Advanced Measurements Laboratory: A Research Facility for the 21st Century

Hratch G. Semerjian

National Institute of Standards and Technology, USA

NCSL International Conference

Metrology - The Process of Providing Good Measurements

Salt Lake City, Utah

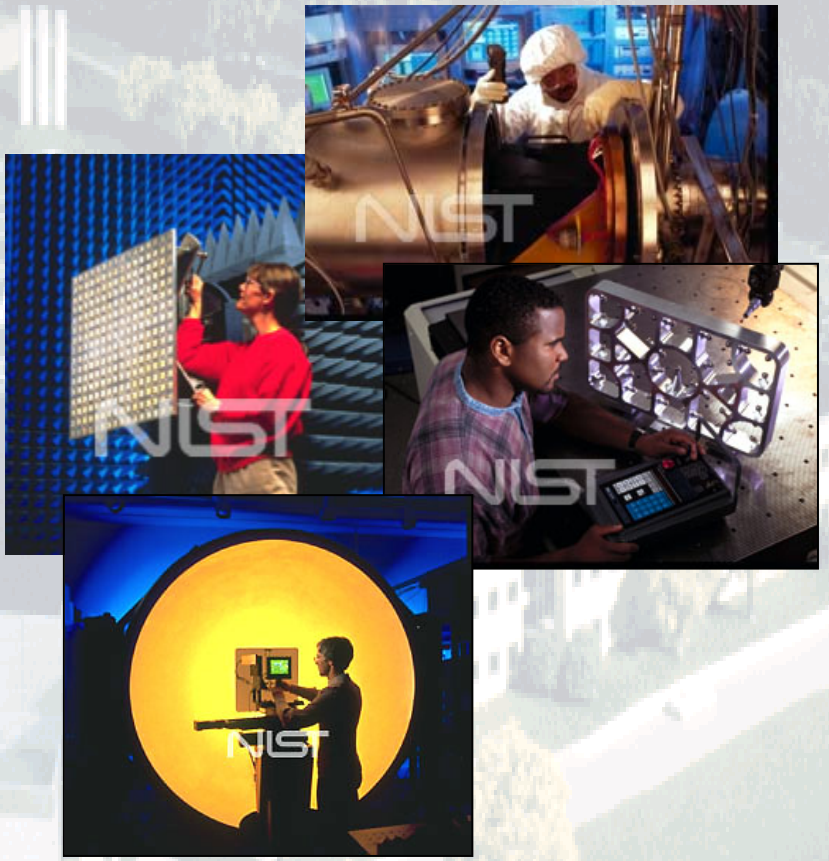
July 12, 2004

Outline

- NIST Mission and Resources
- Early Planning for the AML
- Benchmarking of other Metrology Facilities
- Rationale for AML
- Design and Construction of the AML
- Major Facilities at AML
- Measurements Capabilities Under Development at the AML
- Conclusions

National Institute of Standards & Technology

NIST's mission: to develop and promote measurement, standards, and technology to enhance productivity, facilitate trade, and improve the quality of life.



NIST Assets Include:

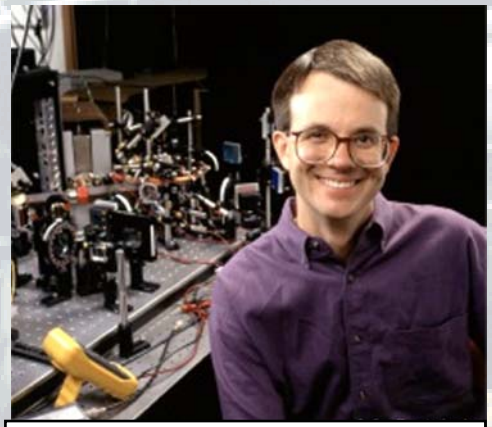
- NIST Laboratories
- Advanced Technology Program
- Manufacturing Extension Partnership
- Baldrige National Quality Award

World Renowned Scientists and Engineers

Bill Phillips
1997 Nobel Prize in Physics

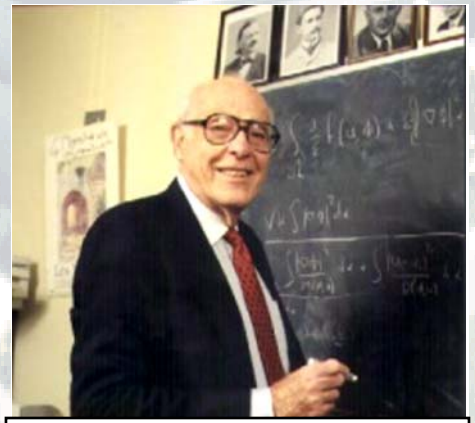
Gregory Linteris
Flew 2 Space Shuttle Missions

Johanna Sengers
2003 Women in Science Award and NAS Member



Eric Cornell
2001 Nobel Prize in Physics

Deborah S. Jin
2003 MacArthur Fellowship '*Genius Grant*



John Cahn
1998 National Medal of Science

Unparalleled Measurement and Research Facilities

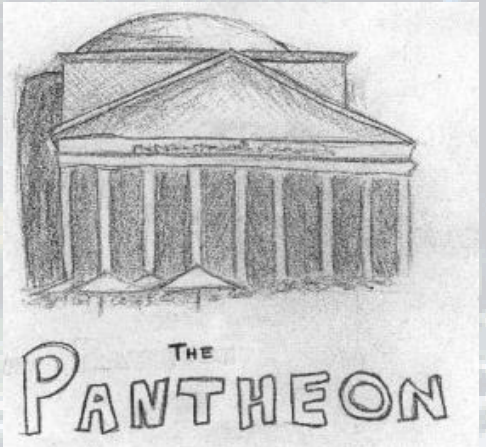
Advanced Measurement Laboratory

Advanced Chemical Sciences Laboratory

NIST Center for Neutron Research

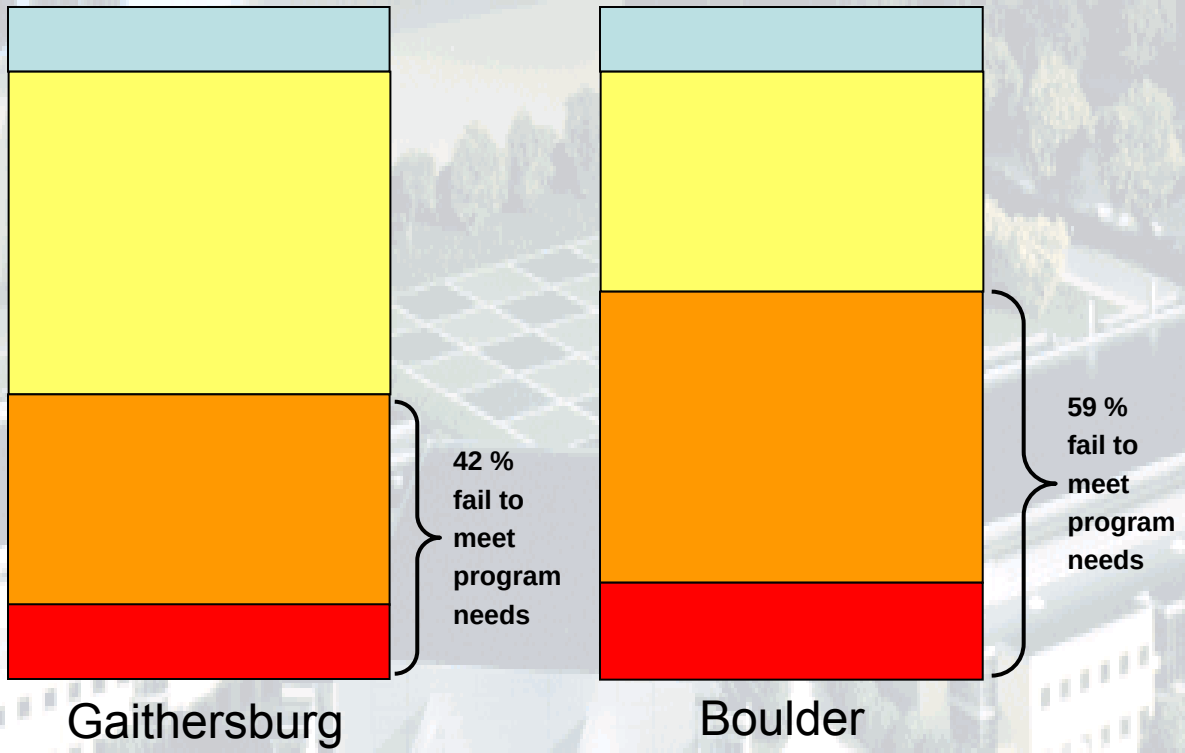
AML – Early Planning

- Early Planning Phase of AML ~1990
  - Changing Needs in Measurement Technology
  - Adequacy of Laboratory Facilities
  - Upgrading of Current Facilities
  - New Requirements (higher ceiling, service corridors, etc.)
- International Benchmark Study (1998)
  - Report on National Metrology Institutes
  - Japan, Germany, Brazil, U.S.
- State-of-the Art Technical Specifications
  - Test Beds for Temperature and Vibration Control

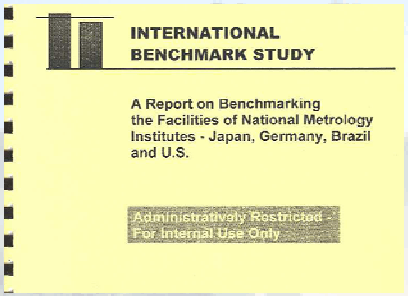


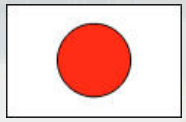
Adequacy of Laboratory Facilities

Smith, Hinchman & Grylls Associates, Inc. (SH&G) Studies, 1991



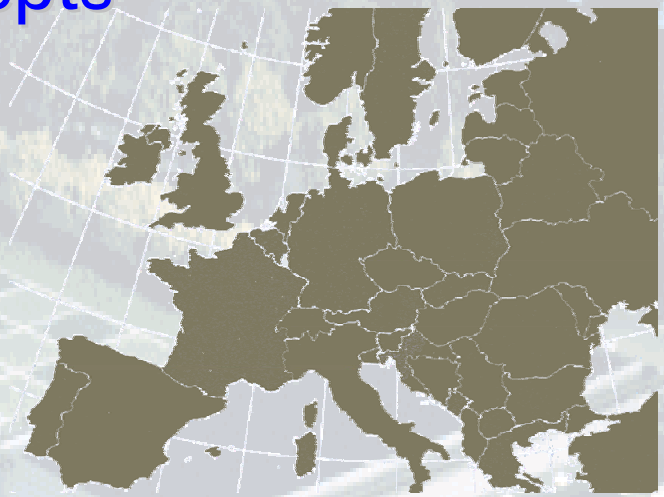
National Metrology Institutes (NMI) Studies





NIST FUNCTION		ACTIVITIES							EFFORT				FACILITIES						DRIVERS		CHANGE			Page Reference
		Calibrations	Primary Standard	Standards	Conformity	Research	% Research	Committees	No. Staff-Years	% S&E Staff	% Tech Staff	Budget ($M)	Space (m²)	Age	Condition	Unique Facilities	Environmental	Info Tech	Customers	Demand	Demand	Capabilities	Resources	
1. Electrical Standards	NIST	•	•	P		•	70	•	73	80	10	8.5	2118	–	–	•	•	•	I A G F	L E	+	•	•	
	Japan	•	•		•	•	80	•	10	100	0	1	809	–	–	•	•		I A G F	L E				
2. Semiconductor Metrology	NIST	•		M D P		•	85	•	61	75	20	9.4	1876	– T	– T	•	•	•	I A G F	E S	+	•	•	
	Japan	•	•			•	50	•	20	100	0	0.2	180	+	–	•	•	•	I G F					
4. Dimensional Metrology	NIST	•	•	M	•	•	60	•	18	70	20	3.5	420	= –	=	•	•	•	I A G F	L E S	+	•	•	
	Japan	•	•		•	•	70	•	10	50	5	0.5	165	–	=	•			I A G	L E S	=	=	+	
5. Surface Finish Metrology	NIST	•	T	M		•	60	•	2.5	50	50	.35	100	–	–	•	•	•	I G F	E S	+	•	•	
	Japan	•	•	M	•	•	56	•	2	90	10	0.07	200	–	–	•	•		I G F	L E S	=	=		

AML Contractor Studies
European Lab Concepts

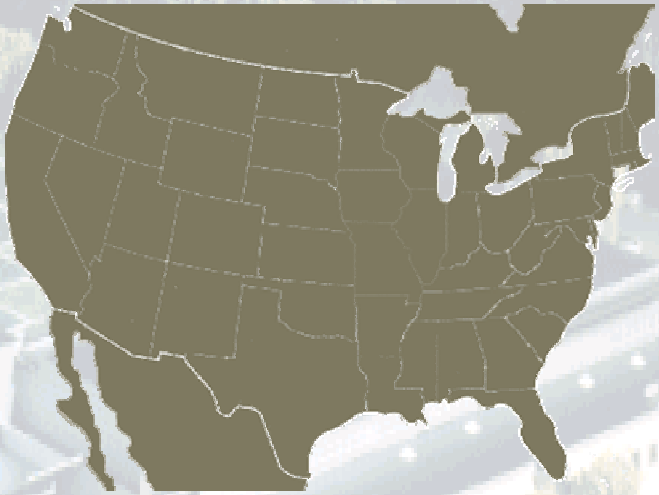


- Physikalisch-Technische Bundesanstalt
  - Braunschweig, Germany
  - Reinraumzentrum - Cleanroom Center
  - Heisenberg Building
  - Metrology Lab
  - Paschen Building - Gauge Block Lab
  - Explosion Research Center
- Max Planck Institute
  - Garching, Germany
  - Center for Quantum Optics
- Swedish National Testing and Research Institute
  - Boras, Sweden
  - Metrology Lab
- Technical Inspection Centre
  - Helsinki, Finland
  - Primary Standards Laboratory

- Carl Zeiss
  - Oberkochen, Germany
  - Quality Assurance Laboratory
  - Length Measurement Calibration Labs
- Bosch
  - Gerlingen, Germany
  - Measurement Research Laboratory
- Bureau International Des Poids et Mesures
  - Sevres, France
  - Breteuil Pavillion

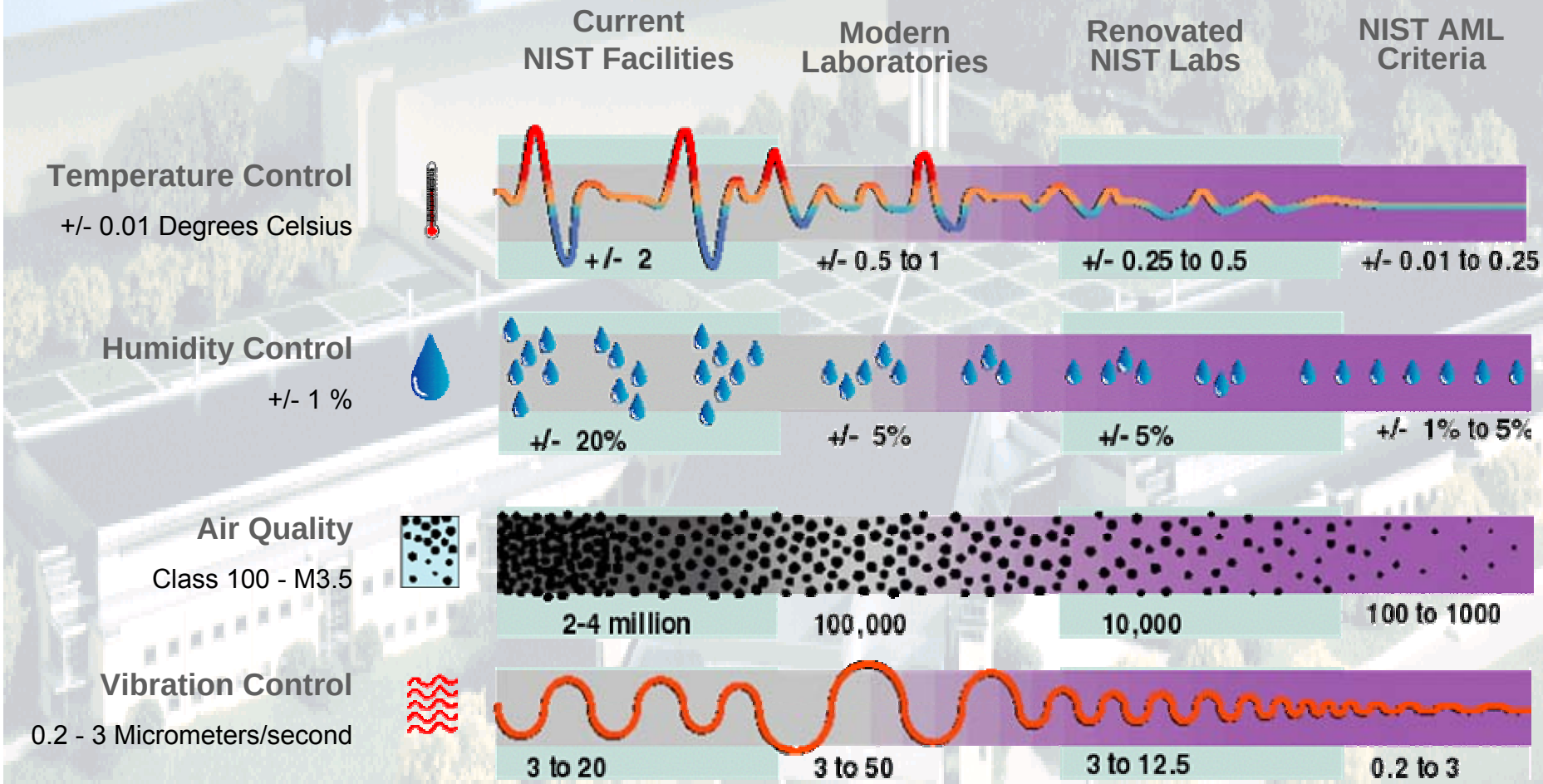
AML Contractor Studies
United States Lab Concepts

- Oak Ridge National Laboratories, Oak Ridge, Tennessee
  - Dimensional Standards Laboratory
- Sandia National Laboratory, Albuquerque, New Mexico
  - Primary Electronics Standards Laboratory
- Los Alamos National Laboratories, Los Alamos, New Mexico
  - Materials Science Laboratory



- Lawrence Livermore National Laboratories, Livermore, California
  - LODTM Laboratory
- CAI Reconnaissance Optics, Barrington, Illinois
  - Camera Alignment Slabs

NIST AML Critical Criteria



AML – A laboratory for the 21st Century

- NIST measurements and standards capabilities are critical to maintaining US industry leadership.
- The AML, a state-of-the-art laboratory complex, will allow NIST to:
  - pursue programs at the forefront of research in measurement science and technology that support the NIST strategic focus areas of Nanotechnology, Homeland Security, and Healthcare and
  - produce and disseminate world-class measurement standards enabled by next generation metrology capabilities beyond currently obtainable levels.

State-of-the-Art & Next-Generation Measurement Capabilities to be Housed in the New Complex

- Improved Standards Capabilities for Next Generation Requirements
  - Length standards ranging from the nano to the meso-scale
  - Mass, Vibration, and Pressure standards
  - Fundamental Electrical standards
  - Optical and X-ray measurements and standards
- Chemical and physical characterization of three dimensional nano-scale structures and interfaces
- Imaging, characterization, and manipulation of matter at nano-scale, single atom, and molecular regimes
- Quantum information processing, optical tweezers, and Bose Einstein condensation

AML Groundbreaking, June 9, 2000

Advanced Measurement Laboratory

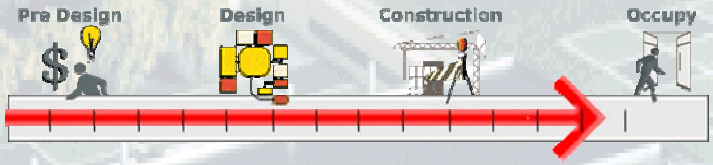
Location:

- NIST
- Gaithersburg, Maryland, USA

Overview:

- Advanced technology laboratories that create the most environmentally stable laboratory in the world.

Status:



Area:

- 511,070 GSF / 210,295 NASF
- (47,489 Gross M2 /19,537 net)

- Two Instrument Wings
- Two Metrology Wings
- Nano Fabrication User Facility

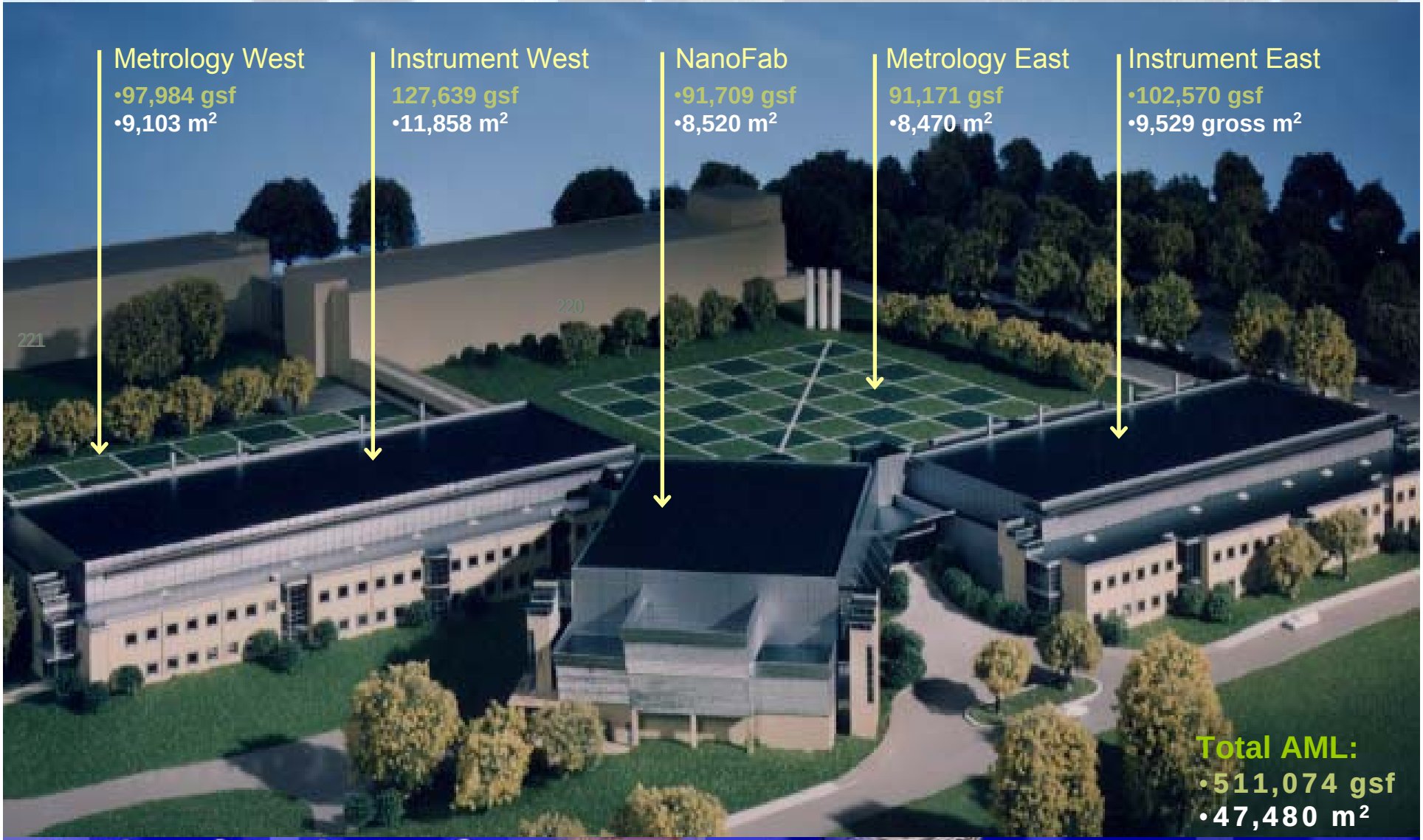
Budget:

- $175 M Construction
- $235 M Program Cost

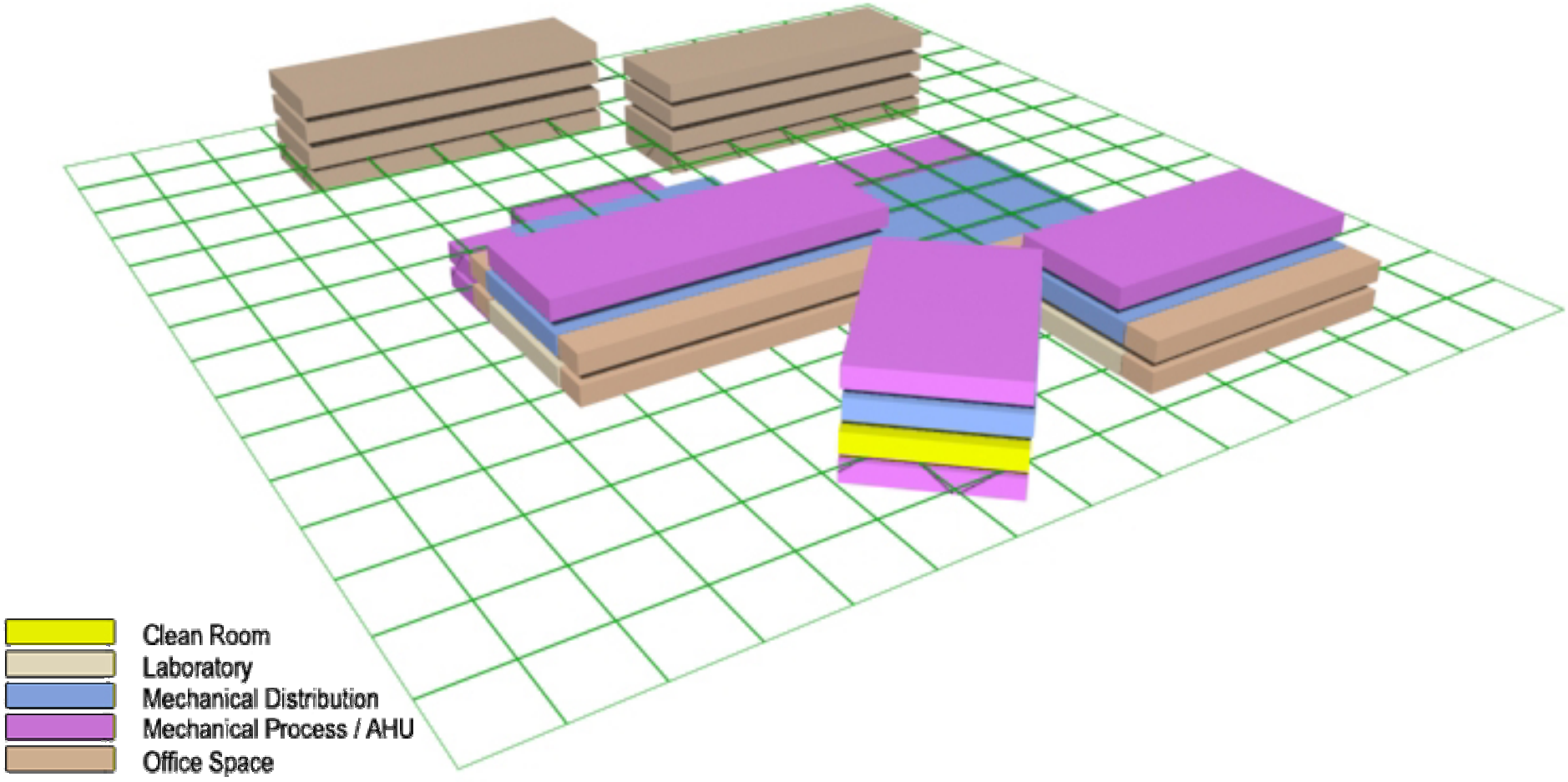
AML Constructed in ~ 3.5 Years !

aml.nist.gov

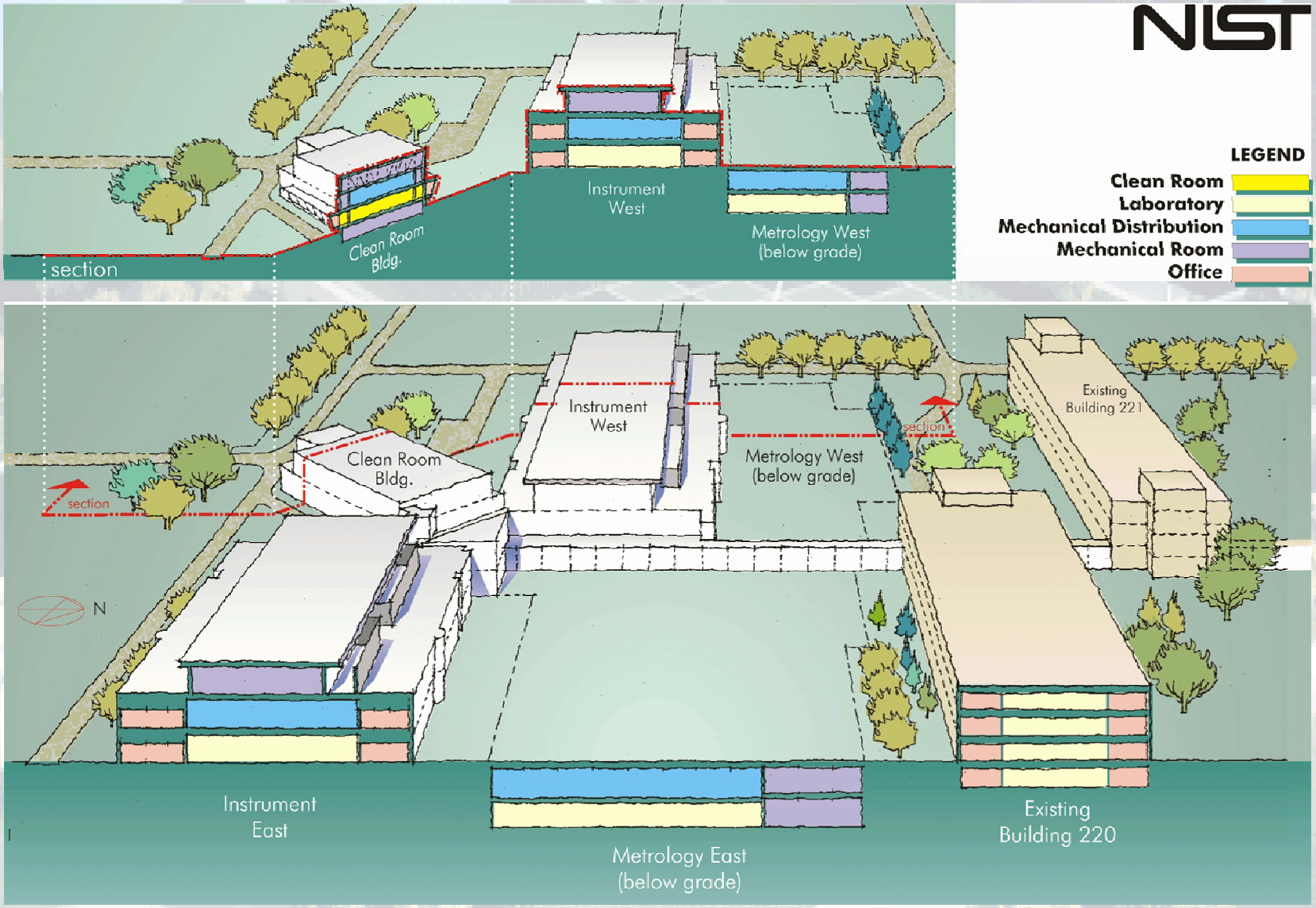
AML Building Layout



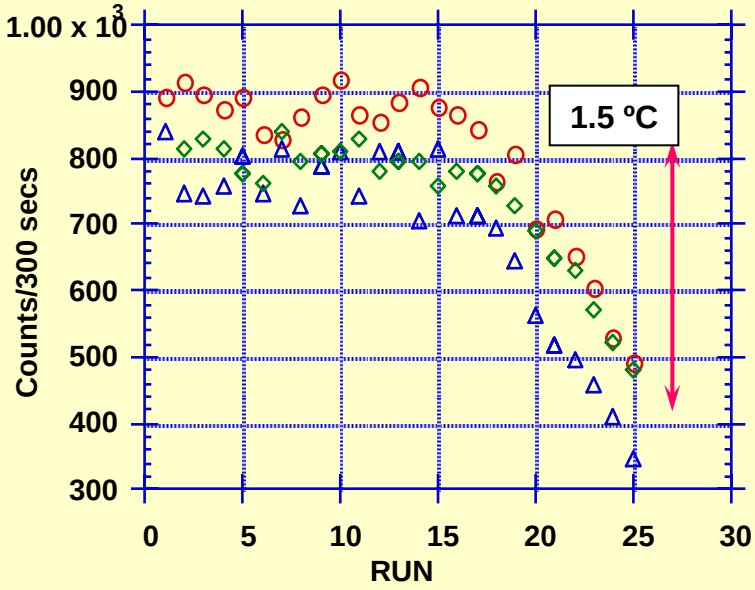
NIST AML Stacking Concept



Instrument Wing Cross-Section



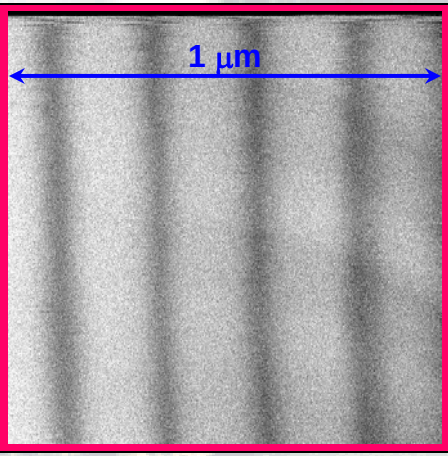
Thermal Drift ... measurement problems with semiconductor thin films

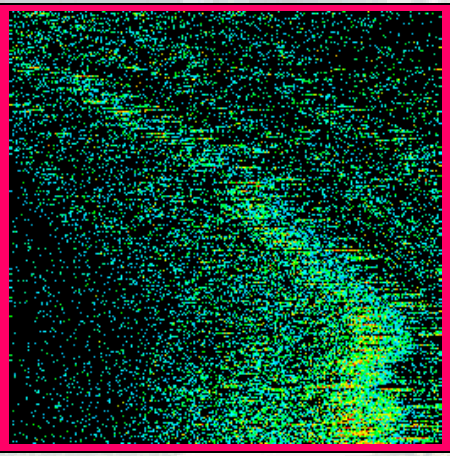


Temperature Variation:

- Spectrometer drifts off peak due to temperature change, causing apparent change in results
- Reduces Accuracy, Precision,and Sensitivity
- Observed effects in X-ray and Mass Spectrometry, Ellipsometry, and Refractometry

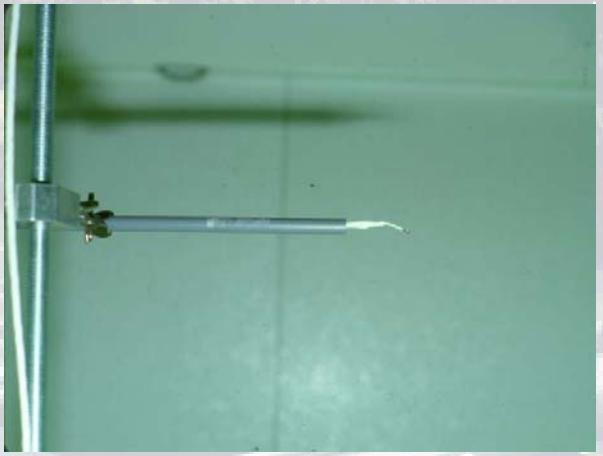
Thin film stack cross section image showing straight lines … secondary electron image, one minute collection time





Chemical image O_2 Auger electron 2 hour collection time. Thermal stability and vibration effects render image useless

Temperature Control Research Project (TCRP)

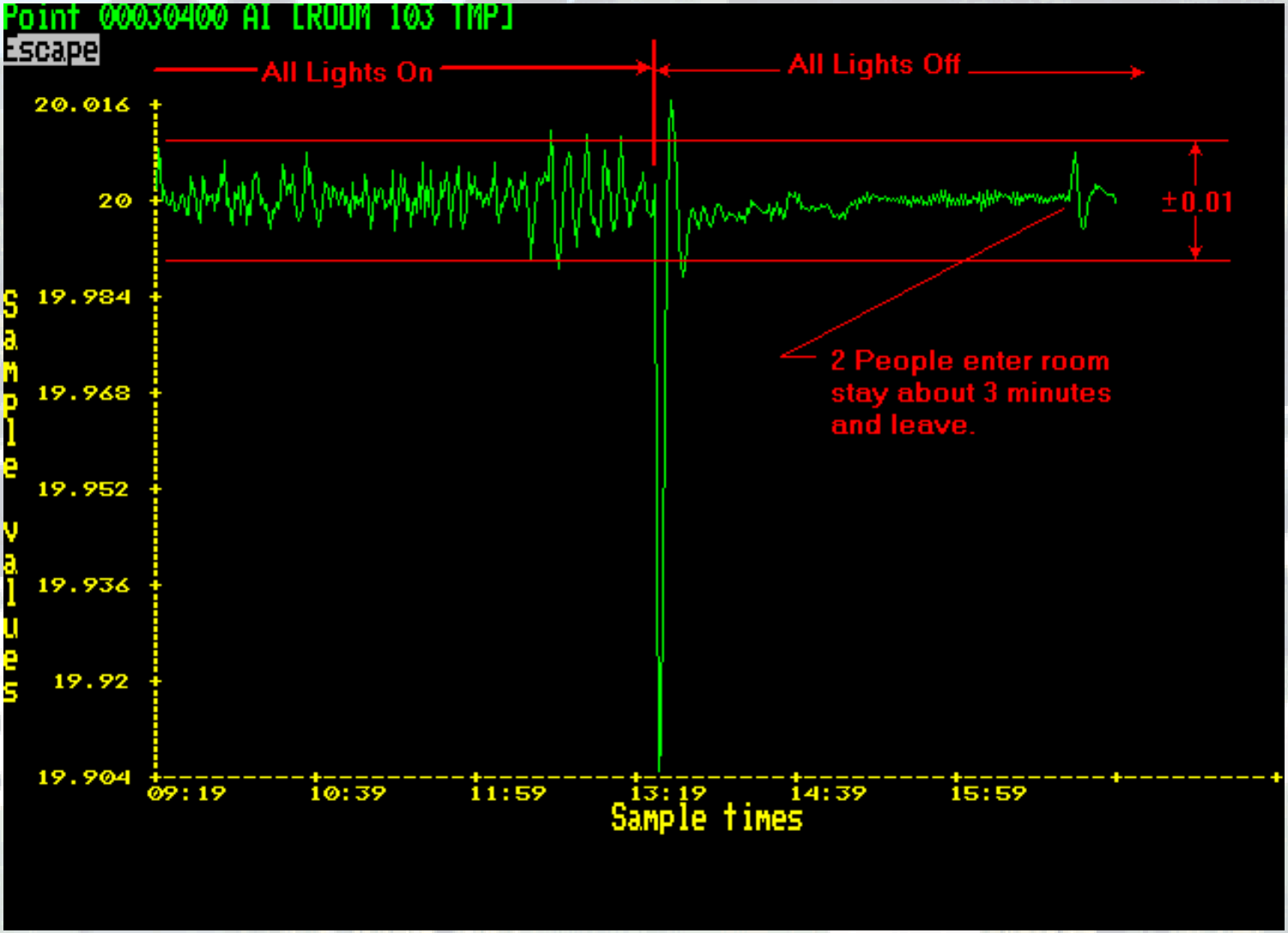


- Resistance Temperature Detector (RTD)
  - Lower sensitivity
  - More linear
  - Used for wide temperature spans

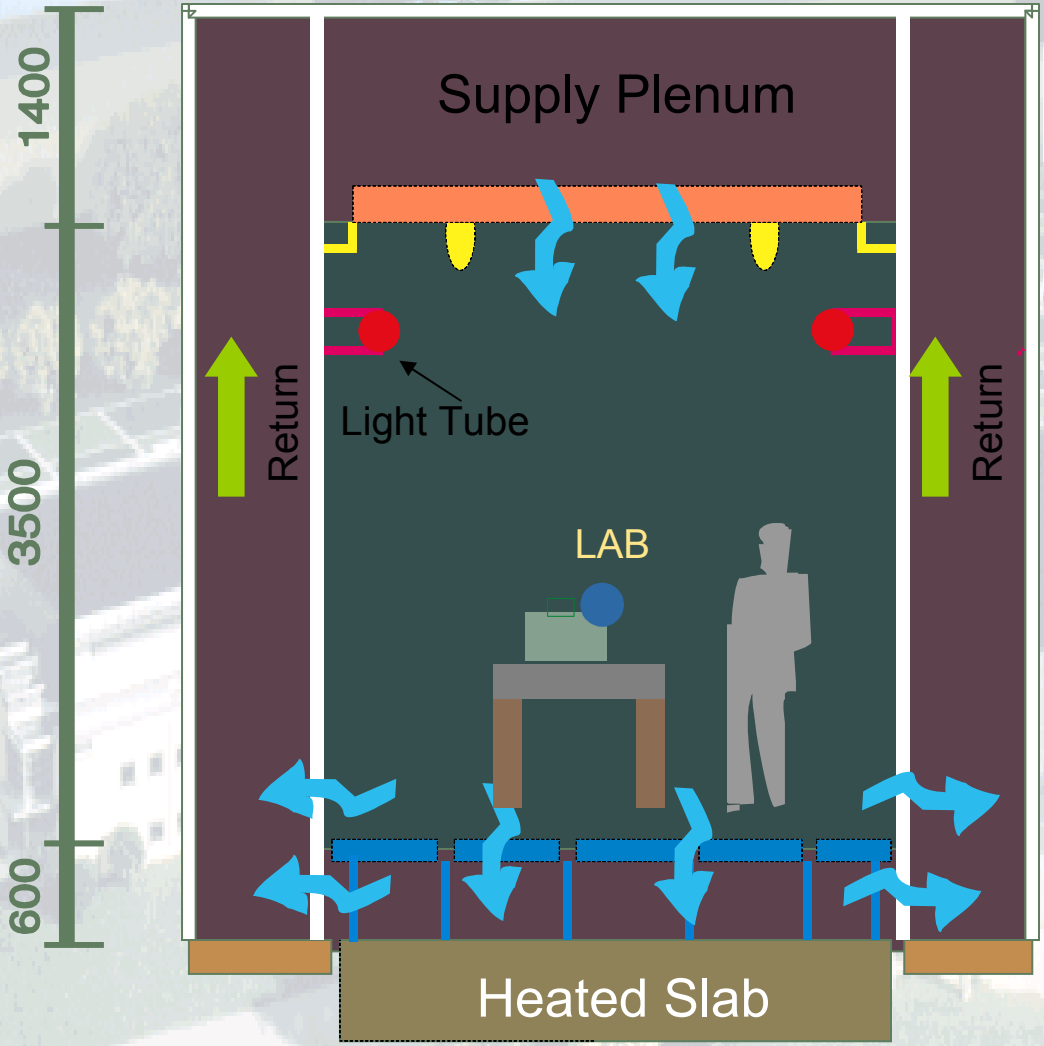
TESTS BY NIST BFRL

- Thermal Resistor (Thermistor)
  - Higher sensitivity
  - Low cost
  - High resistance value
  - Fast response time
  - Nonlinear
  - Used for narrow temperature spans

TCRP Test Results



AML High-Accuracy Lab
±0.01°C Temperature Control Design



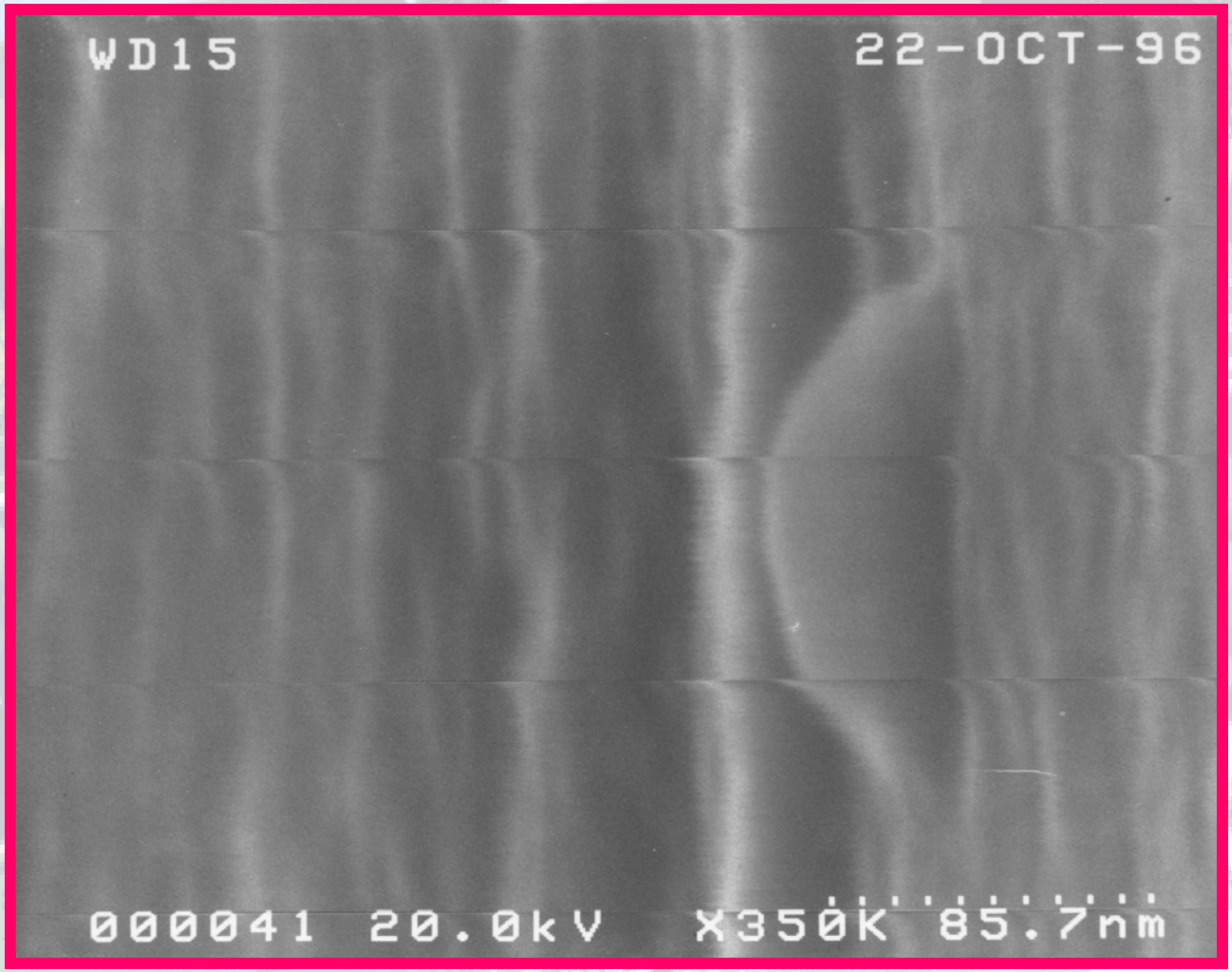
Vibrational Image Degradation
Effects on Physical and Chemical Characterization

Little Vibration

Resolution Destroying Vibration

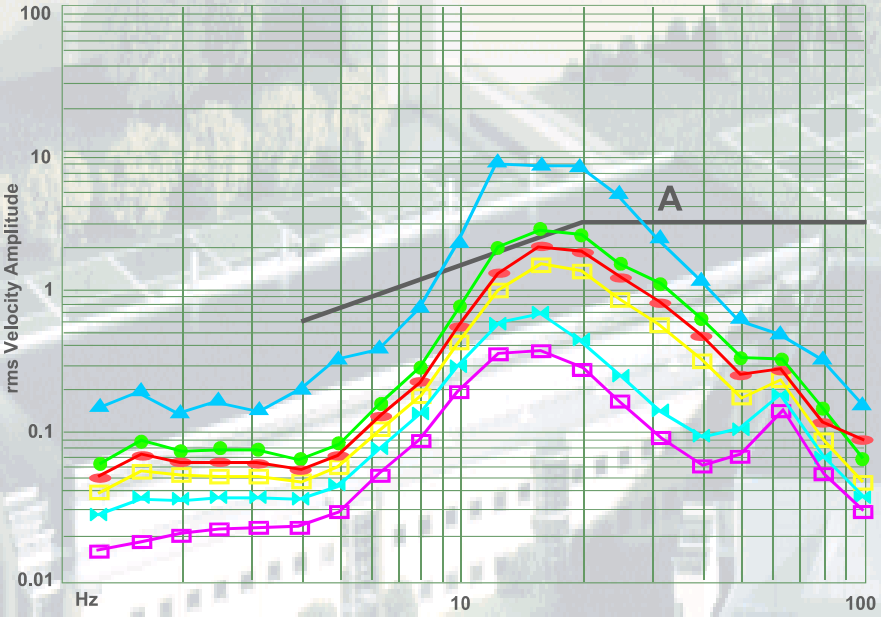
Same Particle – Images Taken Minutes Apart

Vibration Effects – Periodic

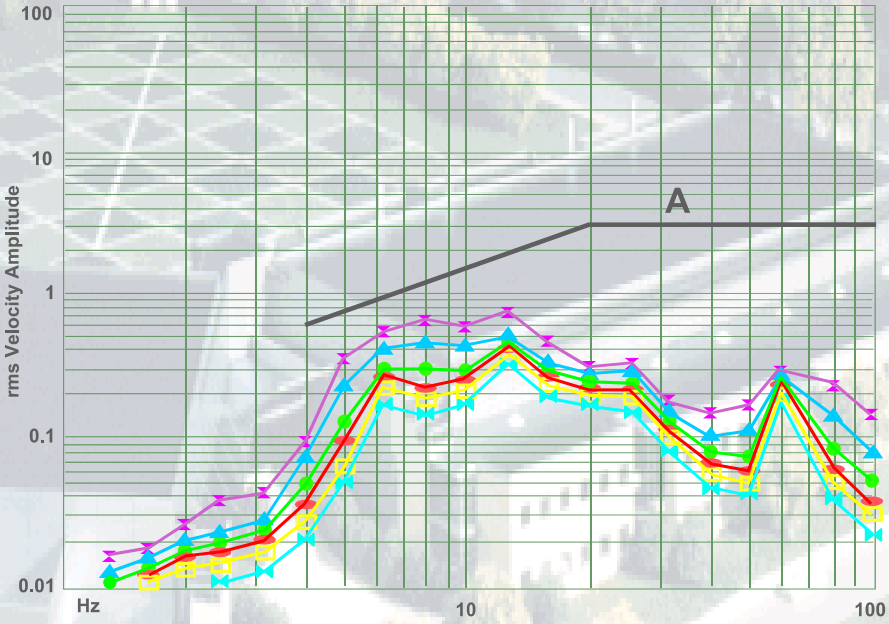


Evaluating Cleanliness of Organic Film on Surface … lines in image are due to periodic vibration

NIST Vibration Isolation Research Project (VIRP)
AML Site Analysis & Vibration



North Site, NE Corner (7:00-7:30am, 5/5/93, Morning Rush)



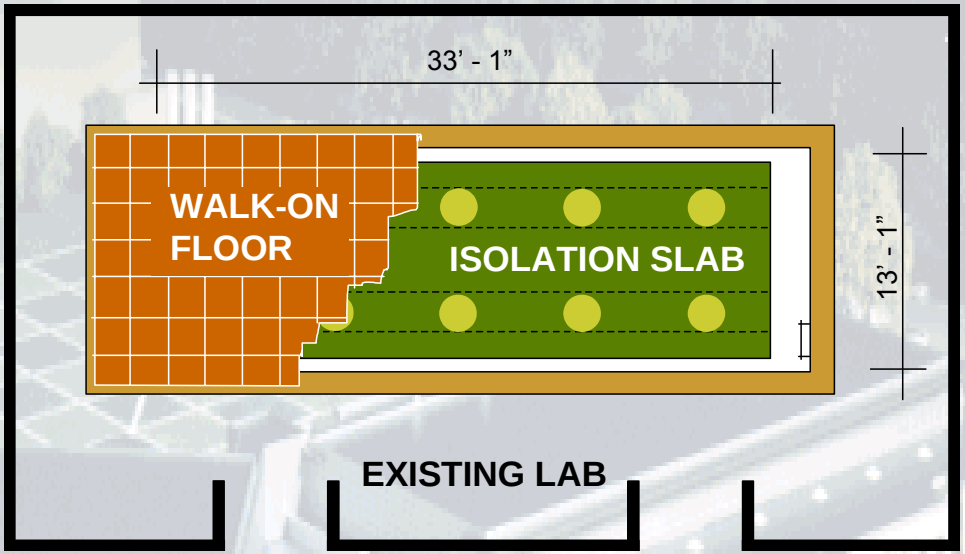
South Site, Center Vertical (4:00-4:30, 5/7/93, Train Passage)

Vibration Isolation Research Project (VIRP)

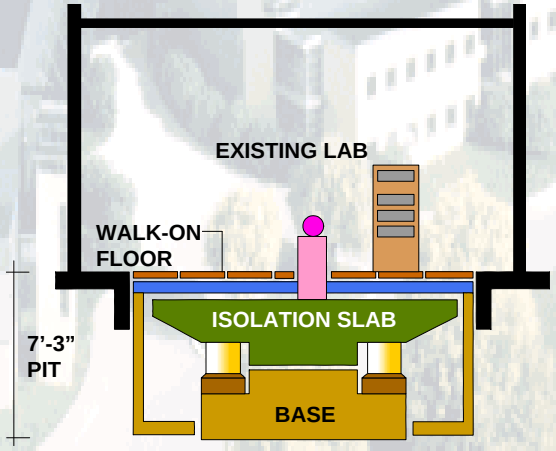
- Opening in walk-on floor can be tailored to experiment footprint
- Pedestal may be used

VIRP Isolation Slab Design

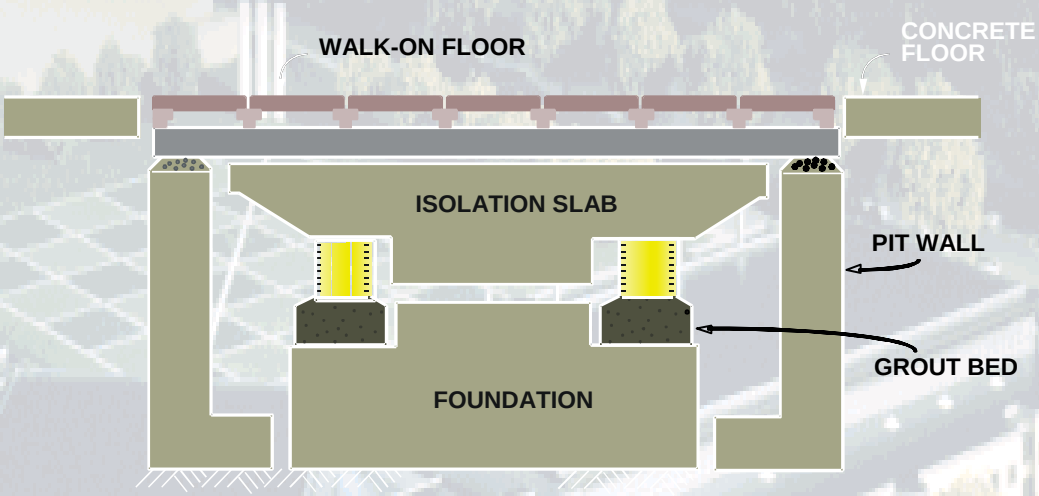
- Slab Plan:
  - Footprint is largest desirable area
  - 13’ x 33’ slab
  - 14’ x 38’ pit
  - Ladders at ends for pit access
  - Ten air springs
  - Access to air springs from below



- Slab Section:
  - Experiment isolated, all else on walk-on floor
  - Built in basement of existing building
  - Almost fills long lab, with perimeter on-grade band
  - Base separated from retaining wall
  - Walk-on floor on steel frame on isolators on retaining wall



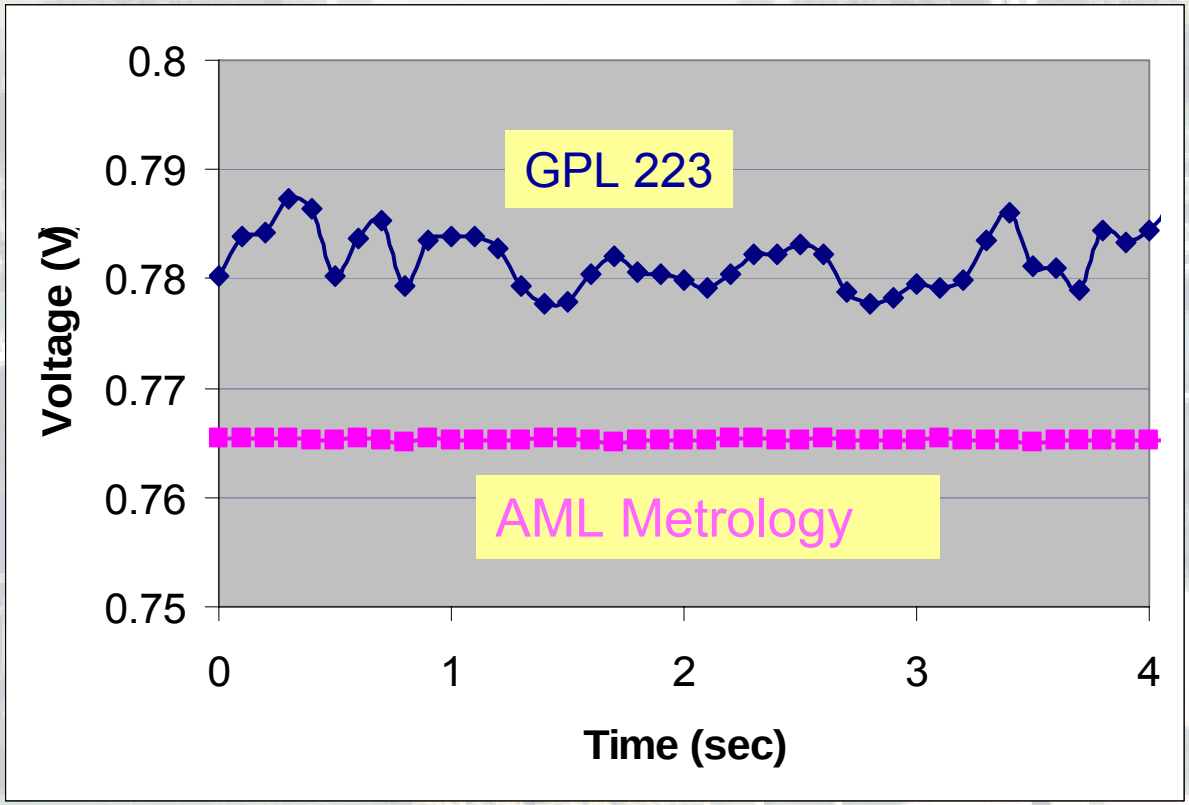
NIST A1 Slab – Pneumatic Isolators

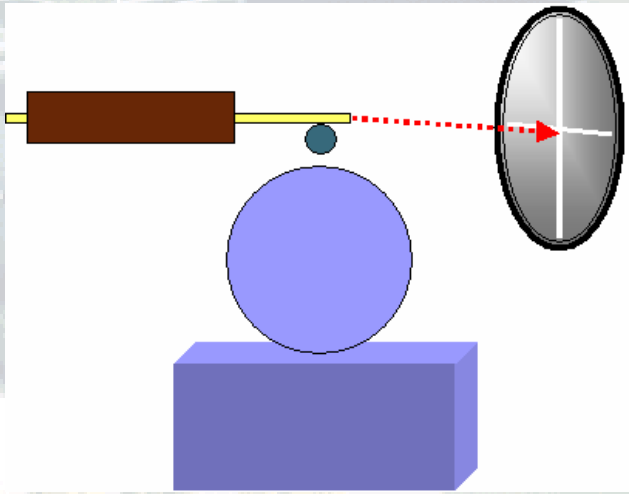


- Two rows of five isolators
- Uses house compressed air
- Active alignment
- Supplemental active isolation

AML Nano-Adhesion Force Measurements Baseline Fluctuations

Reduction of baseline force fluctuation from ~±150 nN to ~±5 nN





Position variation of a laser light spot on a photodiode

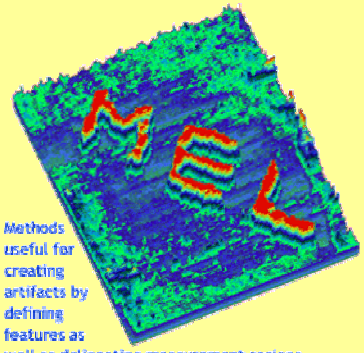
Enhanced Capabilities in Dimensional Metrology Enabled by the AML

AML 0.01 °C temperature controlled rooms are at least a factor of 10 improvement relative to the best-controlled of NIST's present buildings

- **This enables a reduction in measurement uncertainty, i.e.,an increase in measurement accuracy, of the same order.**
- **Temperature control of 0.01 °C rather than 0.1 °C, reduces the temperature contribution to the uncertainty in measurement of a 500-mm long industrial gage to a state-of-the-art level of 50 nanometers.**

Coord. Measuring Machine Ball Plate

Improved vibration control enables fabrication and measurement of "atom-based" dimensional standards with nanoscale dimensions

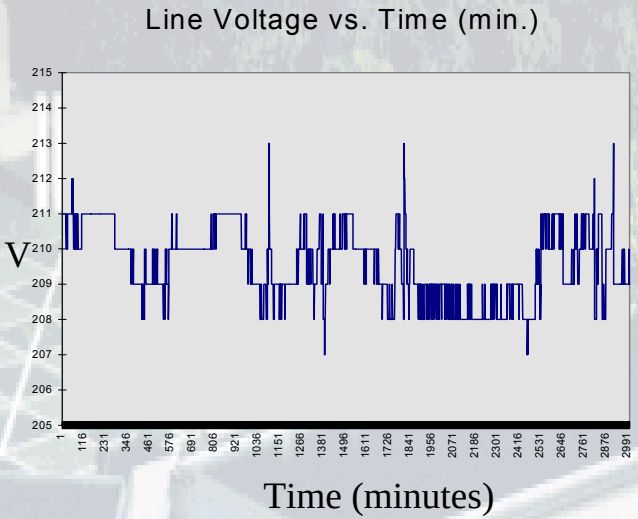


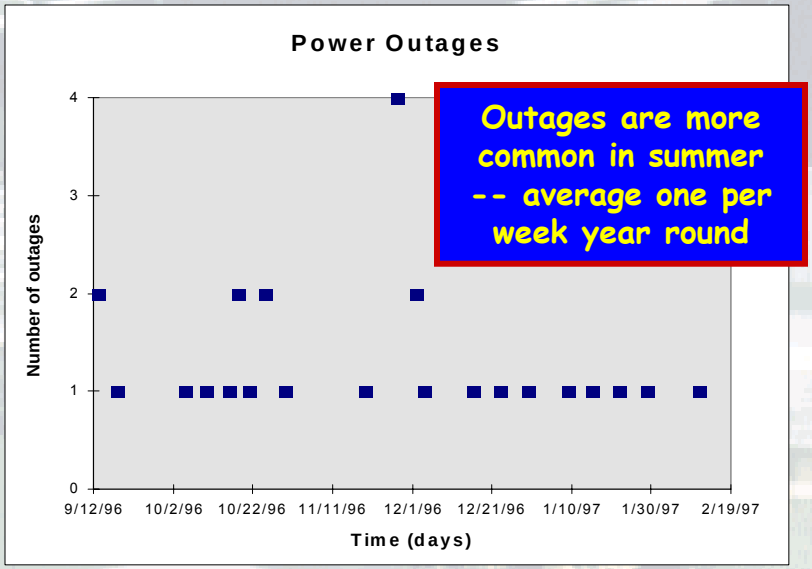
Methods useful for creating artifacts by defining features as well as delineating measurement regions 250nm x 250nm field of view. Feature dimensions are 10nm

- **Extend scanned probe microscopy will produce dimensional standards with nanometer-size features derived directly from the atomic lattice**
- **Both fabrication and measurement of such "atom-based" standards require an ultra vibration free environment**
- **The AML provides multiple laboratories with seismic and acoustic isolation that is superior by factors of 4-10 over that attainable in the best portions of the most vibration free of the GPLs**
- **Vibration reduction directly impacts reduction in "background" thereby increasing signal-to-noise and measurement uncertainty and enabling attainment of picometer levels of measurement uncertainty**

Quality of Power at AML

Limits accuracy and precision
Unreliable for long runs
Reduces analytical sensitivity
Increases downtime (~ 30%)



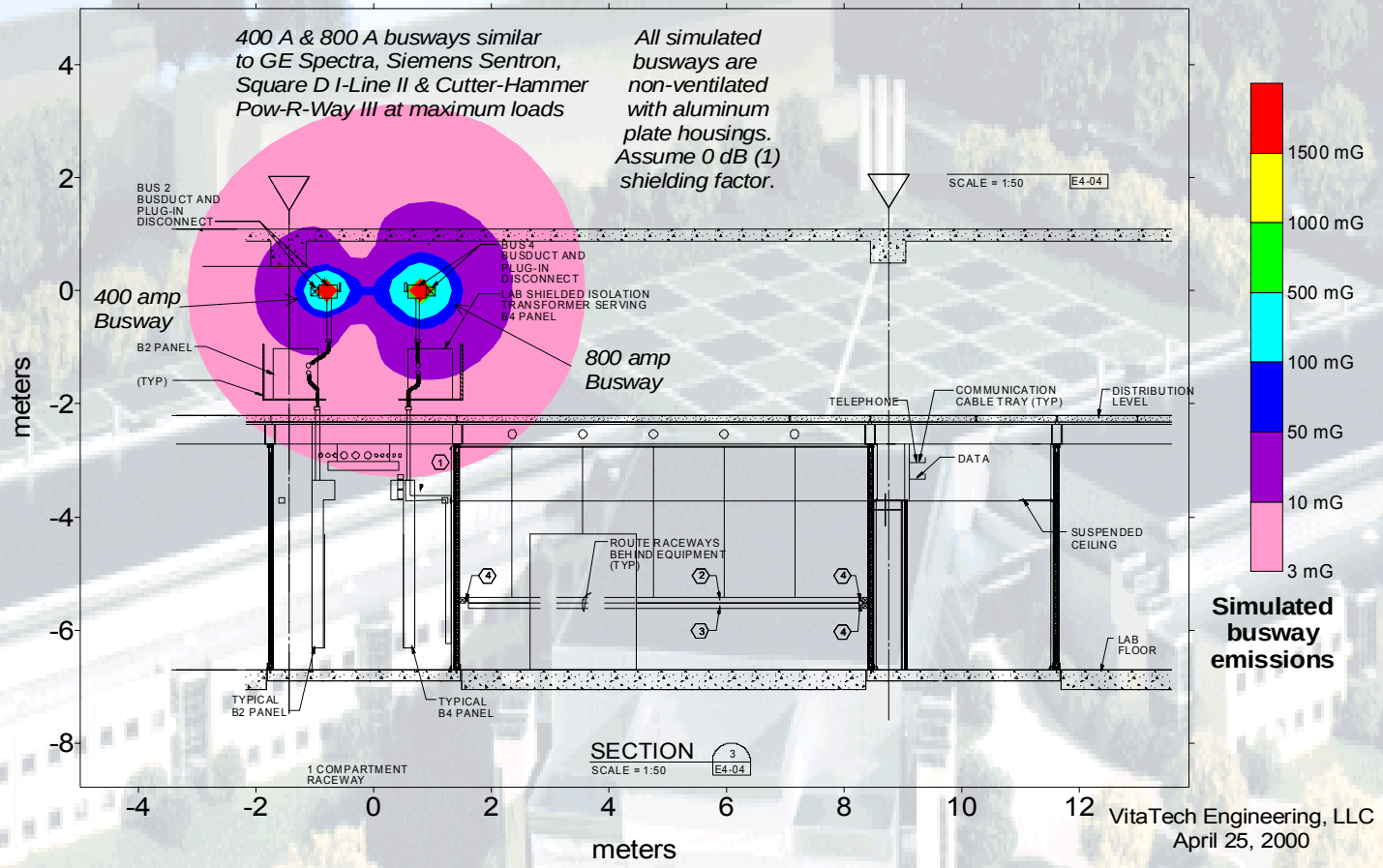


The minor voltage changes and power losses affect the quality & stability of measurements

UPS successfully condition the line noise and prevent outages.

AML designed to have UPS for ALL instrumentation to eliminate over 99% of NIST power problems

Electro-Magnetic Interference (EMI) Free Environment

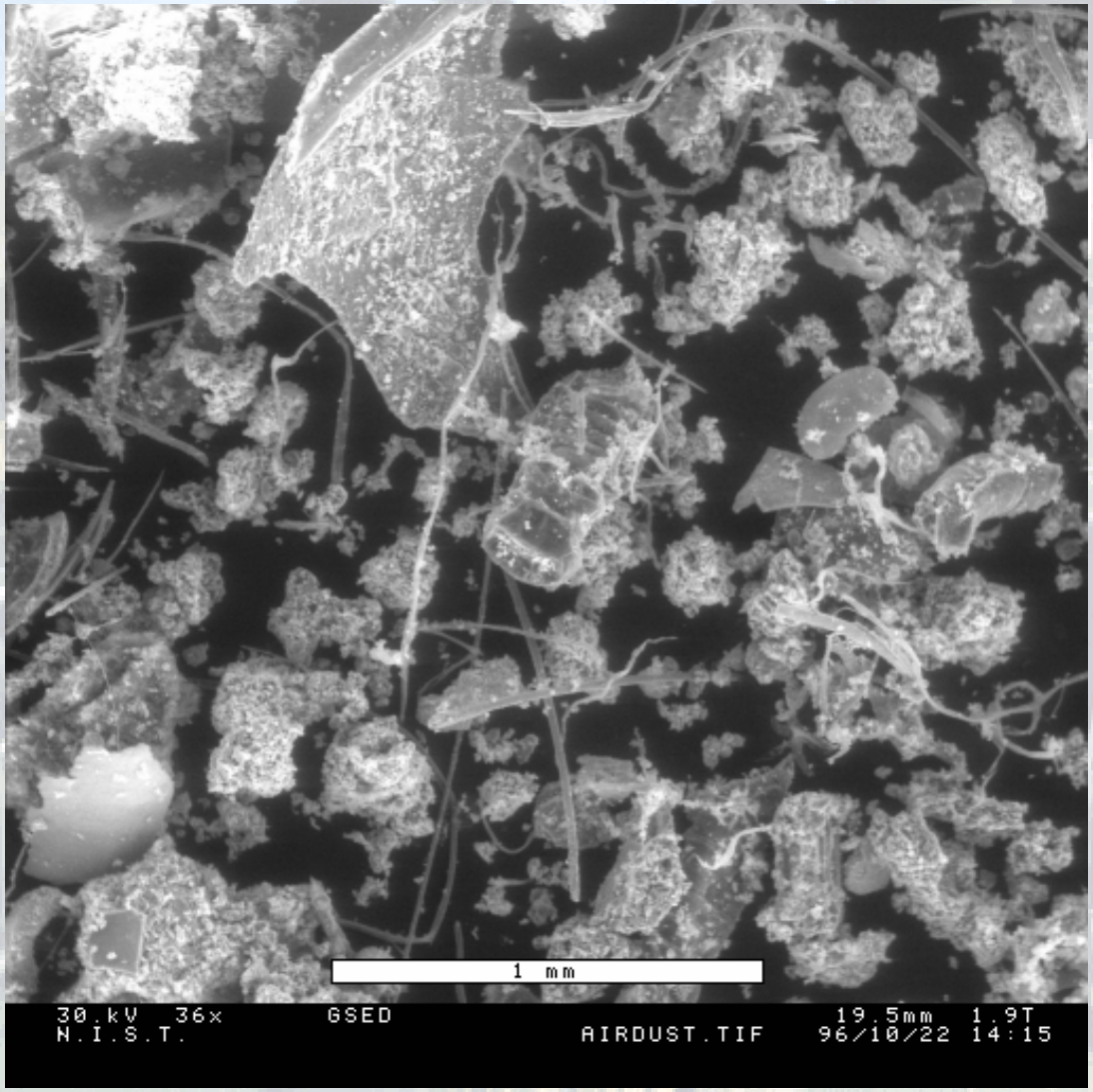


VitaTech Engineering, LLC
April 25, 2000

10 mG EMI threshold for 12-15 inch color monitors, computers & audio/video equipment
5 mG EMI threshold for 17-21 inch color monitors & sensitive instruments

EMI Shielding: 400 A & 800 A Dual Busway Simulation
AC ELF Magnetic Emissions @ 100% Rated Load

Air Quality



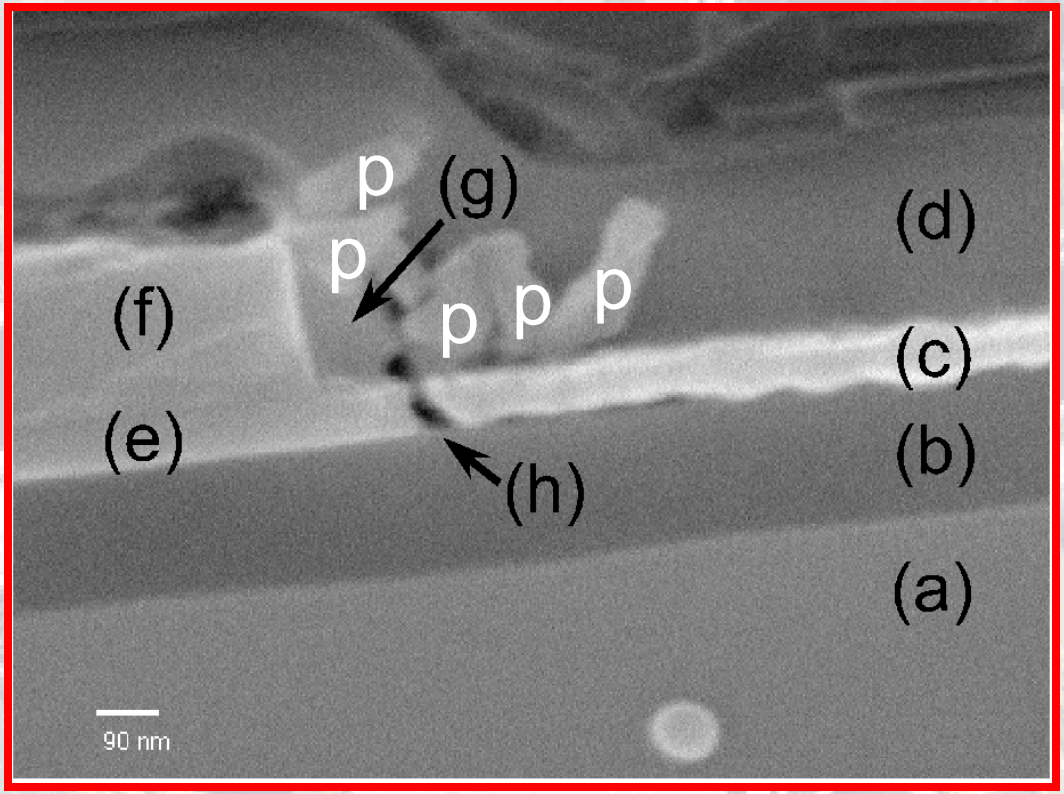
Air Quality at GPL no longer meets requirements for industry needs

Dust Sample from (GPL) Microscopy Lab

Optical Photomicrograph showing particulates having broad size range

Particle Contamination Effects on Semiconductor Materials Measurements

"P" = 0.1 μm Contaminating Particles
Source of Device Manufacturing and Failure



(a) silicon wafer, (b) buried silicon oxide, (c) cobalt silicide layer to the right (d) top layer of silicon oxide (e) silicon channel to the left (f) polysilicon gate and (g) spacer oxide (h) void (h) between the cobalt silicide and silicon channel)

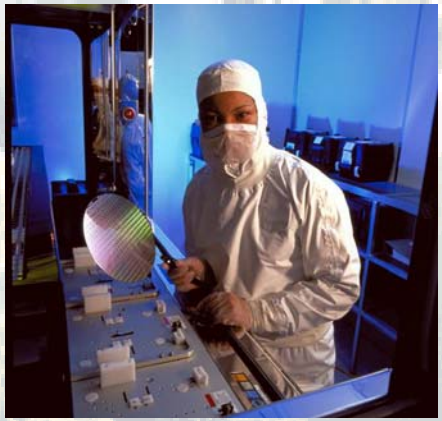
Nano Research Environment Criteria

- Temperature
  - 20°C with ±0.25 to ±0.01°C accuracy
- Vibration
  - 3 to 0.2 micrometer/sec
- Humidity
  - 40 to 45% RH with ±5% to ±1% accuracy
- EMI Free Environment

Cleanliness is the Most Critical Element for Nano - Research, Fabrication and Metrology

AML has:

- Class 1000
- Class 100
- Class 10



AML Cleanroom - A Metrology Enabler

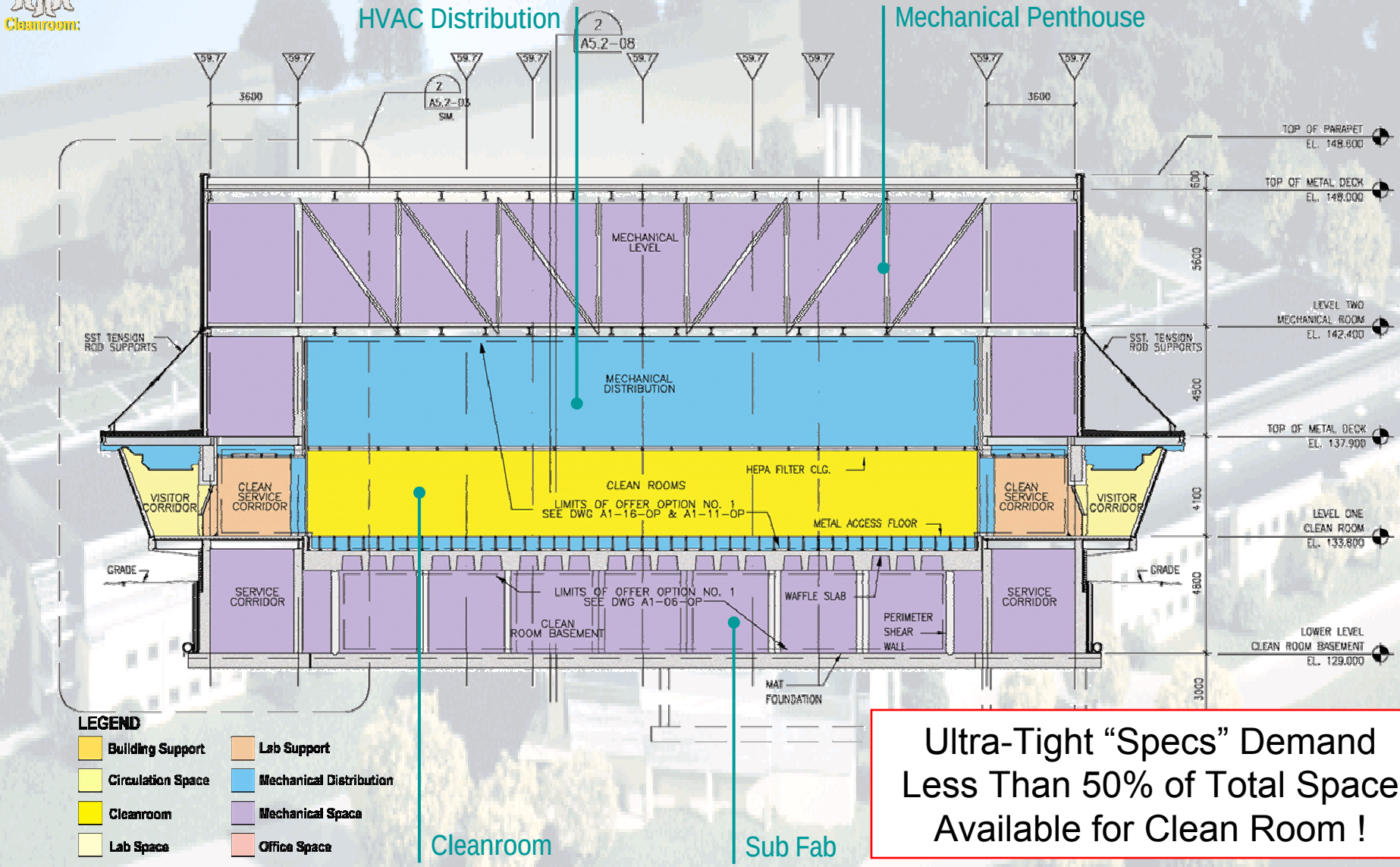
- Capabilities include lithography, thermal processing, thin film and metal deposition, etching systems, and inspection
- Fabricate test structures and prototype devices at the nano and micro-scale in only weeks
- Allow NIST to:
  - Provide advanced metrologies that allow us to understand the process controls necessary for successful fabrication of nanoscale components
  - Develop new measurement methods, instruments, and standard reference materials for nanotechnology, healthcare and homeland security
  - Become a gateway for US Industry to develop necessary measurement and manufacturing skills

Nano Fabrication User Facility

- Non-Reflective Slant Windows
- UV Suppressed Lighting

Nano Fabrication User Facility

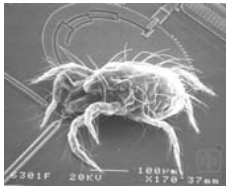
Transverse Section



Ultra-Tight “Specs” Demand
Less Than 50% of Total Space
Available for Clean Room !

Nanoscale Science - The Scale of Things to Come

Things Natural

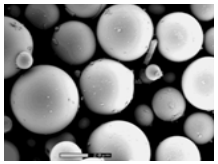


Dust mite

200 μm

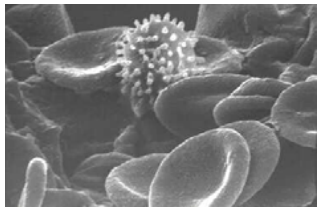
Ant
~ 5 mm

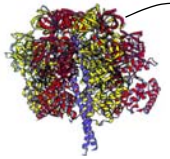
Human hair
~ 10-50 μm wide



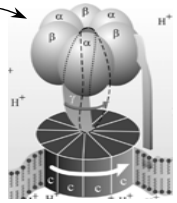
Fly ash
~ 10-20 μm

Red blood cells
with white cell
~ 2-5 μm

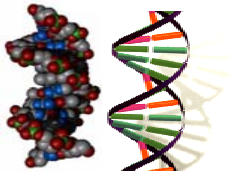




~10 nm
diameter

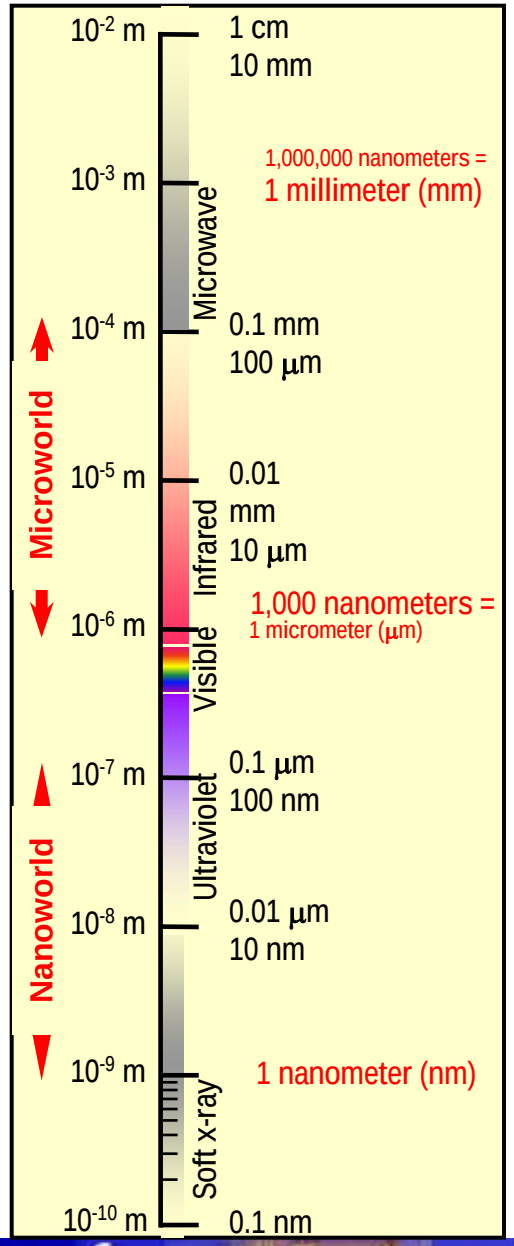


ATP synthase

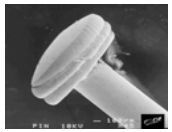


DNA
~2-1/2 nm diameter

Atoms of silicon
spacing ~tenths of nm

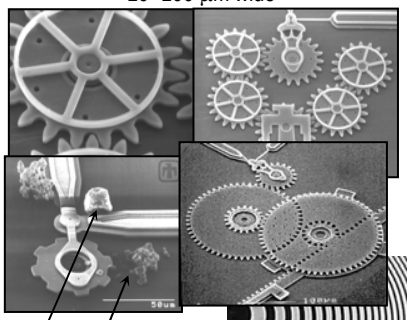


Things Manmade

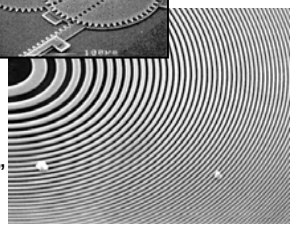


Head of a pin
1-2 mm

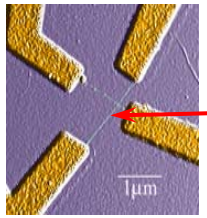
MicroElectroMechanical devices
10 -100 μm wide



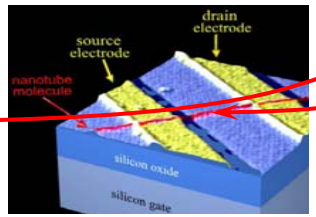
Red blood cells
Pollen grain



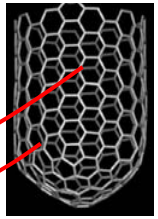
Zone plate x-ray "lens"
Outermost ring spacing
~35 nm



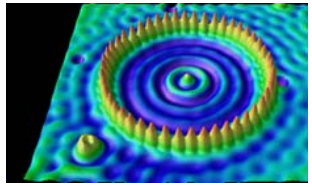
Nanotube electrode



Nanotube transistor



Carbon nanotube
~2 nm diameter



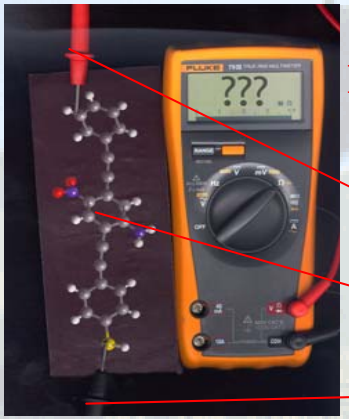
Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm

www.sc.doe.gov/production/bes/scale_of_things.html

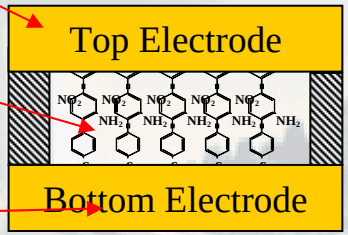
National Institute of Standards and Technology

NIST

Measurements, Standards, & Data for the Nanoscale



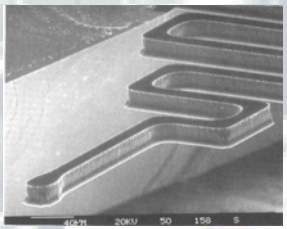
Molecular Electronics

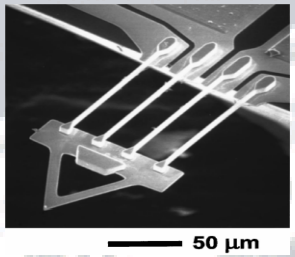


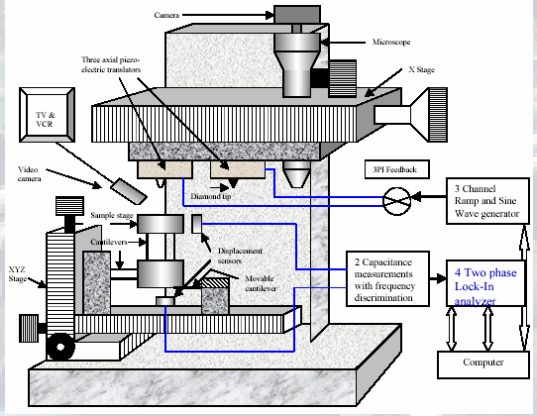
Imaging Magnetic Nanostructures

Nanoconstriction
domain wall

Cantilever Fabrication for Lateral Force Measurement

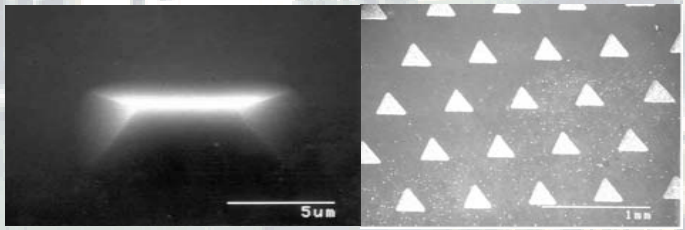




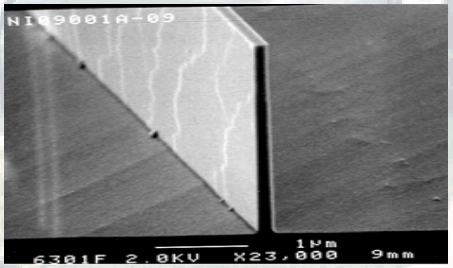


Nanomechanics and Tribology Measurements

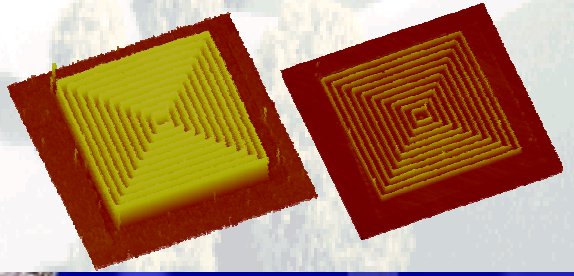
Surface Standards for Biomaterials



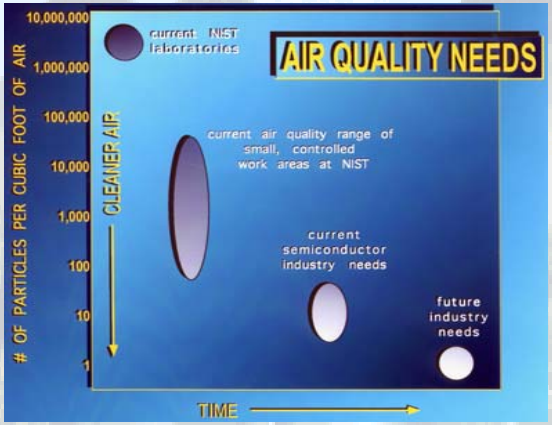
Linewidth Standards



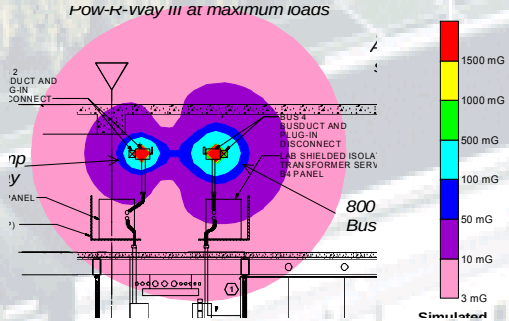
Nanoscale Dimensional Standards



AML: World's Best Measurement Laboratory

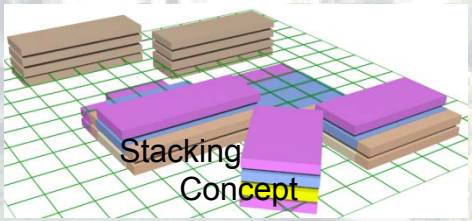


Cleanroom:
Class 1000
Class 100
Class 10

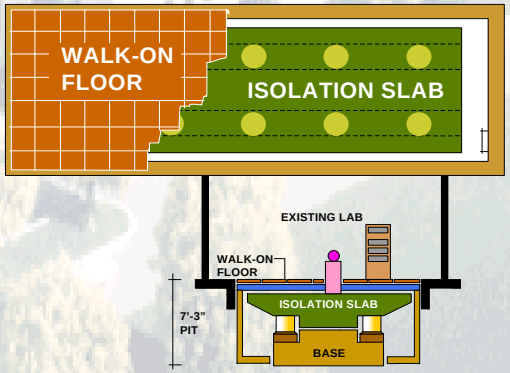


EMI: Free Environment

Temperature:
20°C ±0.25 to ±0.01°C
Humidity:
40 to 45% RH ±5% to ±1%

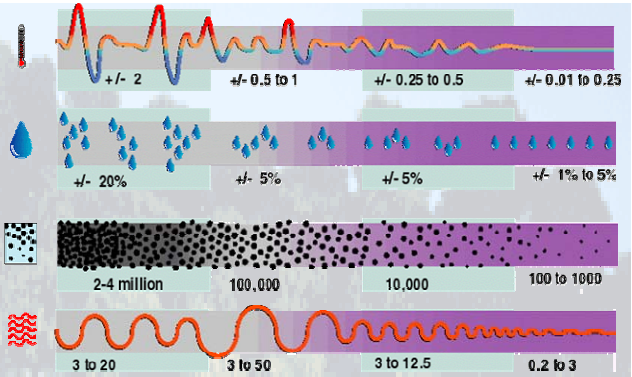


Vibration: 3 to 0.2 mm / sec



AML Dedication June 21, 2004

Conclusions



The AML:

- Is the world's best measurements laboratory
- Will provide the measurements and standards needed for 21st century key technologies
- Establishes a National Nanomanufacturing and Nanometrology Facility to avail the best measurement capabilities to industry

aml.nist.gov