigid legs.
- *Inadequate room height.* Some experimental setups are tall, which can be problematic unless the ceiling is quite high. Besides inadequate ceiling height, another difficulty occasionally presents itself; a tall experimental setup, if it has significant mass, the center of gravity may become quite high with respect to the roll plane of the spring, introducing a degree of instability and increasing the severity of rocking in response to horizontal floor motion.
- *Difficulty with access.* Some off-the-shelf instrumentation is normally intended for use at bench height, and the controls and access ports are positioned accordingly. If one of these devices is placed on an optical table, it is difficult for an operator to reach the controls and ports, without an access platform being built, which may take up too much floor space.

These problems led to a critical question being asked by the TAG group: Was it practical to have large, built-in isolation systems that were large enough horizontally to support the experiment (even if it took up an entire lab module), deep enough to prevent overturning instability, and recessed into the floor? Investigation showed that several labs overseas had taken this approach in several different ways, but the horizontal dimensions were always no larger than a single instrument or optical table.

Amick, *et al*. report the results of the VIRP study undertaken using a large (4m x 10m) concrete mass supported on 10 airsprings.[4] Several key conclusions were reached, which have affected subsequent usages in the AML design and the nanotechnology facilities that have followed.

- Construction of an A1 slab system in an operating laboratory (as was the case with VIRP) is quite disruptive.[†] The worst part of the construction is the removal of the floor slab and excavation of the pit.
- The technology is capable of providing up to 30 dB attenuation at frequencies between 1.4x the highest "rigid body" resonance (it was found to be the rocking resonance) and about eighty percent of the lowest internal resonance of the concrete mass (34 Hz in this case).
- At the internal resonances of the slab, the attenuation provided by the system approaches 0 dB. Thus, the resonances limit the isolation performance of the system. There are two ways to offset this:
  - Proportion the slab's depth to its horizontal dimensions such that the fundamental internal resonance lies above the frequency range of concern; or
  - Modify the concrete damping such that the cancellation at internal resonances is less deleterious.

Of the two treatments offsetting the internal resonances, only the first one was employed in the design of the dozen A1 slabs in the AML, the largest of which is 3m x 4m. The second option, modification of the internal damping of the slab,

---

[†] The impact of retrofit construction was one of the variables deliberately explored in the VIRP. Some AML users were unsure whether they wanted an A1 system, and proposed adding it to their space when (and if) the need arose.

was feasible, but either too expensive (if constrained layer damping was introduced) or associated with uncertainties (damping admixtures for concrete were available, but not well documented.) Much of that uncertainty has since been addressed [5] and key points of the use of these admixtures is explored in another paper at this conference.[6]

The VIRP design evolved into several variants. The VIRP design placed the top of the concrete mass some distance below the elevation of the surrounding floor, and involved a "walk-on" floor of access floor tiles that was suspended over the isolated slab, such that personnel and non-sensitive equipment could be supported without touching the airspring-supported concrete mass. This, however, is not always desirable. In some of the eventual AML installations, the top of the concrete mass was at the same elevation as the surrounding floor, with only the gap around the slab covered with a removable floor.

The experience with excavation in the operating lab environment suggested that future installations would be best served by a compromise. The pit, with its special foundation and retaining wall, would be constructed at the time the AML was constructed, and filled with well-compacted sand. A slab was poured over the top, matching the surrounding slab. This slab could be saw-cut and removed if it were deemed necessary to install a slab system some years in the future.

3.3 Slab joints and the "dropped hammer effect"

Next to the VIRP, the vibration issue leading to the greatest interaction with the TAG group was the one eventually dubbed the "dropped hammer effect." Experience at the time of the design (and subsequently documented in Ref. 7.) was suggesting that there was great benefit to be obtained by using a single slab throughout the lab, as the horizontal vibrations would tend to be reduced. However, some of the researchers had concerns regarding the high-frequency impulses that might propagate through the concrete from the impact caused by dropping a hard, heavy object, such as a hammer. They had had problems with this in the past, and wanted to avoid it in the new facility.

The resulting compromise has been used as a precedent for a number of nanotechnology facilities, in which the same concerns have existed. Joints were introduced, but the isolated "islands" were kept as large as practical. None were smaller than two lab modules, and many were three modules in size. In this way, one experiment was impacted by the risk of a "dropped hammer" in only one neighboring lab, not the entire wing.

4. TEMPERATURE AND HUMIDITY CONTROL

Temperature fluctuation within a room can impact the accuracy of sensitive measurements, and eliminating these fluctuations has long been an elusive goal for metrology laboratories. The baseline temperature of the majority of the AML laboratories is to be controlled to within ± 0.25 degree Celsius. Thirty six labs are designed to control temperature to ± 0.1° C and 12 labs to ± 0.01° C. Humidity is to vary no more than ± 1 percent relative humidity in specialized areas and ± 5 percent relative humidity throughout the rest of the facility.

To the best of our knowledge, control to ±0.01° C has not previously been achieved in a project of this magnitude. Such tight control is a challenge because unlike solids or liquids, air has a low specific heat. To illustrate, given normal airflow in a 3 m x 3 m office, the energy of a single flashlight would change the temperature of the room by more than this amount.

What made the designers' task even more difficult was the requirements imposed by NIST that this high level of accuracy be achieved using commercially available components, and that research to develop specialized products would not be permitted, even if funded by manufacturers. NIST believed that by using standard components, the long-term availability of replacement parts would simplify maintenance.

The users and design team elected to use 300 air changes per hour (AC/h) in the ±0.01°C laboratories in order to make the labs as user friendly as possible, allow some minimum amount of heat gain, provide for fast recovery time, and minimize vibration. To minimize air velocity, the entire ceiling was used to distribute the air through 50mm (2 in.) HEPA filters. Air flow of 120 AC/h was used in the ± 0.1 ºC rooms, and 20 AC/h was used in the ± 0.25 ºC rooms.

Some of the nano research and measurements are extremely sensitive to vibration, even that arising from air flow. For those applications, the design included variable volume air flow capability utilizing adjustable frequency drives. Depending on the heat gain within the room, during the actual tests the air flow can be reduced to as low as 25% of normal without sacrificing control accuracy.

In order to minimize the heat gain from the general lighting system, it must be turned off during testing and measurements. To provide minimum illumination without adding any significant heat to the room, each room has four "light tubes", each with a 400 W lamp at each end, providing a total of 3200 W capacity. All heat producing components are located outside of the room. Infrared filter lenses in the tubes eliminate as much heat as possible and are ventilated to remove the absorbed heat. In order to distribute the light in the entire tube, a special coating is applied inside the tube. As requested by NIST, all components of these light fixtures are readily available and are used in various commercial applications.

Because of the low specific heat of air, maintaining the temperature at every point within a room to within ± 0.01 ºC is impossible if there is any significant heat gain. The goal of the design was to provide the users a tool: a large volume of precisely controlled air supplied at the ceiling with minimum possible velocity. In order maintain the required accuracy, the researchers must use that tool as carefully as possible. If a large piece of heat-producing equipment is located in the room, the temperature downstream from it and in close proximity cannot be maintained within the specified limits.

The concept of the control system is simple. A large volume of air is circulated through the room. In the air handling unit, it is cooled 0.5 °C below the desired room set point with ±0.1°C accuracy. The air is then precisely heated with an electric reheat coil using an SCR. This is controlled by a high accuracy PID controller having a 16-bit resolution, manufactured specifically for the AML. The main supply air temperature sensor, having ±0.001°C accuracy, is located downstream of the reheat coil. The feedback from the room is provided by four temperature sensors, using either their average or any one of the four for control. The accuracy of these four sensors is also 0.001 °C. The feedback from sensors provides the capability to reset the main discharge temperature sensor, maintaining the temperature within the room. To sense the true mixed air temperature at the main sensor location, several air blenders are located between the heating coil and the temperature sensor.

In order to minimize the heat gain from the adjacent space, the air from the room is returned through an air plenum surrounding the lab. Low wall registers located around the perimeter of the room assure even air flow distribution through the lab and minimize stratification.

The air distribution system was designed using "concert hall" duct sizing philosophy. Ducts were sized to provide progressively lower velocities, from 5 m/s in the main duct to 3 m/s in the branch ducts to 1.5 m/s velocity entering the plenum above the ceiling.

Each of the branch ducts is fitted with a series of air control devices: dual isolation dampers having scavenging ducts that remove leaking air from between, airflow measuring devices to monitor the volume of air, electric reheat coils for final temperature control, air blenders to assure a uniform temperature profile, high accuracy temperature sensors, and silencers before the air enters the ceiling space. In order to preserve the temperature accuracy of the air, the ducts downstream of the electric reheat coils have high efficiency insulation consisting of two layers of 50mm phenolic insulation with a thermal conductivity of 0.0188 w/KM.

Ventilation for each lab is provided by a makeup air unit supplying a minimum of six AC/h of outside air. In addition to ventilation, this air provides room pressurization, makeup for smoke evacuation and local exhaust, and most important, humidity control. The makeup air is cooled and dehumidified to 5°C dew point using low temperature glycol coils. Humidifiers located in the make up air duct use high-accuracy humidity controllers and sensors to maintain the desired humidity in the labs to ±1% accuracy.

The AML has a Building Automation System utilizing direct digital control technology based on BACnet communication protocol. All high accuracy controllers have adaptive tuning capabilities. The components of the high-accuracy control system include several operator's workstations, one for each department, allowing access to the entire system by the scientists. In addition, each high-accuracy laboratory has a local operator's panel outside the lab. Its function is to allow the users to easily set the temperature, humidity, and air volume of the room without logging on to the operator's workstation.

4.1 Temperature control research project

At the start of the project, the most difficult task the AML's design team faced was controlling the temperature in a laboratory environment to the unprecedented accuracy of ±0.01°C. In searching for the available control technology, it was discovered that while temperature sensors with the required one magnitude higher resolution, ±0.001°C, were commercially available, controllers typically used in the HVAC industry lacked the required resolution for such accuracy.

After developing the initial design concept, it became clear to the users and to the design team that a so called "Temperature Control Research Project" would be necessary. This would verify that the required control technology design concept would function as intended, and the control systems could be provided by multiple manufacturers for competitive bidding.

The project included a 3.5 m x 5.2 m prototype laboratory, which was about ¾ of the size of a typical lab module for the AML. Adjacent to the lab we constructed a control room that housed the electronics. The module was surrounded by a 0.8 m space on three sides. There was a 0.5 m space under the floor and a ceiling plenum for air distribution. Air flow at the rate of 300 AC/h provided 0.27 m/s average velocity. This entered through a continuous plenum ceiling and returned at three sides of the room through low wall registers into the annular space.

Some of the air was also directed below the raised floor completely surrounding the controlled space. The double glass window cavity between the control room and the lab was ventilated to minimize heat transfer. Air at 50 L/s pressurized the vestibule. To maintain the necessary cleanliness and provide for even air distribution, the ceiling had HEPA filters. The HVAC system included alternate components such as a hot water heating coil to verify if the required accuracy could be achieved with a hydronic system. The weather-maker section of the make up air unit could simulate year around outside air conditions at the site. The hydronic and electric slab heating system allowed the testing of vibration and EMI effects respectively.

After the construction was completed, three temperature control manufacturers were each contracted to install and test their system, verifying that functional controls were available from multiple sources. Testing of the system performance was done by NIST. NIST's Building and Fire Research Laboratory scientists built an independent overlay measurement system to test the controls based on rigorous protocol. The test system was completely independent, except that both the contractors and NIST evaluators used the same type of sensors, and all were calibrated by NIST.

Figure 1 illustrates an early test and shows excellent results. With the lights on, the temperature fluctuation was within ±0.01°C the vast majority of the time. After adjusting for the lights being turned off, the temperature stability was significantly better than this, even with two people entering the room, staying for three minutes, and then leaving.

Among the many test protocols, it was important to verify the system capabilities under conditions of no-load and load, at various air flow rates, and using an air-handler-mounted reheat coil instead of those located closer to the room in the branch ducts. Tests were also carried out to determine if hot water reheat coils could provide the required accuracy.

Under no-load conditions, the average room temperature was within 0.004 °C of the set point, but the individual sensors had a 0.03 °C gradient.

As the airflow was reduced to 120 AC/h, the accuracy reduced somewhat, but was still within the criteria. At about 40 AC/h, the room was out of specification.

The single electric reheat coil gave good results at full airflow, but the accuracy became less as the air flow was reduced.

In order to test the module at actual load conditions, a 300 W lathe was placed in the room. The stability of the average room temperature and at the individual sensors was quite good, but as expected, a large temperature gradient was observed at the individual sensors. Further, at reduced air flows the stability decreased and the gradient increased.

The TCRP provided the following insights:

- Controlling the temperature in a laboratory space with ±0.01 °C accuracy in every location is impossible with any significant heat gain. The best that can be done is to provide a system which will allow the researcher to precisely control the temperature of the air flow into the room. If there is no heat gain between the point of air discharge and the location of the experiment, the temperature of the air at the experiment can be maintained accurately.
- In order to accommodate some minimum heat gain and people movement, and to permit fast temperature recovery in the room, a large volume of air must be circulated. We have found that for ±0.01°C accuracy, 300 AC/h proves adequate in most circumstances.
- Using HEPA filters in the ceiling provides for good air distribution, good acoustical performance, and a cleanliness level close to ISO Class 5 (FS209 Class 100), often desired by the researchers.
- In addition to high accuracy temperature control requirements, some researchers are concerned about airflow-induced vibration. Consequently for those users, high air flows are unacceptable during experiments. In order to allow flexibility in the usage of the room, variable volume air handling units are required. In the AML, this feature is often used by the researchers.
- In order to maintain ventilation, room pressurization, and accurate humidity control, and to allow for smoke evacuation in case of fire, 6 AC/h of outside air is adequate.
- Based on currently available control technology, highly accurate temperature stability can be realized. Under no-load conditions, with no internal and minimum external heat gain, temperature stability of ±0.004 °C can be expected, and accuracy can be obtained to within ±0.01 °C. In rooms requiring stability at more than one point, some gradient greater than 0.01 °C can be anticipated.
- While ±0.1 °C accuracy can be achieved with hydronic reheat coils, greater precision requires low-watt-density electric reheat coils with SCR controllers.

In summary, the Temperature Control Research Project was highly successful, as borne out by the operation of the AML during the past year and a half. The users and the design team have gained valuable experience. Many of the results of the research projects and our design expectations have been verified by the actual usage of the facility. As more laboratories with similar criteria are built in the US and around the world, engineers will refine their designs, and better and better systems will be built with ever increasing energy efficiency and for less overall cost.

5. ELECTRICAL POWER QUALITY

Providing clean electrical power to a laboratory with sensitive and non-sensitive electronic equipment, located adjacent to other labs with their sensitive and non-sensitive equipment, all within a building with chillers, fans, pumps, elevators, etc., and connected to a utility grid with its changing types of power disturbances involves difficult choices and compromises. In a perfect world, each piece of sensitive lab equipment would be supplied by a dedicated power conditioner located adjacent to the equipment. However, these conditioners with their electromagnetic fields, heat output, noise and/or vibration characteristics can interfere with the experiment for which they are providing clean power.

Achieving an acceptable level of power quality required the installation of multiple levels of power conditioning. A separate substation was provided to serve only lab equipment; all other building loads were connected to other substations. Central uninterruptible power supply (UPS) units were provided to serve all sensitive electronic lab equipment. Each pair of lab modules was provided with two panel boards, one for sensitive equipment, and one for non-sensitive equipment. Each panel is served by a dedicated shielded isolation transformer. The transformers are located in the interstitial space just above the utility corridor adjacent to the lab they serve. These transformers provide electrical isolation between equipment within a lab and with equipment in adjacent labs. They also provide a good local ground and minimize stray ground currents. With the addition of shielding at each lab panel board and transformer, to attenuate their magnetic fields, clean electrical power is provided to each lab without compromising other lab criteria.

6. THE BIG STEP "DOWN" – MOVING UNDERGROUND

Experience at several European metrology laboratories suggested that vibration and temperature stability might benefit from placement of the critical spaces well below the surface. Most vibrations at grade elevation are Rayleigh or "surface" waves, which decrease with depth.[9] Thus, the placement of vibration-sensitive spaces as deep as practical should provide some benefit for this reason alone. There would be a secondary benefit (in the eyes of some) of a total absence of wind loading. Thermal load in the building would be stabilized, because there would be no exposure to the temperature variation of outside air.

The two wings housing the most environmentally-sensitive space (denoted the "metrology wings") were placed 12m (40 ft) below grade. The NIST-A1 pits extended below that. Grade beams extended across each wing to absorb the thrust from the bottom of the retaining walls. These were coordinated with the locations of NIST-A1 pits.

7. VIBRATION PERFORMANCE

When the facility became operational, thorough vibration surveys were conducted of each wing. The at-grade vibrations at the Instrumentation level slightly exceed the criterion over a limited frequency range (as do those in the existing NIST labs), but the vibrations at the below-grade Metrology level represent a significant improvement over any space previously available at NIST.

7.1 Slab stiffness

The stiffness of the 200mm (8 in.) slab-on-grade in the metrology wings was determined experimentally. Measurements were made using an instrumented hammer for a force source and an accelerometer on the floor to sense its response. The measurement process produces the property known as *accelerance*, a spectrum of acceleration divided by force. Accelerance may be integrated twice to obtain *receptance*, a spectrum of displacement divided by force. Receptance may be inverted to obtain *dynamic stiffness*, the objective of the measurement.[10]

In all, 70 locations were measured in this manner. These locations were a mix of corners, edges and middle areas of individual slabs in the two below-grade wings. (It is generally known that there is a difference in stiffness between the corner, edge, and middle of slabs on grade.) The average (log mean) interior stiffness was about $8.8\text{x}10^8$ N/m ($5\text{x}10^6$ lb/in). The edge and corner stiffnesses are $5.3\text{x}10^8$ N/m ($3\text{x}10^6$ lb/in) and $3.2\text{x}10^8$ N/m ($1.8\ \text{x}10^6$ lb/in), respectively. These are slightly higher than theory would suggest because the measurements were not made exactly at the corner or edge.

7.2 Floor vibration

Vibrations in the below-grade metrology wings were measured at 32 locations. Vibrations in the at-grade instrumentation wings were measured at 12 laboratory locations. These data are summarized in this section.

Some of the discussions of the data—in particular, those assessing compliance with vibration criteria—make use of a statistical representation of data from a group of measurement locations within a space. The ambient vibrations of a large area may be characterized by a spectrum representing the mean plus one standard deviation spectrum, *L(mean+sig)*, of a collection of spectra obtained at a statistically significant number of locations randomly distributed throughout the area of interest. The *Lmean* and *Lsig* spectra are defined for a collection of spectra X_i, and the statistics are calculated for each frequency. The two spectra are combined in *log space* to obtain *L(mean+sig)*. [This statistical approach is discussed in Ref. 11.]

The data for the two metrology wings were combined and subjected to statistical analysis. Table 1 summarizes the log mean plus one log standard deviation (Mean+SD) vibration amplitudes for all of metrology. The amplitudes lie well below NIST-A. Figure 1 summarizes the spatial statistics for all of the on-grade metrology spaces.

Table 1. Vibration in Both Metrology Wings, Mean+SD of All On-Grade Locations, by Direction

	Vertical	**North-South**	**East-West**
Displacement, nm	10.2	10.0	8.9
Velocity, µm/s (µin/s)	1.0 (41)	0.8 (32)	0.7 (28)
Acceleration, µg	19.0	7.7	7.8

The vibrations in the below-grade metrology wings are significantly better than the design goal of NIST-A. It is in this environment that the pneumatically isolated A1 slabs will be used, further reducing the vibrations by an order of magnitude or more. At frequencies above 10 Hz, the A1 slabs will provide a velocity amplitude of 0.1 m/s at the base of the researchers' instruments. This represents a thirty-fold improvement over what was previously available on the NIST campus.

One of the most important considerations in the vibration design of the AML was the decision to place the metrology wings below grade. The supporting argument behind this decision was based on accepted research, but was somewhat qualitative, since an actual model would have been costly in terms of both modeling effort and field measurement of *in situ* dynamic properties.

The value of having made this decision is shown in Figure 2. At frequencies below 10 Hz, the reduction in amplitude is quite dramatic in all three directions. The reduction (in decibels) in vertical Mean+SD amplitudes is 8 dB or more at frequencies below 20 Hz, increasing to 15-20 dB at lower frequencies. The reduction in horizontal amplitude is less dramatic, 3-5 dB between 10 and 20 Hz, and 5-15 dB between 6 and 10 Hz. The most significant improvement was in the low frequency range ($f < 20$ Hz) in which displacement was the greatest concern. In this respect, we can conclude that placement of the metrology wings at depth accounts for the nearly 8 dB "gap" between the Mean+SD performance and the 25 nm goal.

8. CONCLUSION

The NIST Advanced Measurement Laboratory has been heralded as one of the best research environments in the world. This characterization is based upon several aspects of the research environment, but largely because of its vibration and temperature control features.

Philip J. Bond, Undersecretary of Commerce for Technology, spoke for the government when he stated that "…extreme levels of environmental control make the AML a research facility beyond compare. But it will be emulated around the world. Many of the so-called "nano" buildings under construction—or being planned—will incorporate advances pioneered in this facility. And, in fact, these advances stem from research and technology evaluations done here, by NIST researchers."

We have discussed some of the details that have contributed to this reputation. In many cases, the performance has been enhanced by taking the conservative route when making design decisions. Some of these, such as the decision to move underground, have been expensive. Others, such as the decision to use an essentially off-the-shelf temperature control system, saved the government considerable expense. Many of the "lessons learned" have been portable to subsequent designs of nanotechnology facilities, and important intangible benefit.

ACKNOWLEDGEMENTS

A project of this complexity cannot be carried out without the participation of a large team. The authors wish to acknowledge the contributions of the researchers who made up Technical Advisory Group, the project managers and building professionals of the Capital Improvement Facilities Program (CIFP) team, who pulled it all together, NIST management, and the other members of the design team.

REFERENCES

1. Institute of Environmental Sciences (IEST), Appendix C in Recommended Practice RP-012, "Considerations in Clean Room Design," *IES-RP-CC012.2*, Institute of Environmental Sciences, Rolling Meadows, IL, 2005
2. H. Amick, M. Gendreau, T. Busch, and C. Gordon, "Evolving criteria for research facilities I: vibration," *Proc. Intl. Soc. for Opt. Engng. (SPIE), Vol. 5933: Buildings for Nanoscale Research and Beyond*, San Diego, CA, 31 Jul 2005 to 1 Aug 2005
3. H. Amick and S. Bui, "A Review of Several Methods for Processing Vibration Data," *Proc. Intl. Soc. for Opt. Engng. (SPIE), Vol. 1619* (Nov. 1991).
4. H. Amick, B. Sennewald, N. C. Pardue, C. Teague, and B. Scace, "Analytical/Experimental Study of Vibration of a Room-Sized Airspring-Supported Slab," *Noise Control Engrng. J.*, March/April 1998, Vol. 46, no. 2, pp. 39-47.
5. C. H. Amick, *Concrete Damping Properties and their Modification*, dissertation in partial satisfaction of Doctor of Philosophy, University of California, Berkeley, 2005, 396 pp.
6. H. Amick, "Modification of concrete damping properties for vibration control in technology facilities," *Proc. Intl. Soc. for Opt. Engng. (SPIE), Vol. 5933: Buildings for Nanoscale Research and Beyond*, San Diego, CA, 31 Jul 2005 to 1 Aug 2005
7. H. Amick, T. Xu, and M. Gendreau, "The Role of Buildings and Slabs-on-Grade in the Suppression of Low-Amplitude Ambient Ground Vibrations," *Proc. 11th Intl. Conf. on Soil Dyn. & Earthquake Engng. (11th ICSDEE) & the 3rd Intl. Conf. on Earthquake Geotech. Engng. (3rd ICEGE)*, 7-9 January, 2004, Berkeley, CA.
8. Zsirai, T., Williams, S., and Sennewald, B. (1997). "Researchers Seek Strategies for Metrology Lab Temperature Control," *Lab. Design*
9. Richart, F. E., Hall, J. R., and Woods, R. D. (1969), *Vibration of Soil and Foundations*, Prentice-Hall, Englewood Cliffs, NJ
10. H. Amick and A. Bayat, "Meeting The Vibration Challenges Of Next-Generation Photolithography Tools," *Proc. ESTECH 2001*, 47th Annual Technical Meeting, IEST, Phoenix, Arizona (April 2001)
11. Amick, H., M. Gendreau, and T. Xu, "On the Appropriate Timing for Facility Vibration Surveys," *Semiconductor Fabtech*, No. 25, March 2005, Cleanroom Section

Figure 1. Performance of thermal control in typical VIRP test.

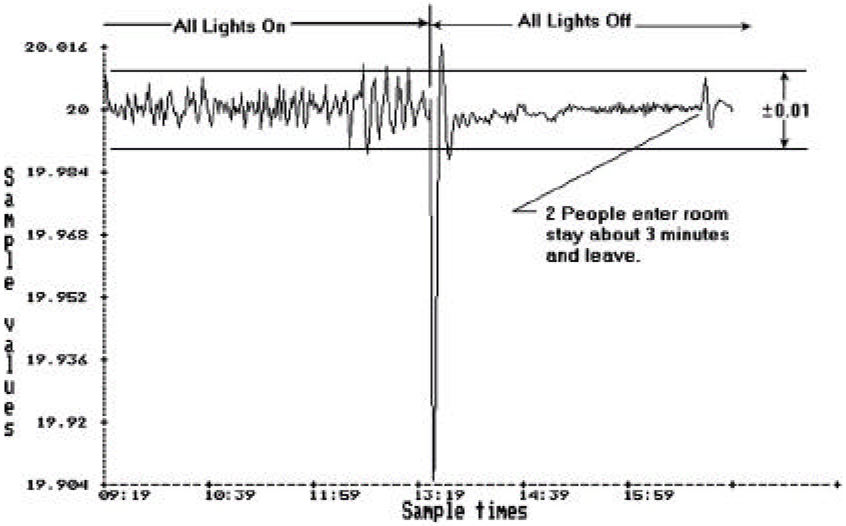

Figure 2. Statistical representation of vibration amplitudes of all on-grade spaces in the two metrology wings

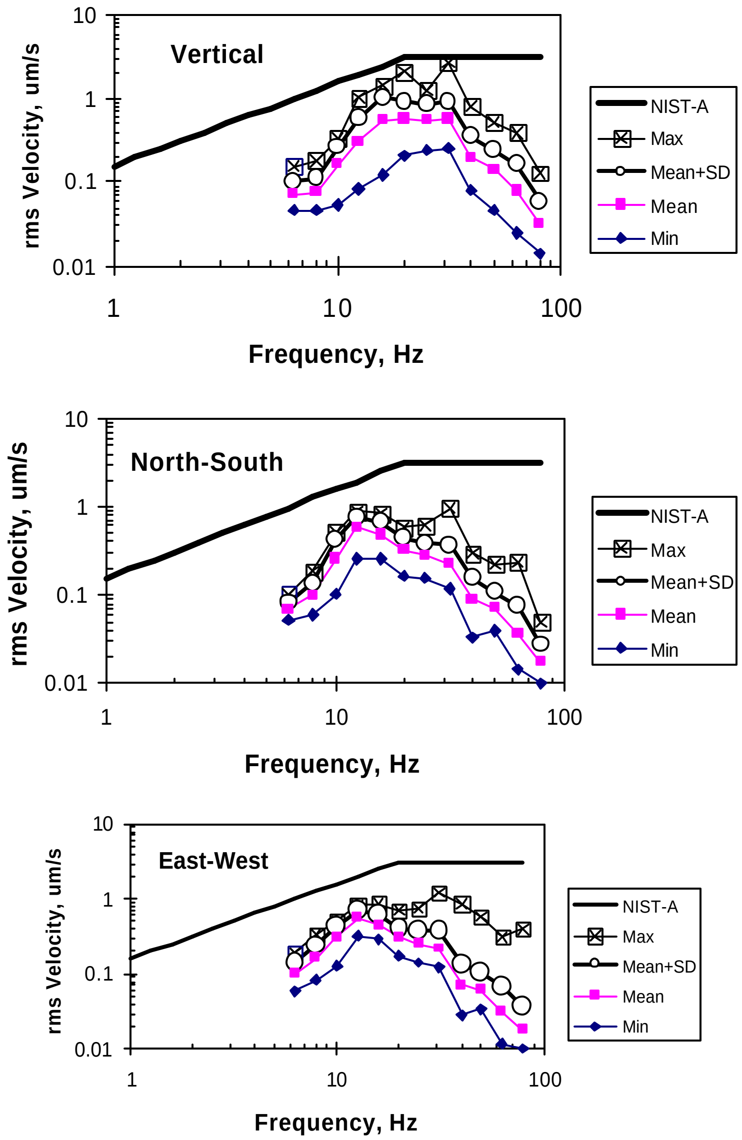

Figure 3. Comparison of Mean+SD in Instrumentation Wings (at-grade) and Metrology Wings (12m below grade)