# NIST - ADVANCED TECHNOLOGY LABORATORIES: METROLOGY LABORATORIES & VIBRATION CONTROL

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The focus of this paper will be on laboratory design and issues related to vibration mitigation based upon the recent experience of Henningson, Durham and Richardson (HDR) and its consultant, Acentech, in designing new Advanced Technology Laboratories (ATLs) for the National Institute of Standards & Technology (NIST). Issues related to site selection, laboratory plan concepts and details designed to mitigate environmental vibration will be discussed. Additional discussions will center on the prototypical research projects undertaken by HDR/Acentech on behalf of NIST, with particular emphasis on the pneumatically supported inertia slab used to verify and refine design concepts to be employed in the metrology laboratories for the ATL.

## OVERVIEW OF NIST ATL PROJECT

### ATL Project Goals

In November of 1992, HDR was selected to design the Ten-Year Facilities Program for NIST. Included in this program is the design of new Advanced Technology Laboratories and the renovation of existing laboratories on both the Gaithersburg, MD and Boulder, CO campuses. The impetus for such a major program is due to the Clinton Administration's policy to stimulate the American economy through technological competitiveness. Historically, NIST has been a major resource to industry because it maintains national standards and undertakes basic research. With such a history of service to industry, NIST has been charged as one of the primary federal agencies to support the new national agenda.

The Advanced Technology Laboratories are an essential component of NIST's enhanced mission of supporting America's technological competitiveness. These new laboratories are required because of the dire obsolescence of the existing laboratory space. Facilities in Gaithersburg were opened in the early 1960's; facilities in Boulder were opened in the early 1950's. The buildings have been well maintained, but have never been substantially upgraded.

During the last four decades, the technology of science has advanced significantly. In 1960, chemistry was studied in the beaker; the advent of scientific investigation at the micro scale was still on the horizon. Science is now at subatomic levels: disciplines such as physics, chemistry, and materials science now converge. At this scale, small inputs of energy induce oscillation and become a critical obstacle to visualization. When working at the scale of a billionth of a meter, stability in temperature is required to within 1/100th of a degree Celsius along with control of vibration to a velocity of less than 3 micrometers per second.

Such conditions cannot be achieved within NIST's existing laboratories. As additions to the existing laboratories on both Boulder and Gaithersburg campuses, the new ATL's will provide highly specialized research space which cannot be achieved through renovation of existing buildings. The new ATLs do not represent any physical growth of research programs or staff; the sole purpose of this building program is to upgrade the technological capacity of the laboratories at NIST.

The primary goal of the Advanced Technology Laboratory is to create the most environmentally stable laboratory in the world. No building has yet achieved concurrent stability in temperature, vibration and power to the degree this project is seeking. While control of each of these environmental variables is challenging in itself, the greater challenge will be the integration of all these criteria into a single space.

*Temperature Control.* Providing temperature control to 1/100th of a degree Celsius will be a major challenge. The volume of air required and the various stages of treatment will be major components of the project. Control systems for this level of performance do not exist and will have to be specially designed and fabricated. Additionally, it is necessary to develop a simple operating system to maintain the environment over time.

*Vibration Control.* Laboratories will be located on grade, the best possible location with regard to vibration. Where more stringent vibration controls are necessary, special airspring isolation slabs will be constructed. While airspring technology has been in use for over twenty years, the ATL will incorporate controls which are significantly more responsive than commonly used. Three different levels of controls for vibration isolation are being tested to evaluate the relative value of high technology systems currently available. The isolation slab design is intended to be very flexible with replaceable springs, allowing scientists to customize laboratories as needs or technologies change.

*Power Quality.* Clean power is important for the accuracy of the instrumentation utilized in the ATL. Providing high quality power involves a difficult compromise. Better power quality results when the distance between the conditioned source and lab instrument is minimized. However, power conditioning equipment creates electromagnetic interference, heat, noise and dust—all major problems in these laboratories. Five different approaches were examined to determine the optimal balance of these competing concerns. A second major issue affecting power quality is the feedback that is generated by lab equipment into the power system. Mitigating this disturbance or "noise" requires segregation of the system into two systems. The proposed design provides complete distribution systems for conditioned and unconditioned power.

*Future Upgrade Capability.* While some labs will have highly specialized environments at move in, all labs will be built to meet a common baseline quality level, with the flexibility to adapt to more specialized requirements and to future needs which may not yet be defined. Even better environmental stability may be added in the future because mechanical space, electrical capacity and utility distribution systems have been designed for change. To assure flexibility and adaptability for future temperature control requirements, base mechanical systems have been designed with auxiliary specialty mechanical systems. Furthermore, vacant space is available in mechanical rooms, so HVAC equipment can be modified or replaced as new technologies become available.

*Real Time Monitoring of Laboratory Environmental Conditions.* The ATL will have a building management system that will allow scientists to observe and, to some degree, control environmental conditions in their labs while experiments are being conducted. In-lab monitors may be set to display factors important to the experiment, such as temperature, humidity, or other variables. Sensors may be installed at the experiment by the scientists, to record real-time conditions of the lab environment.

*Serviceability.* This laboratory has been designed with exceptional attention given to serviceability, allowing for frequent maintenance with minimal interruption of the laboratories. Two separate service zones have been planned, one for plant and maintenance staff and another for scientists. The plant/maintenance service zone consists of mechanical and electrical rooms and the space above the laboratory ceiling. Included above the laboratory ceiling will be a walk-in space for accessing air control boxes, air filters, reheat coils, special humidification equipment, ductwork, and main utility lines.

A separate service zone will allow users to control services to their labs, without interfering with sensitive building-wide systems. The scientists' service zone will consist of a service corridor running the entire length of the labs. All lab-related services will be located here: power panels, hot water, cold water, and all gases, including cylinder gases. The service galleys will be separated from the floor slabs in the labs to control vibration and noise which may be generated by pumps and motorized equipment located in this area.

## Laboratory Design Approach

Requirements of the laboratory space drive both the architectural form of the ATL and the organization of the building as a whole. The same design concepts and detailing are used for Gaithersburg and Boulder. The design incorporates five major lab-planning concepts:

- Modular lab dimensions
- Hierarchical zoning
- Separate service galleys from staff/public circulation corridors
- Separate above-ceiling service zone
- Provision to upgrade lab quality in the future

## Lab Modules

The design reflects the use of a standard module in developing lab program requirements. In the layout, this translates into regular linear module configurations. The module concept is carried through all three kinds of labs, although the application varies somewhat between lab types.

The design uses a modular approach to lab planning, with a standard lab module of 6900 mm by 3600 mm. This module determined the column grid, the placement of corridors and fixed spaces and provided organizational patterns for mechanical, electrical and communication systems. The original planning module for the program was set at 24.5 square meters, 3500 mm by 7000 mm. During design, the module was adjusted to a width of 3600 mm to conform to a 600 mm planning module for the building. Column spacing respects the lab modules, allowing lab interiors to be free of column intrusions. To achieve this, column center lines are 3600 mm by 10,200 mm. Lab partitions are independent of the columns.

A lab may consist of a multiple number of modules. Normally, lab spaces are separated from corridors to assure environmental control. When the corridor is integrated into the lab space (as in the Cleanroom), controls are established for an entire block. Cleanroom lab modules are 3600 mm or 4200 mm by 12,000 mm. They alternate with 2400 or 1800 by 12,000 mm service chases. Some areas of the Cleanroom have a more open concept which expands beyond normal modular dimensions.

## Hierarchical Zoning

Spaces within lab blocks are zoned according to the degree of temperature, vibration and air quality control required. Sensitive labs are placed in internal zones, buffered from disturbing influences by support spaces.

## Service Galleys

In the laboratory block, service galleys alternate with public corridors. They provide secondary egress from labs and serve as circulation for materials handling. Additionally, each service galley contains two 1000 mm wide strips of floor area designated to house scientific support equipment, such as pumps or motors. The floor of the service galley is isolated from the floor of the laboratories to make this segregation of rotating equipment more effective.

The upper part of the service galley will contain the distribution piping for lab utilities. Open grills on either side of the galley will provide access and simplify new connections. It is intended that scientists will have direct control over the gases and liquids used in their labs.

## Above-Ceiling Service Zone

An accessible ceiling space above the labs provides access to the air supply and return ducts, terminal boxes and coils. The ceiling system in every lab can support walking loads. The ceiling will consist of removable panels to facilitate changes in air supply, exhaust or lighting in the labs.

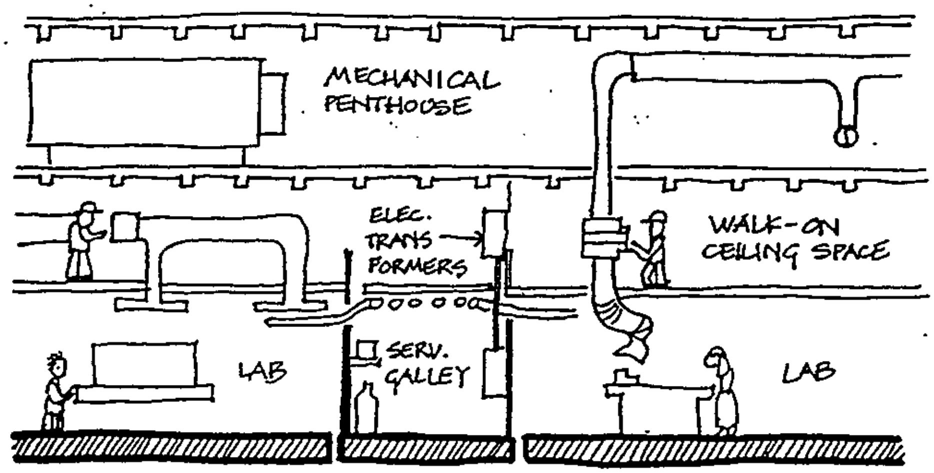


*Figure 1. Typical Section Through Instrument Laboratories*

## Mechanical Rooms for Instrument Labs and Metrology Labs

The air handling units required for the tight temperature and air quality control of the ATL are located in mechanical rooms above the laboratories in Instrument Lab blocks. The structure of the mechanical room is completely isolated from the laboratory floor.

Unlike the Instrument labs, Metrology mechanical equipment space is located in a two-story structure adjacent to the lab block. This configuration reduces the overall height of the structure, thereby reducing the amount of excavation required because metrology is below ground.

## Provisions to Upgrade Lab Quality

Mechanical and electrical space in the ATL is designed to readily accept future upgrades. Space is available in all lab blocks to add air handling equipment for future temperature control or air cleanliness requirements. Access doors and panels, as well as routes within the building, have been planned for maneuvering large pieces of equipment.

The main utility systems - chilled water, steam and power feeds - are sized with ample space capacity. Distribution systems have also been oversized to accommodate future load concentrations for piped and electrical services. The guiding philosophy is to strive for a "loose fit" for all engineering systems which will accommodate future upgrades gracefully.

Each of the mechanical rooms have a number of empty bays that can be equipped for special purpose labs. Future upgrades are limited only by the floor plate size. Instrument labs have the most space available for future units. "Quiet" Metrology has the capacity to upgrade some (but not all) lab modules. "Rotating" Metrology already illustrates the ultimate build-out because of the large number of labs requiring special air quality.

Future upgrade construction can be accomplished with minimal disruption of neighboring labs.

The air handling units for the Cleanroom are located in space between steel roof trusses. The trusses provide a clear span across the cleanroom leaving it column free. The columns supporting the trusses are completely isolated from the Cleanroom floor slab.

## Laboratory Features

*Service module panel.* A service module is planned for each lab. While this panel is not yet totally defined, it will be built as a cabinet housing safety equipment, fire blankets, fire extinguisher, fire alarm strobes, a key pad, and telephone. A space will be left for a future CRT screen on the corridor side.

The monitor could give a summary of the science for tour groups, perhaps in an interactive mode.

The module will be integrated with the moveable partition system, so it can be relocated as needs change. The design will be flexible to accommodate additional functions in the future.

*Suspended Utility Grid.* A utility grid of U-channel steel sections is planned below the walk-on ceiling to support piped services and power for connection to equipment. This grid will also facilitate mounting of local HEPA filters where required.

*Raceways.* The interior of the lab walls is planned to be free of utilities to make relocation as easy as possible. Raceways for power and communications will be surface mounted.

*Wet Zone.* A zone near the service galley will be designated for placement of sinks.

## Cleanroom Design

The Cleanroom is designed as a large block with 12 meter-long lab modules arranged along either side of a clean corridor. Access to this corridor is through a gowning area and airlock vestibule. There will also be a wipe-down station where equipment will be cleaned before it is brought into the cleanroom.

Flanking the Cleanroom modules are service chases for air return, through-wall equipment, and piped service distribution. The entire clean space will be classified M3.5 (Class 100). A service corridor surrounds the Cleanroom. This corridor is intended for delivery of supplies, chemicals and equipment. Pass-throughs from the corridor to the Cleanroom will facilitate handling of supplies and chemicals.

It is envisioned that staff working in the Cleanroom will be fully gowned, while personnel using only the service corridors or chases will only wear shoe covers, caps and lab coats.

A separate observation corridor runs parallel to the service corridor. Glazing in both corridors permits views into and through the Cleanroom.

Vertical laminar airflow passes through the Cleanroom from a HEPA filter ceiling to a perforated raised access floor. It then passes horizontally to the chase on either side and back to the recirculating air landing unit through an open plenum.

The air handling units are mounted on a floor on the bottom chord of the cleanroom truss. Return air is ducted from the plenum below to the return side of the air handlers.

A vertical plenum divider separates the cleanroom into two compartments, separating the air systems. Epitaxy, diffusion and chemical vapor deposition equipment occupy one compartment; other cleanroom functions such as photolitography and wet etch occupy the other. The intent is to confine equipment using pyrophoric and toxic gases.

The Cleanroom floor is a large vibration isolation slab, approximately 1 m thick and supported by closely spaced columns. The floor below the cleanroom will house the distribution systems for DI water, gases, waste, power and communications. It will also contain gas cabinets, most of the vacuum pumps required for the cleanroom equipment and a lab waste treatment system. Two rooms with explosion vents have been designed for storage of toxic and pyrophoric gases.

## Special Laboratory Spaces

*High Accuracy Temperature Control Labs.* Most of the labs requiring ±0.10 or ±0.01 degree C temperature control are located in the east and west blocks of Metrology. These labs are planned as a room within a room. Double walls provide an annular space which allows air circulation around the internal room and acts as a buffer. The inner room is planned to be built from insulated metal panels similar to the construction of a cold room.

Because air handling equipment for these labs cannot be remotely located, meeting the vibration criteria and the desired level of temperature control is a special challenge. The overall goal is to keep all energy generated by building equipment below the background level of the site. Two-stage isolation systems are required for all motors and fans in this area.

*High Bay Areas.* High bay areas may be required at different locations in the lab blocks over time. The architectural configuration accommodates labs requiring high bay clearance because the walk-on ceiling can be raised and ductwork rerouted. The design allows the height of lab ceilings to vary to a maximum height of approximately 7000 mm and high bay spaces to be dispersed through the building. At initial occupancy, only a few labs require high bay space.

*Cleanrooms Within Instrument or Metrology Lab Blocks.* Some lab spaces in the Instrument or Metrology areas will require cleanroom conditions. These rooms will have HEPA filters and low wall returns.

*Support Spaces.* Spaces include temporary lab storage, toilets, break rooms, copy centers, electrical and communications closets, janitor's closets and recycling stations. Support space for offices and labs is located in the zone between them. They serve as a buffer between office and lab areas.

## Space Assignment in the ATL

The ATL occupants may have a high turnover rate, with new experiments and programs replacing completed projects. As part of the philosophy expressed by NIST, division will be assigned permanent space in the ATL. Space allocations will be based on demonstrated need for high quality laboratory space. The facility will be a resource for the campus as a whole.

## Central Mechanical and Electrical Spaces

Because steam and chilled water are provided from a central utility plant on this campus, the ATL will not require extensive physical plant spaces. The building has spaces for pumps for steam and chilled water.

Chillers for the glycol system and the emergency generator are located at the south end of the Cleanroom.

Electrical substations will be placed in rooms along the spine on the service level between main level labs and metrology level labs. Buffer zones around the substations will be sized to preclude electromagnetic interference.

## Site Selection

One of the major considerations in the siting for the ATLs on both campuses was the consideration of ambient vibration existent on the site. Each campus had two alternate sites for consideration as the possible site for a future ATL. Among the evaluation criteria for selecting the future site were the following:

- Site Vibration/Geotechnical Issues
- Adjacencies (new facilities relative to existing facilities)

- Disruption to existing operations
  - Construction vibration
  - Traffic vibration
  - External influences - Noise
  - Dust and pollution

- Masterplanning Issues
  - Future developmental limitation
  - Service traffic
  - Environmental issues

- Impact to existing utilities

- Aesthetics
  - Campus Image
  - Community Relations

Limiting and mitigating environmental vibration was such a fundamental issue for these facilities that it played a major role in the selection of the site on both campuses. Previous preliminary vibration criteria had been established by NIST in their programming document. The programming document identified three levels of vibration criteria, stated as three vibration amplitude functions, given in terms of one-third octave band rms velocity spectra.

*Criterion Type A:* rms displacement amplitude of 25 nanometers at frequencies between 1 and 20 Hz; rms velocity amplitude of 3 micrometer/sec at frequencies above 20 Hz and less than 100 Hz. The displacement portion of the criterion was based on user-defined future desires for NIST's ATL scientists. The velocity portion of the criterion was based on an industry standard intended for high-yield semiconductor photolithography with line widths between 0.3 and 0.7 micrometer, and for electron microscope based systems with magnification on the order of 300kx to 500kx.[1, 2, 3]

*Criterion Type B:* rms velocity amplitude of 6 micrometers/sec at frequencies above 1 Hz. This criterion was based on an industry standard intended for semiconductor photolithography with line widths between 0.7 and 1.5 micrometers, for optical bench microscopes with magnifications on the order of 1000x and for electron microscope-based systems with magnifications on the order of 50kx to 100kx.

*Criterion Type C:* rms velocity amplitude of 25 micrometer/sec at frequencies between 4 and 100 Hz. This criterion was based upon an industry standard intended for optical bench microscopes with magnifications on the order of 250x, and for semiconductor photolithography with line widths between 3 and 7 micrometers.

HDR contracted with Acentech Incorporated to conduct detailed site vibration studies on each potential site of both campuses. Site vibration measurements were taken at two locations on the Gaithersburg and Boulder campuses. While the two Boulder locations proved to be identical in vibration characteristics, in Gaithersburg there were marked differences, with proximity to Interstate

270 defining the noisier site (See Figures 2, 3, and 4). On both campuses the quietest area was chosen for the new Advanced Technology Laboratories.

*Figure 2.* *NIST - Gaithersburg Survey*
*North Site, NE Corner (7:00 - 7:30 am, 5/5/93, Morning Rush)*

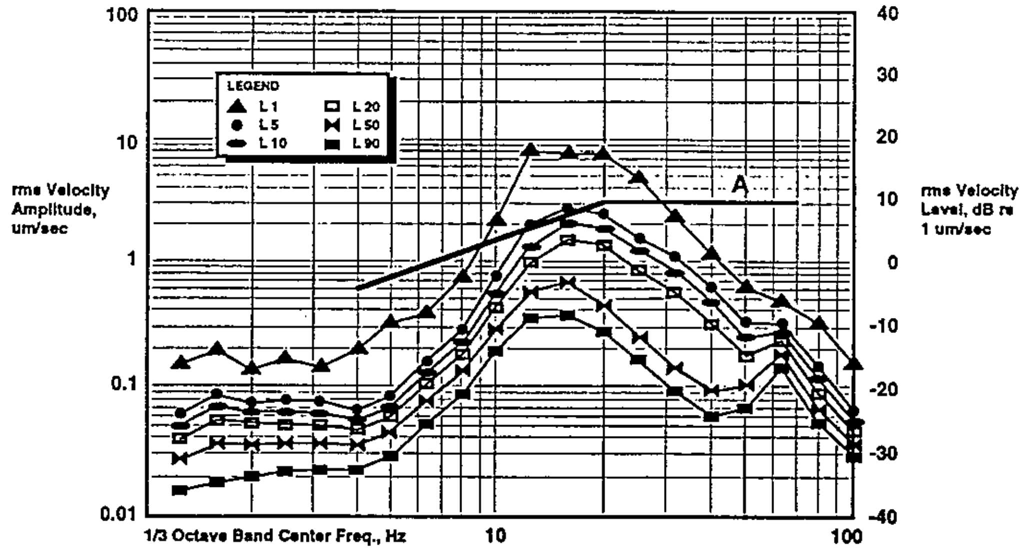


*Figure 3.* *NIST - Gaithersburg Survey, South Site,*
*Center Vertical (8:30 - 9:00 am, 5/7/93, Morning Rush)*

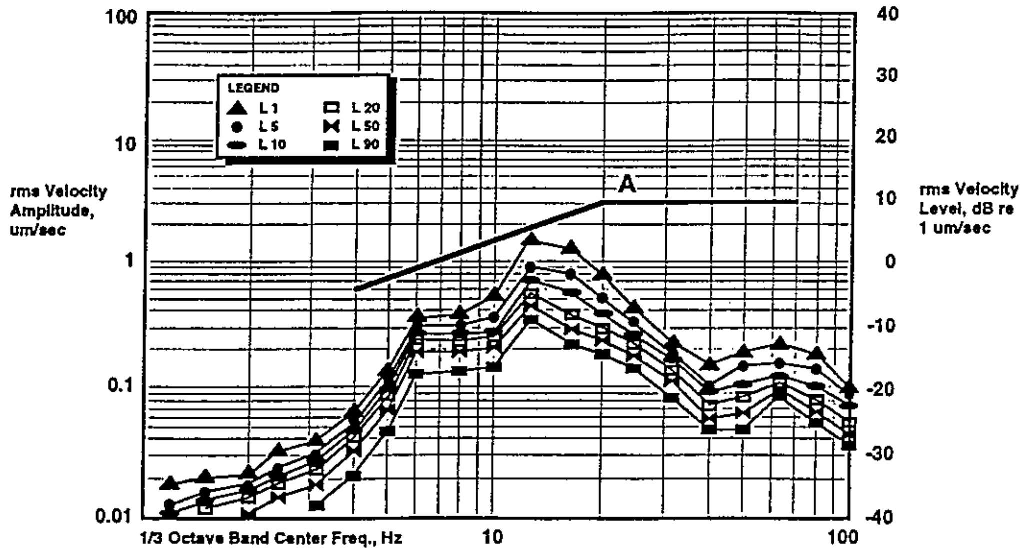
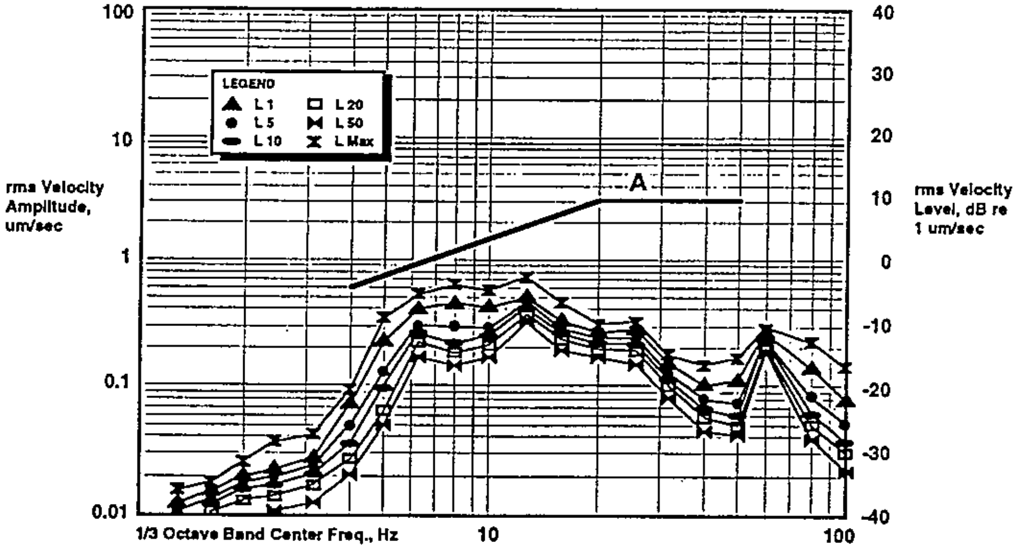


*Figure 4.* *NIST - Gaithersburg Survey, South Site, Center Vertical (4:00 - 4:30 am, 5/7/93, Train Passage)*



At the chosen locations, vibration spectra lie slightly below criterion curve A. The exception is in the frequency range of the 5 and 6.3 Hz one-third octave bands where there are campus-wide (Gaithersburg campus) vibrations that slightly exceed the 25 nanometer criterion. The source of these vibrations has not been found. Also, on both campuses there are some vibrations induced by mechanical equipment located in existing buildings. A diagnostic effort is underway to pinpoint sources and develop a mitigation plan.

Not only did NIST elect to place the new ATLs on sites with the lowest ambient vibration, but these studies resulted in two unanticipated developments:

- Both campuses had relatively quiet sites. The selected sites on both campuses were able to achieve vibration criterion A (The Boulder Campus vibration study discovered significant site-wide vibration due to mechanical equipment on campus, which was was not isolated. This was corrected immediately).

- NIST in discussions with HDR and Acentech soon realized that they could achieve a fundamentally superior vibration environment for all of their ATL scientists, if all laboratories were located at grade.

The mission of the ATL set the tone for further discussions between NIST and the design team. These discussions, in view of the ATL's mission and the site vibration studies, resulted in NIST eliminating vibration criteria B and C. Further, NIST challenged HDR and Acentech to propose a more stringent vibration criterion and a method of achieving it for the most vibration-critical occupants of the ATL - the metrologists. This challenge resulted in the development of a new vibration criterion.

HDR and Acentech proposed the following new criterion, A1, and associated design approach in view of the desire of NIST to improve their environment over ambient vibration levels.

*Vibration Criterion A1:* rms velocity amplitude of 0.75 micrometer/sec at frequencies above 8 Hz; below 8 Hz would be determined after measurements were made on a prototypical concrete inertia slab supported on pneumatic springs (to be discussed below).

Additionally, the conçerns regarding the vibration of metrology led to site and building plans that placed the metrology laboratories on both campuses below grade; that is, a buried metrology.

## APPROACHES TO VIBRATION CONTROL IN NIST ATLS

### Vibration Criteria

As the evaluation unfolded of existing NIST facilities, the proposed sites, and a prototype pneumatically isolated slab, the ATL vibration criteria have evolved from those originally proposed by NIST into those stated below. They are stated as amplitude functions given in terms of one-third octave band spectra.

*Criterion Type A*: RMS displacement amplitude of 25 nanometers at frequencies between 20 Hz; RMS velocity amplitude of 3 micrometers/sec at frequencies between 20 and 100 Hz.

*Criterion Type A1*: RMS velocity amplitude of 3 micrometers/sec at frequencies below 4 Hz; rms velocity amplitude of 0.75 micrometer/sec at frequencies between 4 Hz and 100 Hz.

The base vibration criterion A will apply to most laboratory space in the ATL. Specific areas in the Metrology Laboratory areas will be designed to criterion A1 (high sensititivity).

### Vibration Control Throughout the Design

Vibration control cannot be relegated to just one phase of the design process. It starts with determination of user requirements and establishment of vibration criteria and involves an evaluation of the ambient vibration environment of the site, issues which have already been discussed. It also requires consideration throughout the design and construction of the facility. The primary issues that must be considered during design of a laboratory include mechanical systems, interior vibration paths, and floors.

The successful implementation of vibration control is not simply a function of design. Careful construction observation by experienced personnel is necessary to verify that installation details have been followed.

### Vibration Isolation and Noise Control of Mechanical Systems

Air handling systems, exhaust systems, pumps, chillers, compressers and other items of rotating equipment are the source of both vibration and noise, and must be given considerable attention during development of the design documents for a metrology laboratory.

Additionally, random (broadband) forces are generated in large ducts by discontinuities in air flow such as elbows, tees, dampers and air valves. The spectrum of the forces generated by duct turbulence is like a haystack. Empirical evidence suggests that the amplitude of the dynamic forces is a function of air flow velocity in the duct (higher velocity produces larger forces) and the predominant frequency (at the peak of the haystack) is a function of the inverse of the duct diameter (A larger duct produces a lower predominant frequency).

The response of the building to broadband loading from fan housing and duct turbulence tends to be "shaped" by resonances in the building structural system. It appears that the ground attenuates these vibrations in a frequency-dependant manner but does not "shape" the spectrum. The response of a suspended floor to turbulence-induced broadband forces has been shown to be inversely proportional to the midbay stiffness of the floor[4].

Piping systems of significant size must be vibration isolated. Flexible pipe connections are typically provided in pipe connections to all vibration isolated pieces of equipment. To avoid the transmission of air flow turbulence-induced vibration to the building structure, most of the major ductwork can be resiliently supported. These duct vibrations (which occur at frequencies less than 125 Hz, and which can be expected to be a significant concern in very large ducts) can be controlled by addressing duct size, length and shape, duct layout (including transitions and changes in direction), duct location (with respect to vibration-sensitive areas), flow velocity, and vibration isolation hardware.

Airborne acoustic noise (sound) can also be a source of vibration in a laboratory setting. Excessive sound can excite internal resonances of laboratory equipment. In some cases, the sensitivity is to noise in the audible frequency range, particularly the speech range (200 to 2000 Hz). Some electron-microscope-based systems are unable to provide clear images if someone is talking in the same room.

## Attention to Interior Details

Care is being taken with structural layout of the ATLs to direct as much vibrational energy as possible through columns into the ground. However, it is impossible to completely prevent interior walls from becoming secondary vibration transmission paths. In a conventional building configuration, walls are rigidly attached to the floor, but in the vibration-sensitive metrology areas (and certain other spaces) this is undesirable. The wall can transmit its vibrations into the floor, and/or it can provide a shortcircuit path for vibrations to travel across a joint in a slab. The design of the facility tries to minimize the vibratory energy transmitted by secondary paths by implementing approaches such as that described below.

Demountable partitions are being specified for most walls. The bottom track of the wall will be placed on two continuous strips of neoprene under the base track. The strips will be about 20 mm wide and 5 mm thick, and will be 20 to 30 durometer solid neoprene. The bottom of the wall will be caulked to the floor with silicone sealant. The base of the wall will be anchored to the floor using normal anchoring bolts, but neoprene grommets will be used around the bolts and a washer will be used between the bolt heads and the faces of the grommets.

## Floor Designs

The laboratory floors for the ATLs fall into three categories:

*Slabs-on-grade:* Concrete slabs poured directly on well-compacted soil, used for all metrology space and most other laboratory space.

*Suspended:* Deep concrete grillage-and-slab configurations (so-called "waffle" slabs) with relatively close column spacing for high stiffness and resonance frequency, used in the Cleanroom, where a basement is required. Lateral stiffness will be provided by shear walls.

*Vibration isolated:* Concrete inertia "slabs" supported on springs, used where vibrations must be attenuated to levels significantly below those provided by the site.

Several terms defining floor characteristics have had to be created for this project. For clarity in the discussion that follows, their definitions will be given here.

In the following discussion, the term "walk-on" floor will mean one independently supported above and separate from the structural floor or vibration-isolated A1 slab. When a walk-on floor is used, only vibration-sensitive experimental equipment is supported on the concrete slab, and all other equipment and personnel will be supported on the structurally separate "walk-on" floor, the loads of which are carried to the ground via a separate path. Dynamic loads due to personnel walking or loads being dropped will not travel directly to the concrete slab (However, vibrations due to the vibration-sensitive equipment being put in place or moved cannot be avoided). Several concepts have been discussed for the actual support of this floor, but the detailed means of support are independent of the definition.

The term "conventional" floor will mean one which supports both sensitive equipment and personnel. Personnel can walk on this floor, causing vibrations of the slab, and there is the risk that objects such as wrenches and gas bottles can be routinely dropped on this floor.

When discussing joints in a slab, it is important to make a distinction between the two types of joints that can be encountered (from the point of view of mechanics). An isolation joint, or one with a measurable gap on the order of 12 mm, will act as a discontinuity of the slab with respect to the slab's ability to resist a load or internally transmit a vibration. In general, it will not diminish deflections of the soil beneath the slab nor will it attenuate groundborne vibrations. A construction joint, or one with no measurable gap and which exists only to accommodate interruptions in the construction process, will not act as a discontinuity over the range of amplitudes and frequencies of concern in a laboratory. The presence of these joints can generally be ignored in the formulation of an engineering model; they should be constructed in such a manner as to achieve as good a bond as possible of the two concrete surfaces. In subsequent discussions, use of the term "joint" will be synonymous with "isolation joint."

## Laboratory Slab-on-grade

The primary variables governing the vibration performance of a slab are the stiffness of the subgrade, the slab thickness and the horizontal dimensions of the slab. The damping properties of the concrete itself enter influence performance when considering propagation of vibrations at higher frequencies (say, those above 30 Hz) that are associated with impact loads by hard objects such as tools, gas bottles or high heels.

To achieve vibration criterion A, all Instrument and Metrology laboratories will be placed on concrete slabs on grade. Concrete slabs on grade of 300 mm thickness will be used for laboratory floors. The slabs will be constructed on virgin soil or 95 percent compacted fill.

Isolation joints will separate the laboratory floor slab from adjacent floor slabs and thus block those vibrations transmitted through the concrete itself. Generally these will have frequencies of 30 Hz or higher. Nominal slab dimensions are planned at 7 m by 7 m; this addresses the desire of the researchers to be isolated from their neighbors' research equipment.

Isolation joints will separate structural columns and walls passing through the slab on grade. This will serve to decouple the lab floor from structure borne disturbances. Expansion joints will also separate the structural frame of the individual building sections from each other. This decouples the systems, minimizing the transmittal of vibration between building sections and from the structural frame to the floor slabs.

Corridors will be slab-on-grade construction, separated from the laboratory floors by isolation joints. Several construction methods are under study (see Figure 5a & b). Construction tolerances of all slabs will be closely controlled to minimize variation in levelness and flatness, thus mitigating perturbation of laboratory floors from wheel or roller traffic in the corridors.

*Figure 5a. Baseline Floor*

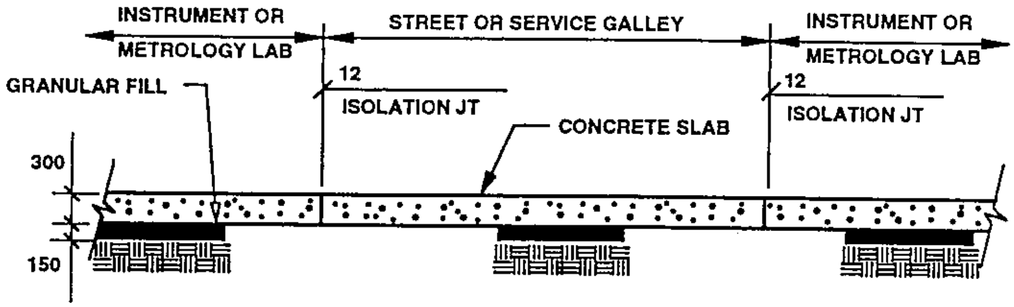
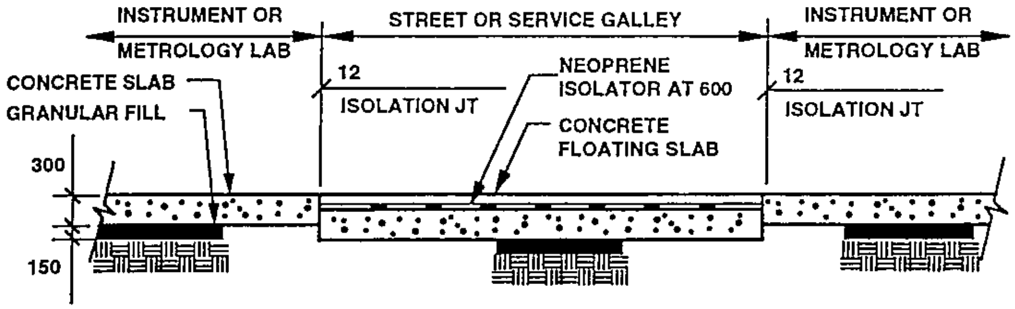


*Figure 5b. Neoprene Isolated Street and Galley*



## Cleanroom Floor

The cleanroom is characterized by downward flowing laminar air offering many air changes per hour. To achieve this, a raised access floor will be supported on a structural floor over a basement. The space between the raised floor and structural floor will act as a return-air path. The structural floor will be a waffle slab. The high vertical stiffness and resonance frequency required for vibration control will be achieved by means of floor depth and close column spacing as well as by using large column cross-sections and a stiff foundation scheme. Horizontal stiffness will be increased by means of shear walls at the basement level. Cast-in-place concrete is the material for this structural system.

The floor configuration discussed in the previous paragraph was sized with two parameters in mind:

- Limit walker-induced vibrations to amplitudes lying below criterion curve A using a model derived from classical shock response analysis methods and empirical coefficients. It is assumed in this analysis that the dynamic forces generated by walker are transmitted directly into the floor.

- Limit airflow-induced vibrations to amplitudes lying below criterion curve A using an empirical model developed from a study of the response of the floors of a number of cleanrooms. The empirical constants used in the model are periodically reviewed as new cleanrooms are built and evaluated.

In state-of-the-art cleanrooms, it is the custom to support the cleanroom floor (typically an access floor) on the structural floor using support pedestals. Because the structural floor has been sized to resist the walker-induced dynamic loads assuming the walker is directly on the concrete, the predominant vibratory response of the floor will be less than the criterion. However, the access floor itself can be the source of vibrations at higher frequencies as the tiles slide horizontally and strike each other or rock and strike the support pedestals. These vibrations can be mitigated by the use of corner bolts, which firmly attach each corner of the tile to a support pedestal. Lateral vibrations of the bolted floor can be further mitigated by use of "stiff" diagonal bracing (which differs from the "seismic" diagonal bracing commonly used). The U.S. manufacturers of access floors have developed and made available corner bolting details and "stiff" diagonal bracing.

Process and laboratory equipment not sensitive to vibrations can be supported directly upon the access floor. Vibration-sensitive equipment will not be supported on the access floor; even with corner bolting, the flexibility of an access floor allows walker-induced vibrations that can be quite troublesome. Instead, vibration-sensitive equipment will be supported directly from the concrete structural floor using stiff steel frames or pedestals to provide stiff support at the elevation of the access floor. These stiff bases, as they are often called, are custom designed for each piece of equipment as part of the fitout design, taking into account the locations of the equipment feet.

## Vibration Isolation Inertia Slabs with Walk-on Floors

*Criterion A1 Slabs.* The A1 floors are intended to create vibration environments meeting criteria more stringent than the site itself can provide. The RMS amplitude criterion is 0.75 micrometers/second, one-fourth of the amplitude of criterion curve A. In concept, the A1 environment is to be provided by a large inertia mass supported on air springs with low resonance frequencies. An A1 floor will be similar in concept to an optical table with air spring legs. The typical floor will vary in size from 1/4 lab module (1.85 m by 3.5 m) to a whole lab module (3.5 m by 7 m). The larger size will support long-beam path experiments on multiple optical tables.

Only vibration sensitive equipment will be supported on the A1 floor. Personnel, support equipment and carts will use a separately supported "walk-on" floor above the A1 floor. Thus, dynamic loads from traffic, support equipment, dropped objects etc. will be carried to the foundations by a separate path. Figures 6 and 7 illustrate the concept.

*Figure 6. A1 Slab Section*

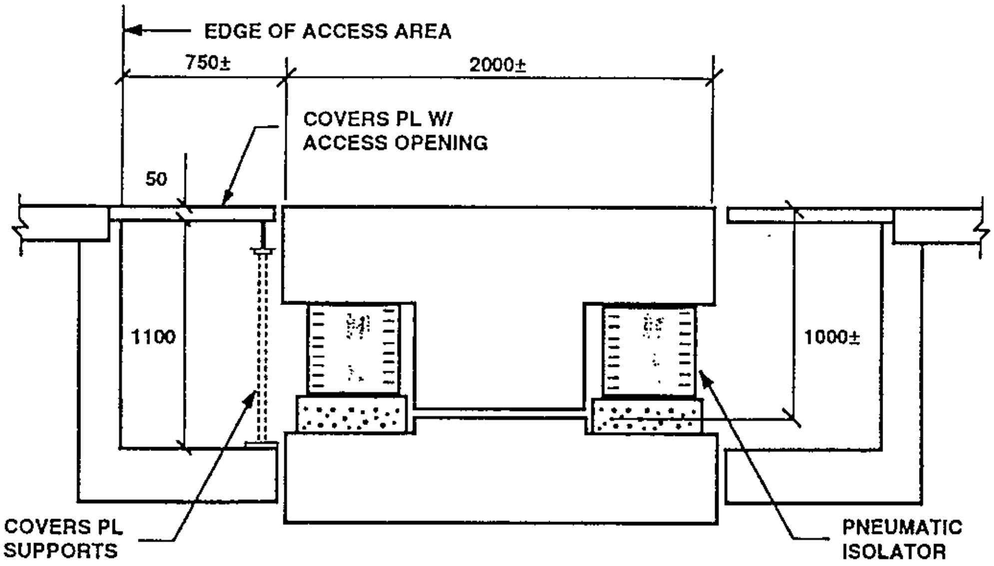
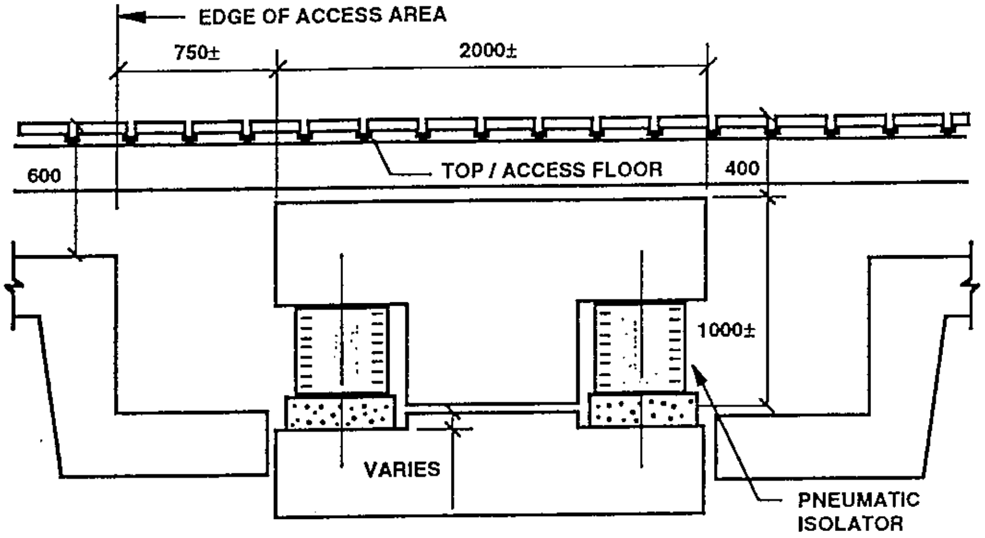


*Figure 7. A1 Slab Section with Walk-on Floor*



A1 laboratories will have unique construction requirements compared to the slab-on-grade that satisfies criterion A. The inertia mass will be constructed in a pit and will be supported by separate foundation. An access space is required below the inertia slab for the installation or future replacement of springs. The "walk-on" floor is also mandatory, necessitating that the surface elevation of the inertia slab be somewhat lower than the surrounding slab on grade. It will be difficult and very inconvenient to add more A1 floors in the future. This makes it important to anticipate the needs of future users during the initial building design. Both amount and location of A1 area are still under discussion. One concept proposed is to construct a depressed "trench" connecting a number of lab modules that could accommodate either an inertia slab on springs or a rigidly supported slab.

After vibration criteria were prepared and the conceptual design for implementing the A1 requirements were developed, they were presented to NIST's ATL Technical Advisory Group. With the concurrence of that group, the specific requirements of individual users were solicited via in-person and telephone interviews, which followed the development of a "matrix" of specific technical issues of concern raised by the Technical Advisory Group. An important issue discussed with each user was the acceptability of a "soft" suspension system such as that provided by airsprings. Of particular concern was the criticalness to each user of spatial orientation, as this would enter into decisions regarding the type of control systems each user required. This concern eliminated any consideration of pneumatic isolation for several users.

Several installations of large, pneumatically isolated slabs were found in Europe and the U.S., but there had apparently been no quantitative studies of their dynamic performance. Many unanswered questions arose regarding the performance of extremely large inertia slabs. How well would a large system perform compared to a smaller, well-understood system, such as an optical table? It was logical that good vibration performance could be expected above 10 or 20 Hz, but what amplitudes might be expected at low frequencies near the typical resonance frequencies expected from airsprings? What would be the effects of the internal structural resonances of the inertia slab? To answer these and other questions, the design, construction and evaluation of a full-scale prototype of an A1 floor was proposed to be built in space made available by one of NIST's metrology groups. This prototype was built and thoroughly evaluated (and will be discussed later in this paper).

The quantitative details of the performance of the prototype were reviewed with candidate users. They were surveyed once again to obtain refined quantitative requirements (where possible) and to review with them the proposed solutions to their vibration needs. Presently, it can be said that the A1 criterion is now a frame of reference that continues to be used because of its familiarity, and that individual needs of users are being used in the evolution of specific solutions to vibration control problems in the laboratories.

The A1 floor will have many of the same drawbacks of an optical table, some of which are enumerated below.

- The support system is "soft," so that an applied load (whether due to the placement of equipment or a person stepping on the slab) will cause a relatively large displacement. Because the inertia mass will be much larger than a typical optical table top, the springs will be stiffer and the A1 surface less compliant. However, the motion will be observable. Typically, vertical excursion of the floor will be limited by the size of the air gap between the bottom of the keel and the foundation. This will be on the order of a few millimeters.

- The system is susceptible to small excitation forces that might not typically be of concern. For example, the force associated with the air flowing from an air conditioning duct could push against the experimental apparatus and move the whole system causing either offset or oscillation or both.

- Without extra precautions, an airspring supported system is susceptible to rotational motion. Very little resistance is offered against motions about the two horizontal axes or the vertical axis. This characteristic is a problem for some types of experiments and not a problem for others.

- The vibration isolation is provided by means of a rigid (more or less) mass on a set of springs. There are many resonance frequencies associated with this system, any of which may cause amplification of the base vibrations which excite it. To some extent, the amplification associated with these resonances can be controlled via damping, either that occurring naturally in the air spring, that associated with flow of an orifice, or that induced by active vibration control. However, one cannot expect the baseline A1 systems to provide vibration environments as stringent as A spaces at frequencies below 10 Hz. The best one can typically say is that the rms vibration velocity (measured in one-third octave bands) should not exceed 1 micrometer/sec at frequencies greater than 1.4 times the air spring resonance frequency, providing that the environment below the air springs does not significantly exceed curve A.

Much of the NIST's experimental metrology work is sensitive to tilt or changes of orientation in space. Thus, it will be necessary to control the position of the isolated mass, and some sort of active control of position will need to be used, depending upon the particular application (Steel springs were originally considered as an option to airsprings but rejected for this reason, because it is difficult to implement active vibration control with simple steel springs). The baseline airspring and control system is that used for the prototype A1 slab vibration isolation research project. The quantity and load capacity of the airsprings for a particular slab will depend upon the weight and shape of that slab.

It is important to recognize the difference between the terms **active vibration control** and **active position control**. The latter uses feedback to control orientation in space of the isolated, but does not use feedback to attenuate vibrations (This type of system has been successfully implemented at another NIST experiment, and the technology, if necessary, is portable to an A1 slab). The former uses feedback to actively cancel vibrational energy originating from below the springs or on the mass itself (within some limitations). This has been proposed as an upgrade of the prototype floor in Building 220 and may be specified for some floors in the ATL.

### Superstructure

Separate superstructure systems are planned for the four major functional areas of the building: the Instrument laboratory areas, the Metrology laboratory areas, the Cleanroom areas and the office areas. These areas are isolated from each other by expansion joints.

The basic structural system will be a reinforced concrete frame and skip joist system. The column grid fits the lab module and allows the columns to be placed outside the laboratory walls where they do not interrupt lab flexibility.

Attributes of the structural system include the following:

- The structural system can hold heavy loads without modification.
- Modular, preformed openings are planned throughout the mechanical level to simplify future modifications.
- The structural system provides adequate fire resistance without the addition of coatings that may degrade air cleanliness.
- The structural system has sufficient mass and stiffness to improve vibration characteristics.

### Special Substructure

The Metrology laboratories will be a single story underground structure without a superimposed building. There are advantages and limitations to locating Metrology below ground:

- Wind will not blow directly on the shell of the structure. Dynamic forces from wind would be eliminated.
- The Metrology floor would be placed at a greater depth reducing the effect of the ambient surface waves in the soil that cause the floor to vibrate. Because amplitude of surface waves decreases with depth, amplitudes would be a fraction of what they might be at the surface.

- Vibration-generating activities in the open area above the structure can degrade the quality of the metrology laboratory environment. Recreational activities such as volleyball or football would have to be prohibited as would motorized mowers.

- The surrounding soil must be decoupled from the structure to prevent it from becoming an alternate path for vibrational energy from surface waves. A layer of resilient material such as styrofoam is envisioned to be placed outside the buried structure.

## PROTOTYPE INERTIA-SLAB VIBRATION ISOLATION SYSTEM

Experience at European metrology laboratories suggested that the use of pneumatically supported concrete inertia slabs could permit achievement of a criterion such as A1. Unfortunately, little or no measured data was available on the European systems. As a result, a prototype A1 slab of significant size was planned and constructed in an existing pit in Building 220 at NIST's Gaithersburg campus (4m X 10m). Its design was patterned after European systems and used "off-the-shelf" vibration isolation hardware and an "off-the-shelf" control system with automatic leveling. The elevation of the top of the isolated floor was depressed from the surrounding floor slab; a separately supported "walk-on" floor was installed which would support personnel. Only vibration-sensitive equipment was to be supported on the isolated floor.

Prior to selection of a particular technology for the isolator hardware, three options were considered:

(1) A self-leveling system, in which isolation is passive and the system is capable of slowly adjusting to changes in elevation of three points, but does not otherwise control positioning;

(2) An active positioning control system, in which a computer-controlled system monitors all positional and rotational degrees of freedom and adjusts all degrees of freedom to keep attitude within fixed limits;

(3) An active vibration control system, in which a computer-controlled system monitors the displacement of the base of the system and counteracts with out-of-phase dynamic forces which cancel the dynamic load coming in from the supports.

It was decided that the prototype would act as a demonstration of a baseline concept, allowing evaluation of the vibration attenuation performance of the first option, an off-the-shelf passive isolation system with a mid-grade self-leveling system.

### Measurement Program

A measurement program was conducted in January 1995[5] to examine vibration isolation performance of the pneumatically isolated inertia slab, and included measurements of the following:

- Ambient vibrations in the pit and on the inertia slab with the airsprings inflated and deflated.

- Transfer functions from the pit to the top of the inertia slab, with the intent of assessing the vibration isolation performance of the isolation system (A transfer function in this case is the frequency-dependent ratio of the motion of the top to that of the pit, expressed as a frequency spectrum).
- Vibration of the inertia slab due to walking on the "walk-on" raised-floor system.
- Time histories of the motion of the inertia slab caused by removal of a load from the slab.
- Modeshape analysis of the airspring system and slab, with the intent of identifying natural frequencies and associated deformation distributions (modeshapes).
- Response of the slab and the walk-on raised-floor system to acoustical (airborne sound) excitation.

Additionally, a comparison was made with a finite element model study of the inertia slab and airsprings.

## Modal Analysis

Resonance frequencies were identified by means of averaged measurements at representative locations while the slab was supported on inflated airsprings and repeatedly struck with a rubber mallet. The spectrum in Figure 8 shows the resonance peaks that were identified by impacts at one corner. Once the frequencies were identified, the deformed shape at each resonance frequency (the modeshape of that frequency) was determined by measuring displacement while the slab was mechanically shaken at that frequency. Figure 9 summarizes the measured modeshapes.

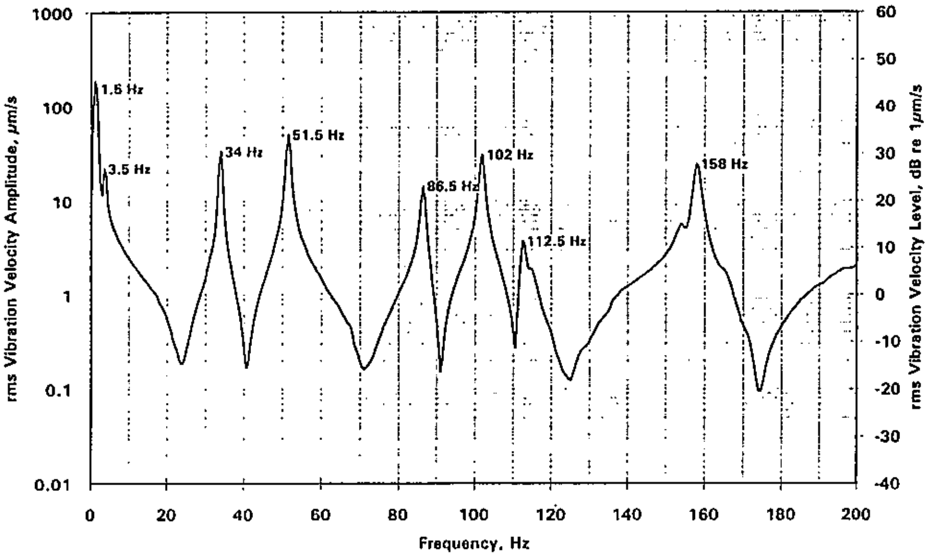
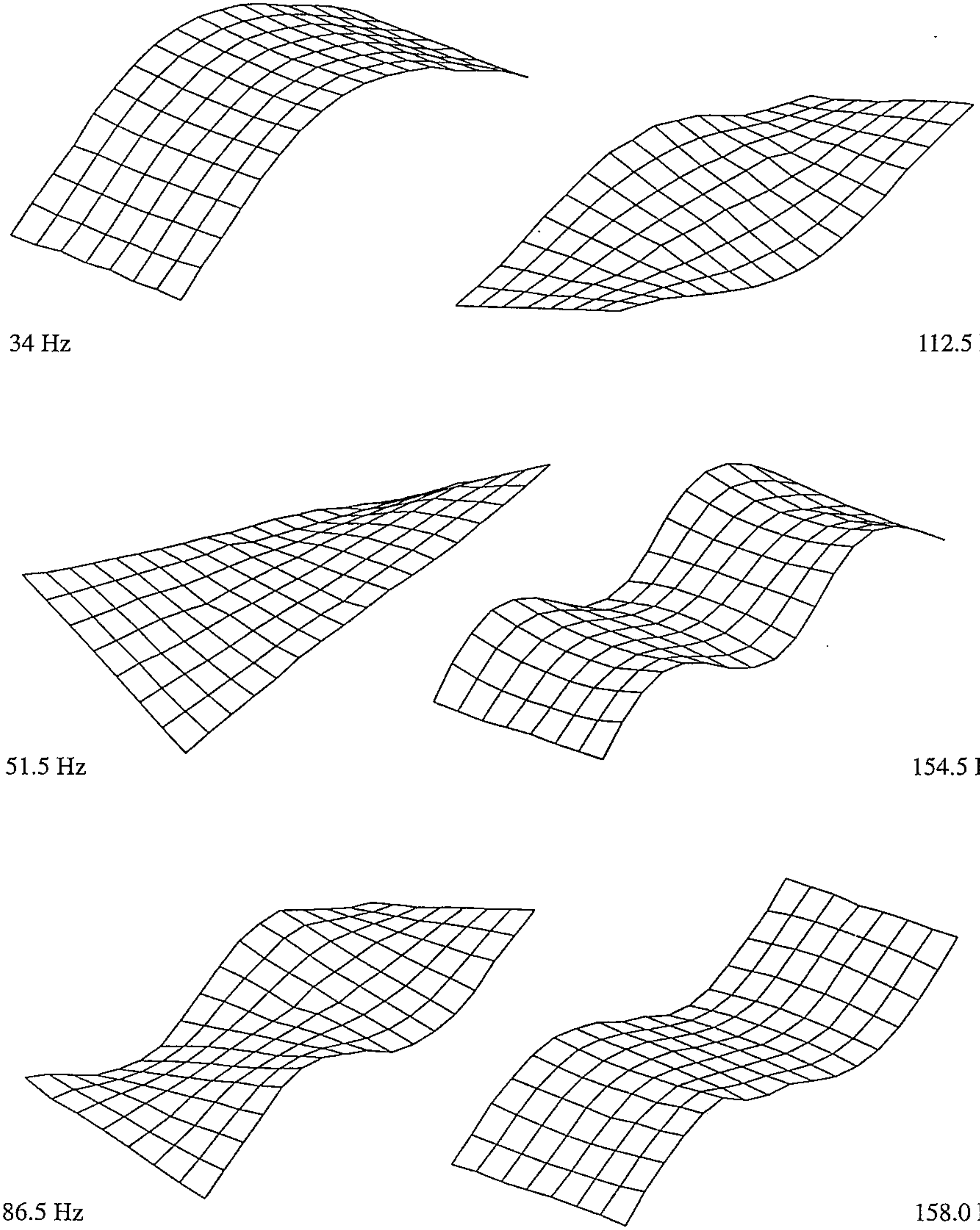


*Figure 8. Response of Prototype A1 Slab to Hammer Blows at Corner, showing Resonance Frequencies.*

*Figure 9: Deformed Shapes of Prototype A1 Slab Associated with its Resonance Frequencies.*



34 Hz

112.5 Hz

51.5 Hz

154.5 Hz

86.5 Hz

158.0 Hz

The fundamental resonance frequency in all three directions was found to be 1.4 Hz. This is consistent with airsprings manufacturer's product specifications. The resonance frequency of rocking about a north-south axis was also 1.4 Hz. The resonance frequency of rocking about an east-west axis was 3.5 Hz. In all of these modes, the inertia slab remained relatively rigid. The airspring fundamental frequencies are significant because they are the primary determinant of the vibration isolation characteristics of the system as a whole. Theory predicts that vibration attenuation occurs at frequencies above about 1.4 times the resonance frequency of the spring.

The fundamental resonance frequency of the inertia slab was found to be 34 Hz (The design goal was to obtain a resonance frequency above 30 Hz). At this frequency, the slab is bending up and down as a beam, with two nodal lines (lines along which there is no displacement, only rotation) oriented north-south. The lowest resonance frequency associated with plate twisting (one nodal line north-south and one east-west, with the center of the plate immobile) was found to be 51.5 Hz. The frequency at which the slab bends side to side as a beam is 102 Hz.

### Vibrations with Airsprings Inflated

Figure 10 shows RMS velocity spectra measured in three directions and analyzed in one-third octave bands of frequency. At frequencies greater than 5 Hz, the vibration velocity amplitudes were less than 0.2 micrometer/sec, about 75 percent below the A1 goal of 0.75 micrometer/sec. In horizontal directions, the amplitudes were less than 0.075 micrometers/sec at frequencies greater than 8 Hz, an order of magnitude less than the goal. At frequencies below 5 Hz, the horizontal amplitudes were as high as 2 micrometers/sec due to amplification by rocking resonances. Below 2 Hz the amplitudes in all directions were high, as expected, because of the airspring resonances.

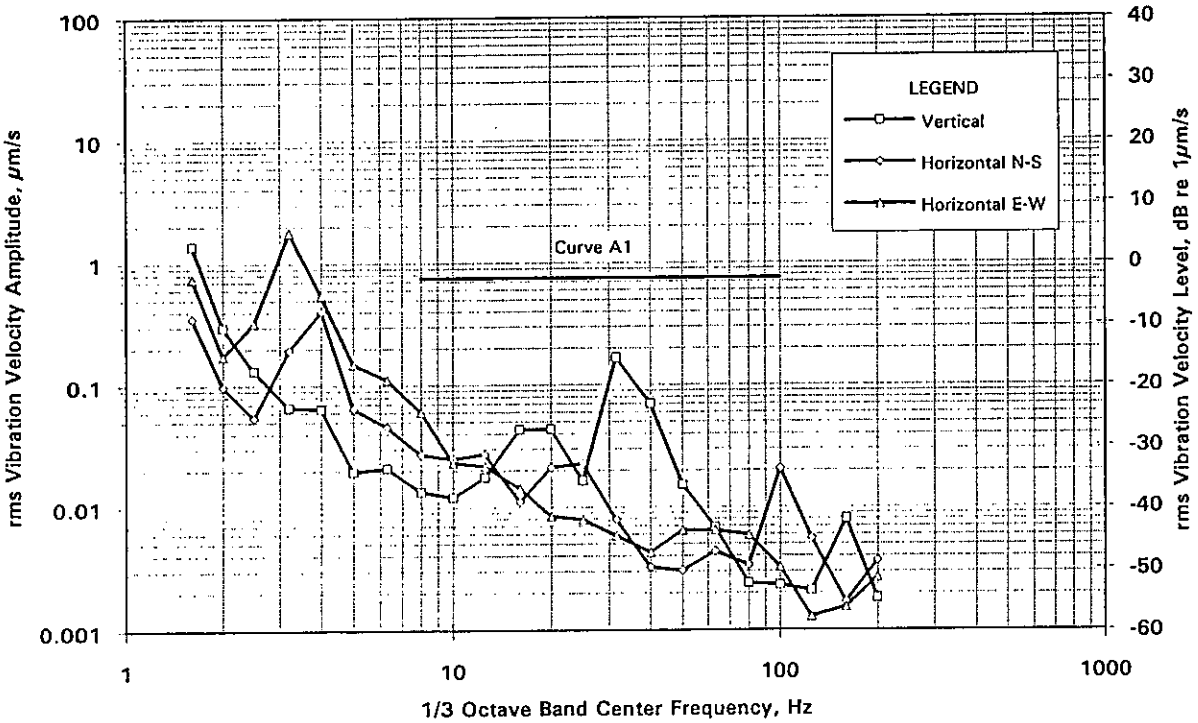


*Figure 10. Ambient Vibrations Measured on Prototype A1 Slab*

At frequencies greater than 5 Hz, the maximum occurs near the 34 Hz fundamental resonance of the inertia slab. Design of future A1 slabs will involve forcing this frequency to be higher by stiffening the slab, thus decreasing its effect.

### Vibrations with Airsprings Deflated

The prototype system was designed so that it could be lowered and support experiments with the airsprings deflated, attempting to simulate slab-on-grade performance. When deflated, the inertia slab rests on a large bearing area between the ten airsprings.

In the vertical direction, the vibrations of the pit and the top of the inertia slab were identical, providing amplitudes equal to or slightly better than slab-on-grade performance in the basement of Building 220. In the horizontal east-west direction (the long axis of the inertia slab), there was slight amplification of vibrations at frequencies between 12 and 60 Hz due to a combination of rocking and cantilever action, but the curve A1 criterion of 0.75 micrometer/sec was not exceeded. In the horizontal north-south direction (the short axis) there was more significant amplification due to rocking and cantilever action at frequencies between 8 Hz and 80 Hz. The amplification caused the A1 criterion to be exceeded, with an amplitude of 2 micrometers/sec at 25 Hz. In all three directions the velocity amplitudes were below the curve A requirement for on-grade slabs in the ATL. Also, in all three directions, the displacement amplitudes were less than the 20 nanometer requirement of some researchers.

### Walking on the Walk-on Floor

The vibrations of the inertia slab on inflated airsprings due to a person walking on the walk-on floor appear to be the greatest shortcoming of the current configuration of the prototype. Vibrations are generated which appear as peaks at the fundamental resonance frequency of the walk-on floor's supporting steel framework (21 Hz) and the fundamental of the inertia slab (34 Hz). The amplitudes of these peaks were on the order of 0.4 micrometer/sec at 21 Hz and 1.3 micrometer/sec at 34 Hz, both about an order of magnitude above ambient. When the airsprings were deflated and the experiment was repeated, the peaks were not evident. There were two reasons. The 34 Hz peak was not present because in the deflated condition this modeshape does not exist. The 21 Hz amplitude of 0.4 micrometer/sec (as measured in the inflated condition) was less than the ambient vibration amplitude at that frequency in the deflated condition.

Due to their dramatic effect, several recommendations have been developed for mitigation of vibrations caused by personnel activities on the walk-on floor. These include installation of resilient, vibration-isolating bearing pads between the steel framework and the concrete walls supporting the framework as well as the possible use of damping treatments for the framework and impact-absorbing matting for the traffic areas of the walk-on floor.

## Comparison with Finite Element Study

A separate study was carried out in which the inertia slab, airsprings and foundation were modeled using finite elements. A modal analysis identified all the resonance frequencies below 200 Hz.

Transfer functions of the support systems (frequency-dependent ratios of inertia slab motion to base motion) were obtained from the finite element model. In the vertical direction at frequencies below 80 Hz, there was a general similarity between transfer function shapes, but at all frequencies the magnitude of the calculated transfer function was significantly less than that measured. In the horizontal directions, the differences were even more pronounced. These differences are thought to be due to several reasons:

- It was not possible to apply enough dynamic force to the ground to overcome the ambient vibrations at the measurement locations.
- The vibration measured on the slab in a given direction may be due to vibrations in the pit in all directions, with conversions occurring due to flexure and rotational motions of the spring supports and the springs themselves. A finite element model would not be able to represent this behavior.
- Significant nonlinearities may occur in the springs at the small amplitudes with which we are dealing, so that pit motion at one frequency may give rise to motions at a multitude of frequencies.
- Airsprings have long been suspected of "hanging up" at small displacements at small displacements, giving rise to highly non-linear effects.

It has been concluded that finite element techniques are not appropriate for predictive modeling of the performance of an airspring-supported inertia base. However, it does appear to be an adequate means of calculating resonance frequencies and modeshapes, which are important in the design of an inertia slab.

## Overall Value of Vibration Isolation Research Project

Judged as a research project, the construction, modeling and evaluation of the prototype A1 slab appears to have been quite useful. The key benefits to the ATL project include:

- Successful proof of concept of a "baseline" A1 system: pneumatic vibration isolation of a large-scale inertia slab using "off-the-shelf" passive isolation hardware and an "off-the-shelf" positioning system.
- Thorough measurement evaluation of the dynamic performance of a large pneumatically isolated slab.

- A prototype with which improvements can be made to the basic design of A1 slabs for the ATL.
- Determination that the use of finite element modeling should be limited to calculation of resonance frequencies and modeshapes.

Additionally, a large, high-quality A1 space has been created in Building 220 for use by NIST researchers.

## Lessons Learned and Modifications being Considered

The severity of the amplitudes associated with rocking modes was one of the most significant pieces of information provided by the prototype study. In the prototype design, the elevation of the centroid of the inertia base was allowed to be above that of the roll plane of the springs. Comparison of the measured spectra on the prototype with those measured on another large pneumatically isolated slab on which the two elevations are the same, showed that rocking might account for an order of magnitude increase in amplitude at frequencies on the order of 3 to 4 Hz.

The apparent non-linear behavior of the pneumatic support system at extremely low amplitudes demonstrated that designers should not use finite element analysis (or any other analytical tool that assumes linear spring behavior) to predict vibration amplitudes on the top of the isolated slab. However, finite element analysis does appear to be useful for prediction of resonance frequencies and modeshapes.

The non-linearity may be dependent upon the type of airspring used. Examination of the conceptual design of the airspring suggests that other spring technologies might exhibit different transmissibility behavior (though they may still be non-linear). NIST is considering a study of other types of springs.

The vibrational “weak link” in the prototype design was clearly the walk-on floor. The severity of the vibrations generated by a person walking on the floor was not anticipated. Several options are being considered to reduce these vibrations. The easiest to implement will be the installation of soft (low-durometer) neoprene bearing pads beneath each beam supporting the walk-on floor. Others include alternative types of access floor panels and floor coverings as well as damping treatments for the framing supporting the access floor.

The large amplitudes at frequencies below 2 Hz are due to resonance amplification by the airsprings. Some users had no adverse reaction to the severity of the vibrations in this frequency range because their concerns were with frequencies above 10 or 20 Hz. Other users, particularly those in metrology, were concerned that these vibrations might pose problems for their work. Manufacturers have found that the addition of an active vibration control system to a passive pneumatic system has significantly reduced the vibrations at these lower frequencies when used on a large (though smaller) inertia mass. An active control system is being considered for the prototype. If installed, additional measurements will be made to assess the improvement in system performance.

The vibration isolation performance was degraded (though not eliminated) at the lowest internal structural resonances of the inertia slab. As a result, the "target" fundamental resonance frequency for A1 slabs for the ATLs is being increased from 30 Hz to 60 Hz, which will effectively stiffen the slab and move the resonance peak to a frequency range in which amplification will be less troublesome. Additionally, alternative construction approaches are being considered which would increase the damping of internal resonances. These options include the use of constrained-layer damping or a damping admixture for the concrete.

## DESIGN OF VIBRATION ISOLATION SLABS FOR NIST ATLS

The following issues are being considered when planning and designing the A1 spaces:

*Functional Requirements:*

- Area and shape of isolated area
- Load to be carried
- Center of gravity of load to be carried
- Type of isolation and position control required
    - Passive isolation with automatic leveling
    - Passive isolation with active position control
    - Active vibration isolation

*Design Requirements:*

- Quantity and type(s) of airsprings

- Resonance frequencies and modeshapes of inertia base (frequencies should be as high as practical, on the order of 40 Hz or higher; a 60 Hz fundamental should be avoided; classical methods or finite element analysis are appropriate for calculating frequencies)

- Resonance frequencies and modeshapes of support system (frequencies should be as low as possible and positioning system should consider modeshapes)

- Aspect ratios of inertia slab (1:1 aspect ratios are to be avoided, as are any others that will lead to resonance frequencies that are too closely spaced)

- Relative positioning of the combined center of mass of inertia slab and experiment load, elastic plane of spring system, position sensors, and position-control force actuators (ideally, the center of mass of the inertia slab and the roll plane of the system should be at the same elevation, or the center of mass should be lower)

- Type(s) of control of vibration isolation and position of springs

The A1 space in the ATL has been assigned with a degree of discretion. Some of the vibration-sensitive experimental work will not benefit from an A1 environment. Despite the use of active control of positioning, experimental systems may require the greater stability at low frequencies that can be obtained from firm support on a curve A floor.

The design of the A1 slabs allows for substitution of alternative spring systems and/or control systems if found necessary by individual users.

In some spaces, a continuous trench will be constructed for multiple A1 slabs. An infilled masonry wall will be provided in the trench between rooms which will prevent air movement between rooms. In rooms in which an A1 slab is not needed at the time of initial occupancy, the trench will be filled with sand and topped with a 300mm slab. (The wall in the trench will in this case act as a retaining wall.) This will provide a Type A slab in that space. However, if an A1 space is needed in the future, the slab can be removed, the sand excavated, and an A1 slab poured without the significant disruption provided by excavation of soil.

Each A1 slab will be evaluated after construction using a measurement program designed to document ambient vibration, resonance frequencies and modeshapes of the inertia mass. The plan is to employ what is being called a "brass plaque" for each slab, a report which will provide for the user information regarding the dynamic properties of the slab and isolation system which can be used in planning such aspects of the experiment as where to place instrumentation to achieve minimum vibration at a particular frequency.

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