Metrology Measurement Capabilities

Federal Manufacturing & Technologies

Kermit Shroyer

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AlliedSignal Inc.
Federal Manufacturing
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Table of Contents

Measurement Capability Tables

Measurement Standards Tables

INTRODUCTION

Since 1958, the AlliedSignal Federal Manufacturing & Technologies (FM&T) Metrology Department has developed measurement technology and calibration capability in four major areas of measurement:

Mechanical;

Environmental, Gas, Liquid;

Electrical (D.C., A.C., RF/Microwave); and

Optical and Radiation.

The capabilities developed include unique capabilities in many areas of measurement and engineering expertise to develop measurement techniques and resolve measurement problems in these major areas.

FM&T Metrology was established in 1958 to provide a measurement base for the Department of Energy's Kansas City Plant. The Metrology Engineering Department provides the expertise to develop measurement capabilities for virtually any type of measurement which falls into the broad areas listed above. The engineering staff currently averages almost 16 years of measurement experience.

A strong audit function has been developed to provide a means to evaluate the calibration programs of our suppliers and internal calibration organizations. This evaluation includes measurement audits and technical surveys.

The requirements placed on Metrology require traceability of measurements to the National Institute of Standards and Technology or to nationally recognized methods or natural phenomena.

A description of Metrology capabilities, traceability flow charts, and the measurement uncertainty of each of the measurement capabilities is contained in the following pages.

MECHANICAL

MECHANICAL

Length and Coordinate Measurement

Three-dimensional coordinate standards are measured interferometrically using a helium-neon laser light source. Laser interferometers are mounted on each axis of a three-dimensional coordinate measuring machine. Corrections are made for wavelength variation due to air density by an on-line computer. Accuracies are listed in the accompanying table. Many length measuring systems are calibrated using the laser interferometer.

Gage Block Measurement

Gage blocks are compared to blocks certified by the Primary Standards Laboratory (PSL) using a gage block comparator.

Roundness Measurement

Roundness measurements are made using a machine that indicates out-of-roundness on a circular paper graph with a resolution of 1 min. The roundness machine is calibrated using a roundness standard certified by the PSL.

Flatness Measurement

Flatness of small surfaces is measured using an optical flat, a transparent plate with at least one surface finished to nearly perfect flatness. When this face is placed on another nearly flat surface under a monochromatic light, interference fringes are observed. Because the wavelength of light is known, the curvature of the fringes can be used to determine the flatness of the unknown surface.

Surface plate flatness is measured using an autocollimator and two mirrors. The flatness of the surface plate is determined from the small angles measured from point to point on the surface plate.

Angle Measurement

Small angles are measured using an autocollimator. The autocollimator is calibrated using a small-angle generator consisting of a pivot arm of known length and a set of certified gage blocks.

Large angles are measured using an autocollimator, a rotary table, an optical polygon, and angle gage blocks.

Surface Finish Measurement

Surface finish standards are measured using a profile-type surface finish analyzer. The surface finish analyzer is calibrated using a lever arm calibrator and roughness standards calibrated by NIST.

Vibration

Accelerometers used for vibration testing are calibrated on a computer-controlled shaker. Comparison is made to a NIST calibrated accelerometer. The acceleration capability is up to 75 g. The frequency range is 10 Hz to 10 kHz at ambient temperatures. Calibration at temperatures ranging between -65°C and 125°C can be performed up to a frequency of 4 kHz. A control standard is measured before calibration, to verify that systems are functioning properly.

Mechanical Shock

Accelerometers used for mechanical shock testing to 8000 g's are calibrated in a back-to-back configuration on an air-activated shock pulse generator. For shock levels above 8000 g's, an elastic cord assisted impact device generates the shock pulse. A computer determines the velocity change and provides calibration data. A control standard is measured before calibration, to verify that systems are functioning properly.

Sound Level

Calibration of sound level is made by comparison of a sound level meter to a standard pistonphone that is calibrated at NIST.

Mass Measurement

Mass measurements are made by comparison to master weights using seven precision balances. The master weights are calibrated through the NIST Mass Measurement Assurance Program.

Metrology also has the capability to perform extremely precise weighing on 1-2-3-5 decade progressions over the range from 1 mg to 5 kg.

Force Measurement

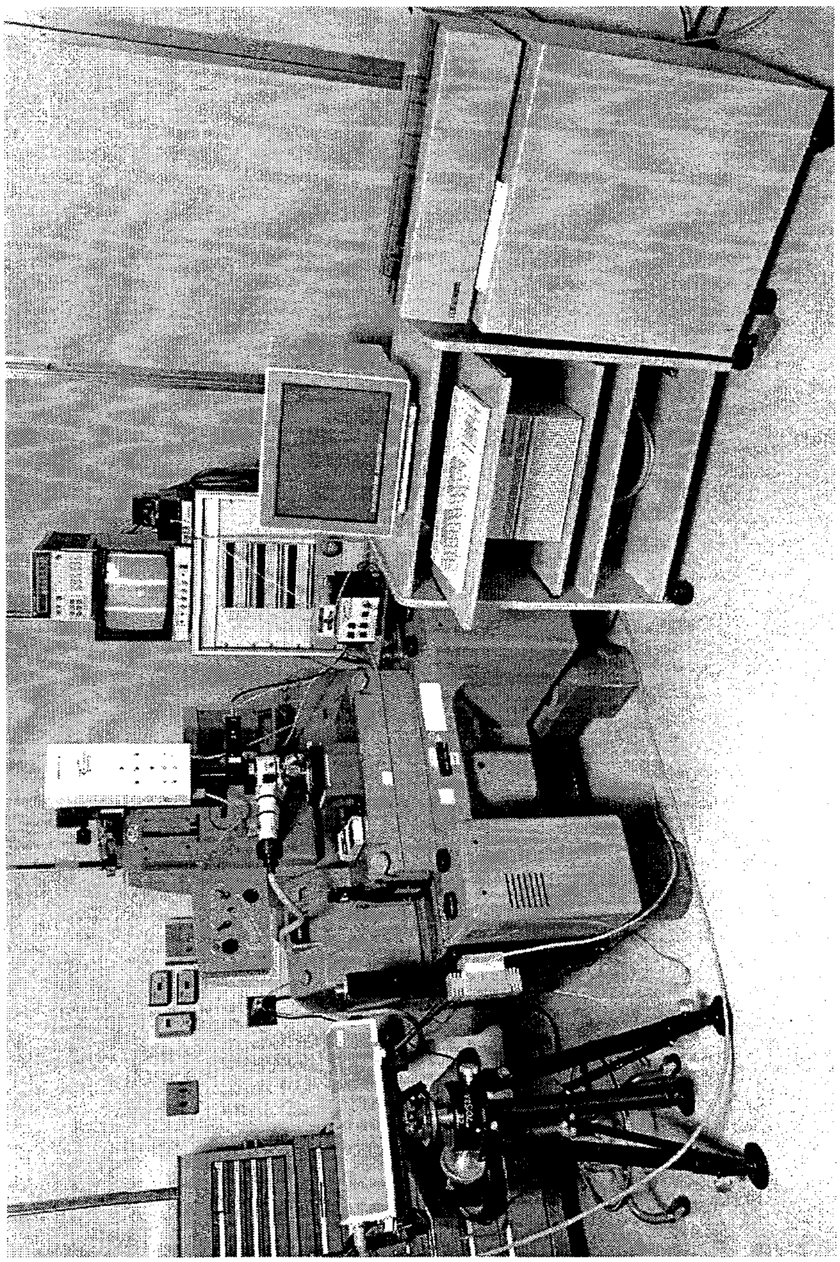
Force transducers up to 2400-lbf capacity are measured using weight sets or dead weight testers which are certified in force units in our Mass lab. Larger force devices are measured by comparison to NIST-calibrated proving rings using a universal force tester.

Torque Measurement

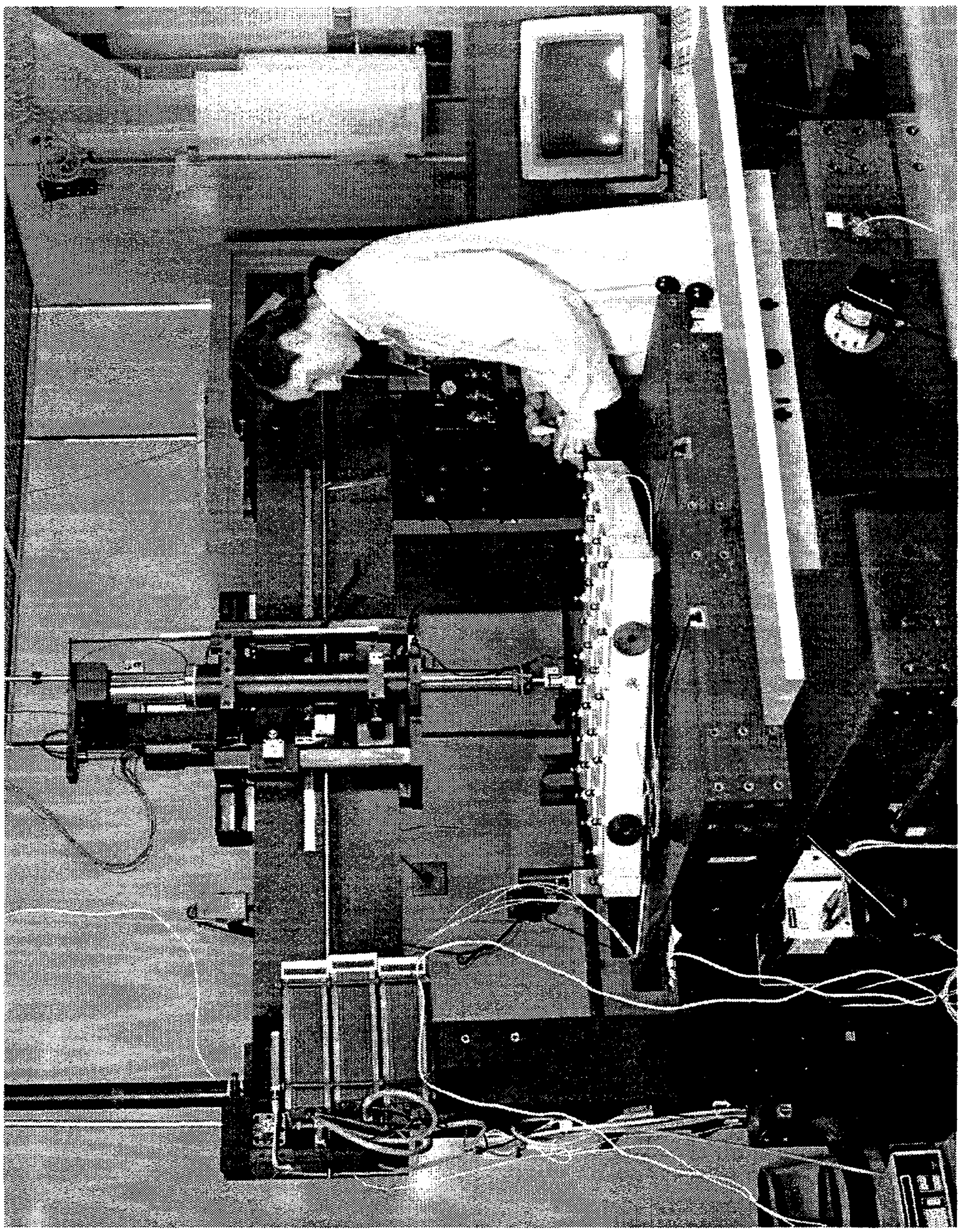
Torque transducers are measured using weights which are certified in force units in our Mass lab and lever arms of known length. The lever arms are calibrated on a coordinate measuring machine using a helium-neon laser as a standard.

Laboratory Glassware Volume

Laboratory glassware volume is measured by the gravimetric method using precision balances and distilled water.



CMM With Laser-Based Edge Detector



Shelton CMM With Two-Dimensional CMM Calibration Artifact

Dimensional Measurement Capability

Type	Range (in)	Accuracy (±) Measuring
Length-Gage Blocks	To 1	5 μin
	2	6 μin
	3	7 μin
	4	8 μin
	5	9 μin
	6 to 7	10 μin
	8 to 11	12 μin
	12	13 μin
	16	15 μin
	20	18 μin
Length-Coordinate Measurement *	Along an axis	(2 ppm + 20 μin)
	In a plane **	(7 ppm + 60 μin)
Internal Diameters	0.02 to 15 in	(4 ppm + 10 μin)
Roundness	To 20-in diameter	3 μin
Thread Wires	All standard pitches	8 μin

* Maximum range of length-coordinate measurement is x = 48 in, y = 36 in, and z = 12 in

** Certain artifacts, such as ball plates, can be designed in such a way to allow the use of a single-axis calibration technique. The technique requires the balls to be located in an orderly array with one ball located in the center. Artifacts of this design can be certified to ±(2 ppm + 30 μin).

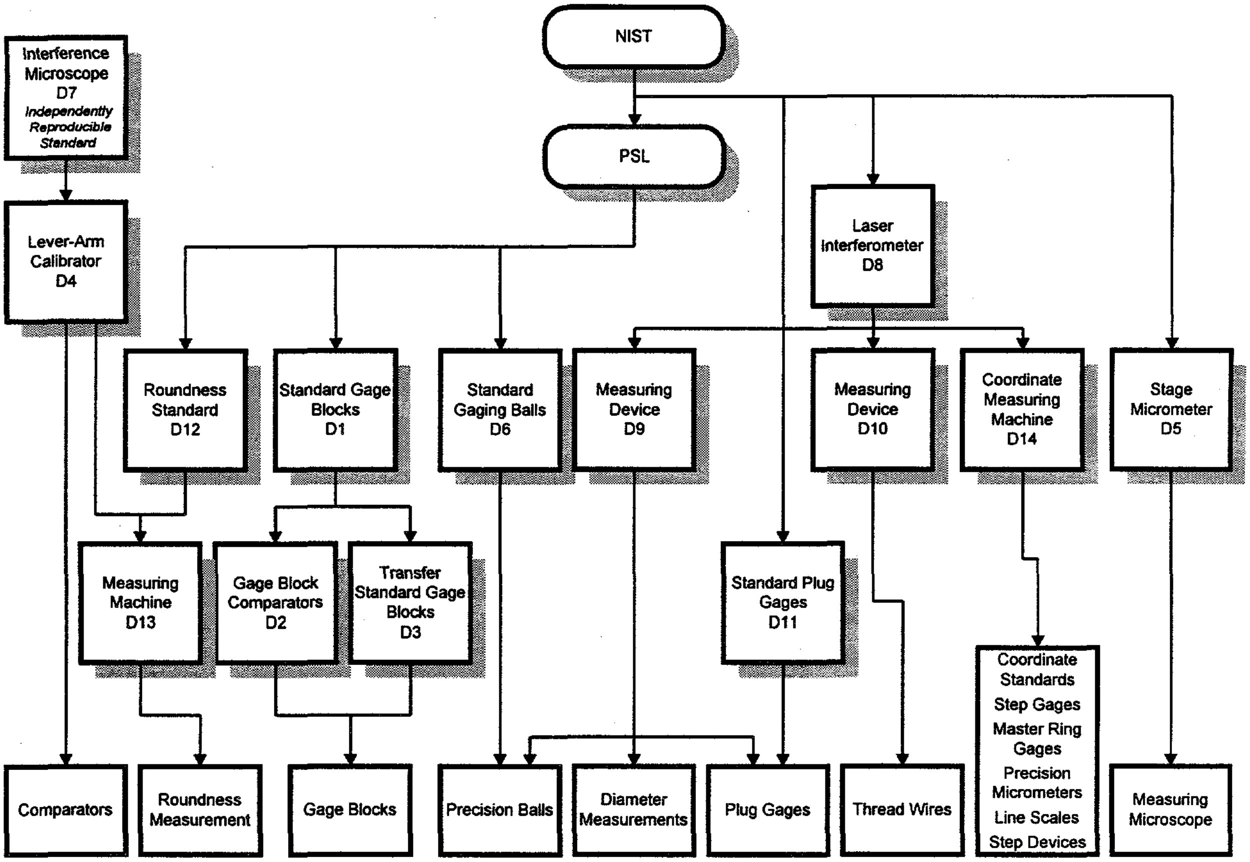


Figure 1A. Mechanical Calibration Traceability (Dimensional)

Dimensional Standards

Code	Description	Manufacturer	Range	Accuracy (±)
D1	Standard Gage Blocks	Do All	To 1 in	3 µin
		Do All	2 in	4 µin
		Do All	3 in	5 µin
		Do All	4 in	6 µin
		Pratt & Whitney	5 in	7 µin
		Pratt & Whitney	6 in	8 µin
		Pratt & Whitney	8 in	9 µin
		Pratt & Whitney	10 in	10 µin
		Pratt & Whitney	12 in	11µin
		Pratt & Whitney	16 in	13 µin
		Pratt & Whitney	20 in	16 µin
D2	Gage Block Comparators	Link	0 to 2 in	3 µin
		Federal	0 to 4 in	3 µin
		Pratt & Whitney	0 to 20 in	3 µin

D3	Transfer Standard Gage Blocks	Do All	To 1 in	5 μin
		Do All	2 in	6 μin
		Do All	3 in	7 μin
		Do All	4 in	8 μin
		Pratt & Whitney	5 in	9 μin
		Pratt & Whitney	6 to 7 in	10 μin
		Pratt & Whitney	8 in	11 μin
		Pratt & Whitney	10 in	12 μin
		Pratt & Whitney	12 in	13 μin
		Pratt & Whitney	16 in	15 μin
		Pratt & Whitney	20 in	18 μin
D4	Lever Arm Calibrator	FM&T Metrology	0 to 0.0002 in	0.2 μin + 0.5% of travel
		Mitutoyo	0 to 0.05 in	4 μin + 0.25% of travel
D5	Stage Micrometer	American Optical 15680	0 to 25 mm	0.15 μm
			0 to 1 in	4 μin
D6	Standard Gaging Balls	AA Industries	1/16 to 1 in (1/32-in increments)	7 μin
D7	Interference Microscope	Zeiss	0 to 0.01 in	1 μin
D8	Laser Interferometer	Hewlett-Packard	NA	0.05 ppm
D9	Measuring Device	Pratt & Whitney	1 in	10 μin
D10	Measuring Device	FM&T Metrology	0 to 2 in	8 μin
D11	Standard Plug Gages	Lincoln	0.050 to 1 in	5 μin
D12	Roundness Standard	Taylor Hobson	NA	3 μin
D13	Roundness Measuring Machine	Bendix A & M	20-in diameter	3 μin
D14 *	Coordinate Measuring Machine	Shelton	x axis	(2 ppm + 20 μin)
			y axis	(2 ppm + 20 μin)
			z axis	(2 ppm + 20 μin)
			x-y plane	(7 ppm + 60 μin)
			y-z plane	(7 ppm + 60 μin)
			x-z plane **	(7 ppm + 60 μin)

* Maximum range: x = 48 in, y = 36 in, z = 12 in

** Certain artifacts, such as ball plates, can be designed in such a way to allow the use of a single-axis calibration technique. This requires the balls to be located in an orderly array with one ball located in the center. Artifacts of this design can be certified to ±(2 ppm + 30 μin).

Angle, Roughness, and Flatness Measurement Capability

Type	Range	Measuring Accuracy (±)
Angle	0 to 360°	1 arc second
Surface Roughness	0 μin to 0.008 in Ra	0.7 to 400 μin Ra
Optical Surface Flatness	To 3-in diameter 3 - 12-in diameter	2 μin 4 μin
Surface Plate Flatness	1 by 1 ft 4 by 6 ft 5 by 10 f.	50 μin 75 μin 100 μin

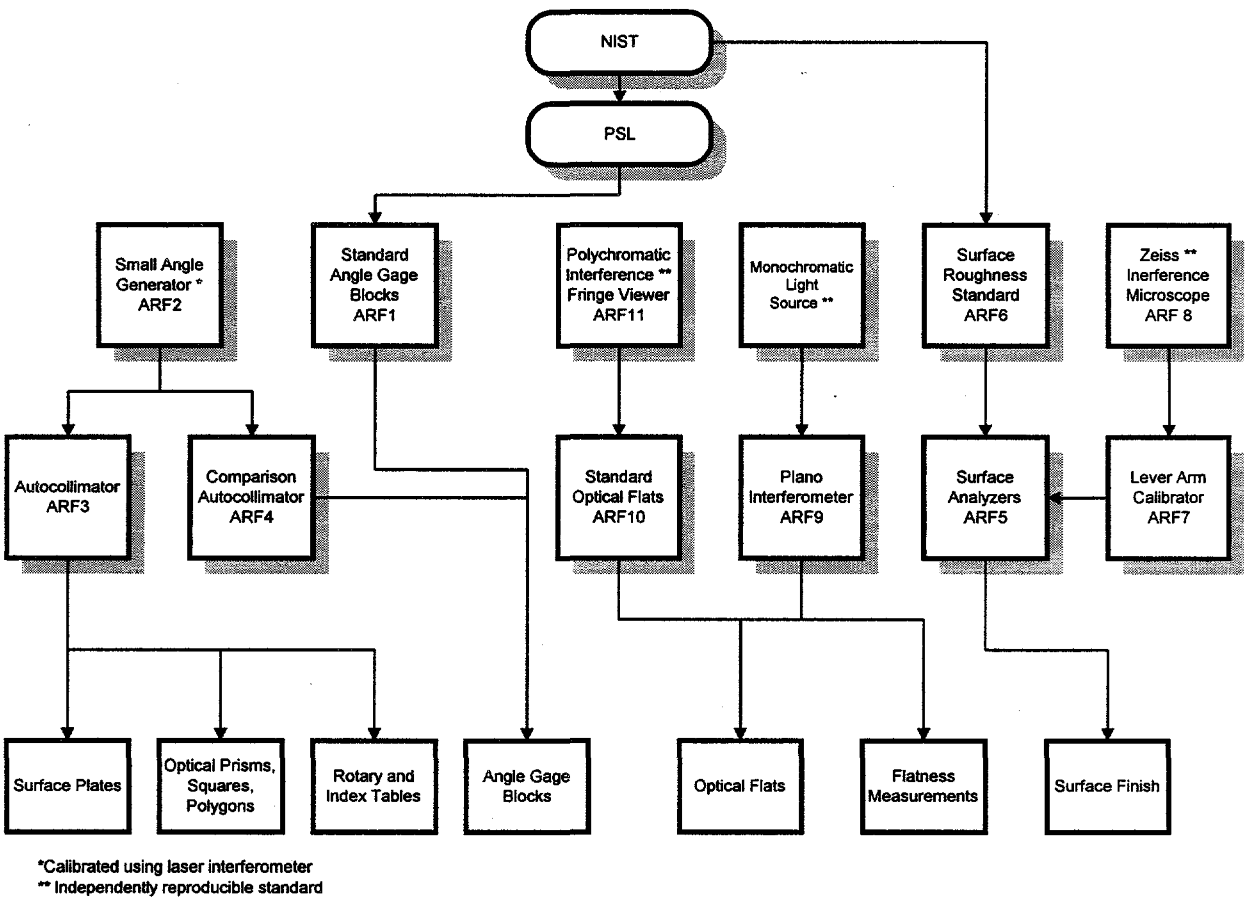


Figure 2A. Mechanical Calibration Traceability (Angle, Roughness, Flatness)

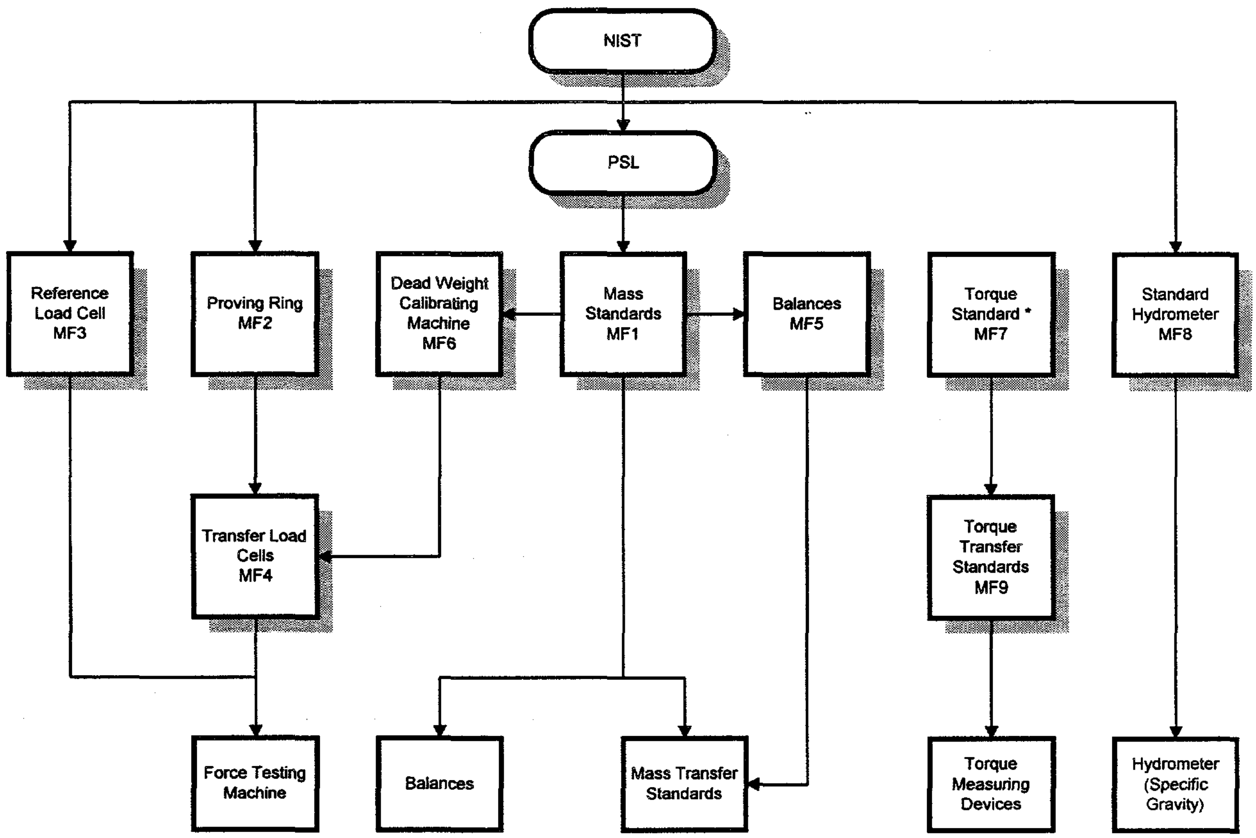
Angle, Roughness, Flatness Standards

Code	Description	Manufacturer	Range	Accuracy (±)
ARF1	Standard Angle Gage Blocks	Webber	1 arc second to 45° (16 blocks)	0.7 arc second
ARF2	Small Angle Generator	Matrix	10 arc minutes	0.1 arc second
ARF3	Autocollimator	Davidson	10 arc seconds	0.15 arc second
		Nikon	20 arc minutes	0.4 arc second +0.25% of measured angle
		Hilger Watts	10 arc minutes	0.5 arc second +0.25% of measured angle
ARF4	Comparison Autocollimator	Davidson	120 arc seconds	0.3 arc second +0.5% of measured angle
ARF5	Surface Analyzer	Federal	0 to 0.008 in Ra (10 ranges)	0.7 to 400 μin Ra
ARF6	Surface Roughness Standard	NIST	120 μin Ra	3.1 μin Ra
ARF7	Lever-Arm Calibrator	FM&T Metrology	0 to 0.0002 in	0.2 μin +0.5% of travel
ARF8	Interference Microscope	Zeiss	0 to 0.01 in	1 μin
ARF9	Plano Interferometer	Davidson	2 3/4-in diameter	2 μin
ARF10	Standard Optical Flats (set of 3)	Do All	12-in diameter	Flat within 4 μin
ARF11	Polychromatic Interference Fringe Viewer	Strang	NA	1 μin

Mass, Force, Torque, Specific Gravity, and Laboratory Glassware Volumetric Measurement Capability

Type	Range	Accuracy (±)
Mass (Direct Weighing)	To 15 mg 15 to 100 mg 100 mg to 1 g 1 to 3 g 3 to 20 g 20 to 100 g 100 to 1000 g 1000 to 5000 g 5000 to 60000 g	0.020 mg 0.025 mg 0.035 mg 0.055 mg (4 ppm + 0.07 mg) (3 ppm + 0.4 mg) (3 ppm + 0.5 mg) (3 ppm + 11.0 mg) 2 g
Mass (Substitution Weighing)	1 to 100 mg 200 mg to 10 g 20 to 50 g 100 to 5000 g 5 to 22 Kg	0.013 mg 0.015 to 0.04 mg 0.07 to 0.20 mg 3.5 ppm 25 to 50 mg
Mass (Calibration Design Using 1-2-3-5 Decade Progressions)	1 to 500 mg 1 to 5 g 10 to 50 g 100 to 5000 g	0.004 to 0.006 mg 0.006 to 0.011 mg 0.018 to 0.030 mg 0.12 to 0.7 ppm
Mass (1 Kg Design)	1 Kg	0.12 ppm
Mass (Class Weights and Weight Sets)	1 mg to 20 Kg 1/16 oz to 50 lb	ANSI/ASTM Class 1, 2, 3, 4, 5, 6 NIST Class M, S, S-1, P, Q, T, F, C ANSI/ASTM Class 1, 2, 3, 4, 5, 6 NIST Class S, S-1, P, Q, T, F, C
Force	0.0625 to 5 lbf 5 to 300 lbf 300 to 2400 lbf 750 to 3000 lbf 3000 to 5000 lbf 5000 to 10000 lbf 10000 to 20000 lbf 20000 to 30000 lbf 30000 to 60000 lbf 60000 to 100000 lbf 100000 to 300000 lbf 300000 to 500000 lbf	0.1% of reading 0.01% of reading 0.01% of reading 0.45 lbf 0.75 lbf 1.5 lbf 3.0 lbf 4.5 lbf 9.0 lbf 15.0 lbf 105 lbf 500 lbf

Torque	1 to 160 oz-in 1 to 5 ft-lb 5 to 50 ft-lb 50 to 700 ft-lb	0.175% of reading 0.125% of reading 0.15% of reading 0.2% of reading
Specific Gravity	1.050 to 1.500	0.005
Laboratory Glassware Volume		
Burets	10 to 100 mL	NIST or ASTM Class A, B
Volumetric Pipets	0.5 to 100 mL	NIST or ASTM Class A, B
Measuring Pipets	1 to 30 mL	NIST or ASTM Class A, B
Volumetric Flasks	1 to 5000 mL 5 to 2000 mL	NIST Class A, B ASTM Class A, B
Graduated Cylinders	5 to 2000 mL	NIST or ASTM Class A, B



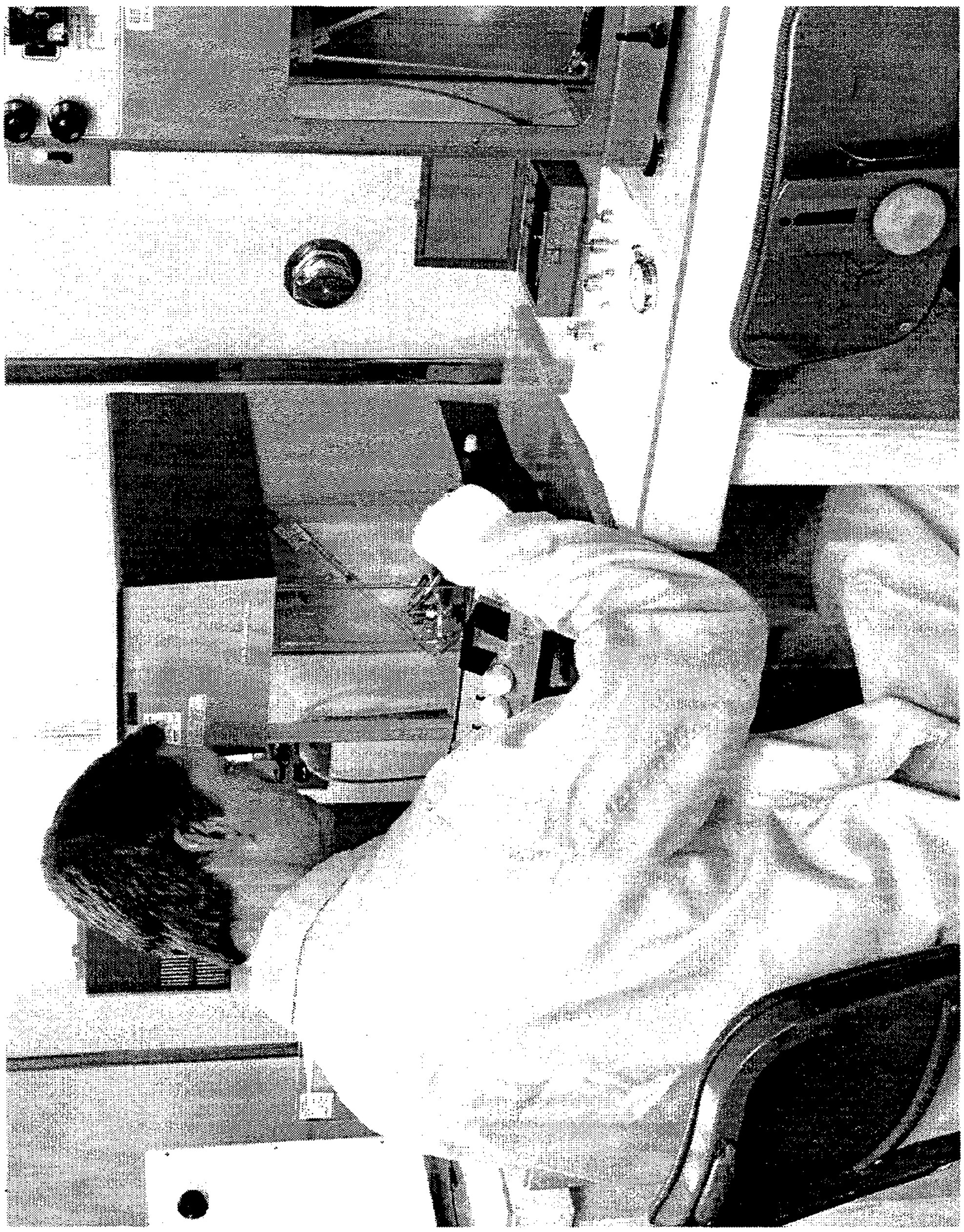
* Calibrated using Metrology dimensional and mass standards.

Figure 3A. Mechanical Calibration Traceability (Mass, Force, Torque, Specific Gravity

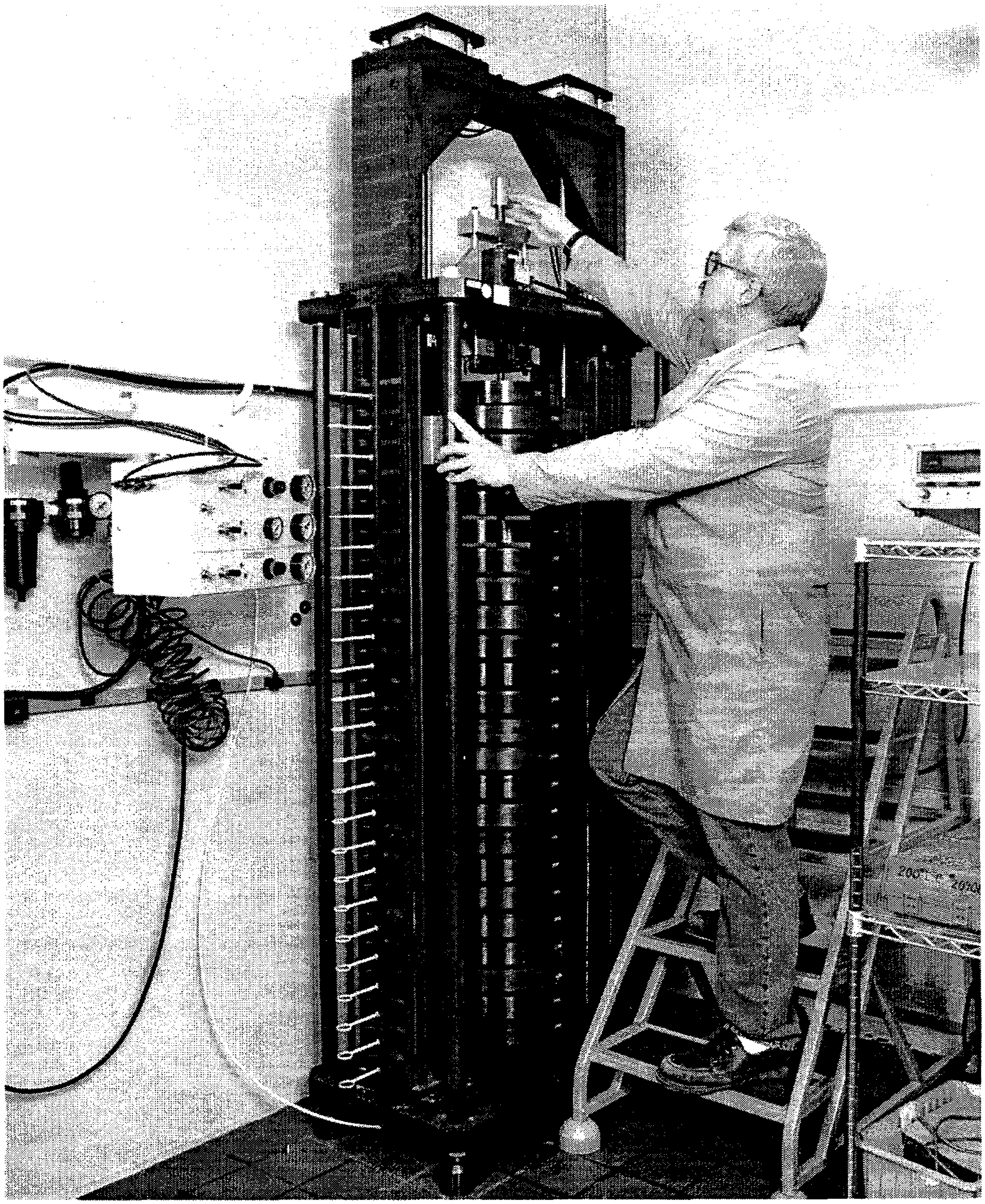
Mass, Force, Torque, Specific Gravity Standards

Code	Description	Manufacturer	Range	Accuracy (±)
MF1	Mass Standards	Troemner, Rice Lake	1 mg to 100 g	0.004 to 0.043 mg
		Troemner	200 g to 5000 g	0.12 to 0.7 ppm
		Troemner	1 lb to 50 lb	2 ppm
MF2	Proving Rings	Morehouse	3000 to 100,000 lbf	0.0125 to 0.015% of range
			300,000 lbf	0.035% of range
MF3	Reference Load Cell	BLH	500,000 lbf	500 lbf
MF4	Transfer Load Cells	Various	0 to 240,000 lbf	0.05% F.S. +0.1% load
MF5	Balances	Mettler *	0 to 3 g	0.020 to 0.055 mg
		Mettler *	0 to 20 g	(4 ppm + 0.07 mg)
		Sartorious *	0 to 100 g	(3 ppm + 0.4 mg)
		Mettler *	0 to 1000 g	(3 ppm + 0.5 mg)
		Mettler *	0 to 5000 g	(3 ppm + 11.0 mg)
		Stanton	5 to 22 kg	25 to 50 mg
		Mettler *	0 to 60 kg	2 g
MF6	Dead Weight Calibrating Machine	Morehouse (modified)	5 to 300 lbf	0.01% of reading
	Dead Weight Calibrating Machine	FM&T Metrology	50 to 2400 lbf	0.01% of reading
MF7	Torque Standard	FM&T Metrology	0 to 700 ft-lbf	0.125 to 0.2% of reading
MF8	Standard Hydrometer	H-B Instruments	1.050 to 1.500	0.005
MF9	Transfer Torque Standard	Norbar	0 to 700 ft-lbf	(0.15% of range + 0.75% of reading)

* Accuracy listed is for direct weighing.

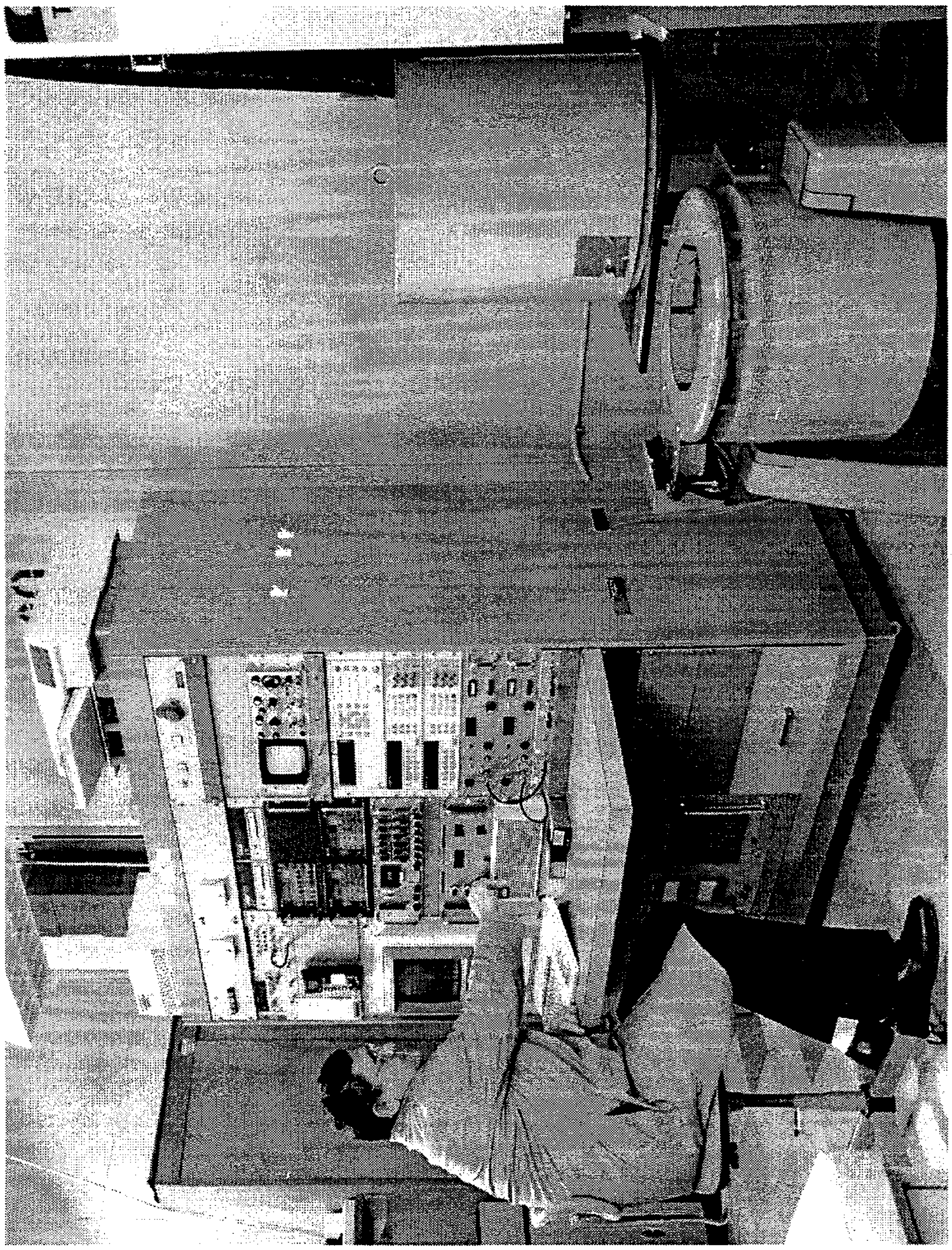


Mass Calibration



Dead Weight Force Calibration

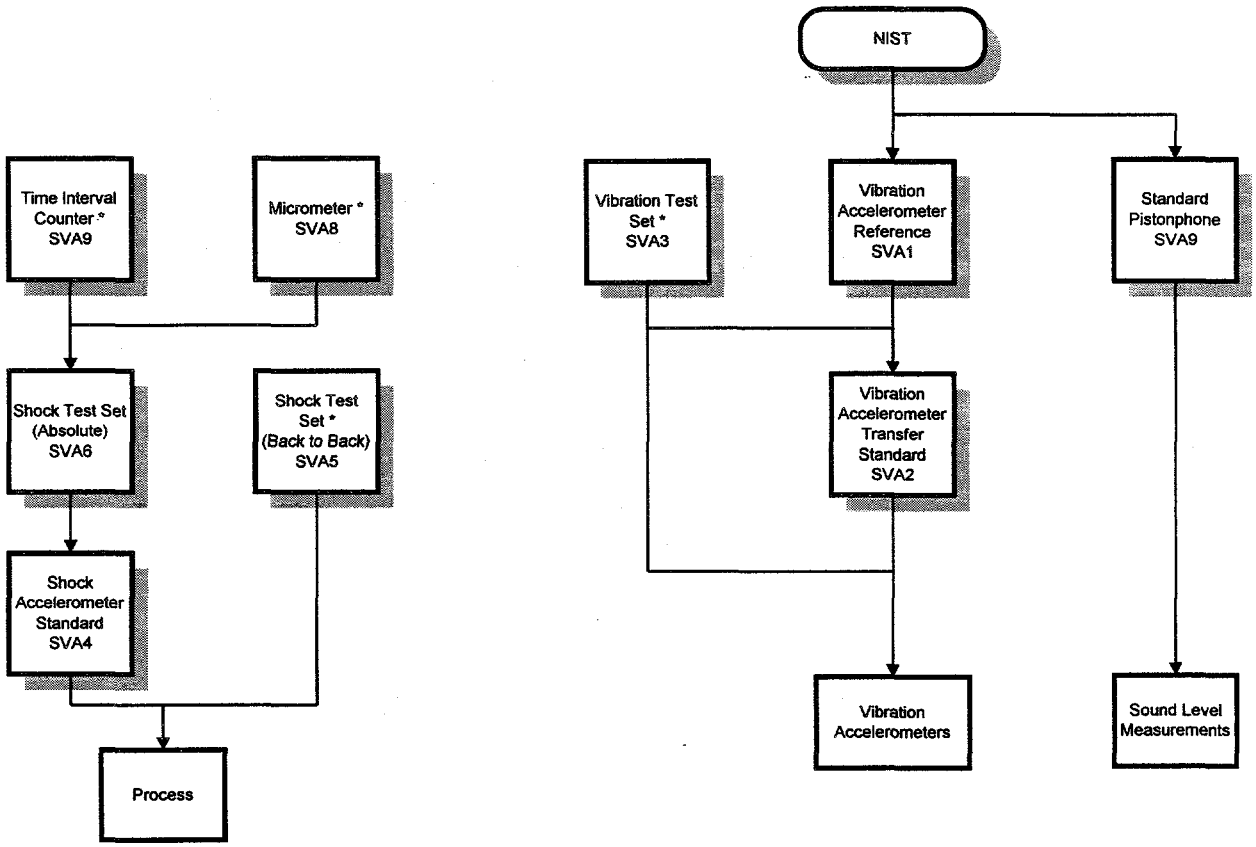
Proving Ring Calibration



Accelerometer Vibration Calibration

Vibration, Acceleration, Shock, Sound Level Measurement Capability

Type	Range	Measuring Accuracy (±)
Vibration	0.3 to 75 g at 10 Hz to 10 kHz at ambient temperature	2.5%
	10 g at 100 Hz to 4 kHz at -65 to +125°C	2.5%
Shock	100 to 10,000 g at 0.1 to 10 ms	2.5 to 4.0%
Sound Level	124 dB at 250 Hz	0.5 dB



* Indicates items certified using Metrology standards

Figure 4A. Mechanical Calibration Traceability (Vibration, Shock, Sound Level)

Vibration, Acceleration, and Shock Standards

Code	Description	Manufacturer	Range	Accuracy (±)
SVA1	Vibration Accelerometer Reference	Endevco	0.3 to 10 g 10 Hz to 10 kHz	1-2%
SVA2	Vibration Accelerometer Transfer Standard	Unholtz Dickie	0.3 to 10 g 10 Hz to 10 kHz	1.8-2.5%
SVA3	Vibration Test Set	FM&T	0.3 to 75 g 10 Hz to 10 kHz	Used only with other calibrated measuring standards
SVA4	Shock Accelerometer Standard	Endevco	100 to 10,000 g	3%
SVA5	Shock Test Set (back to back)	FM&T Metrology	100 to 10,000 g	Used only with other calibrated measuring standards
SVA6	Shock Test Set	FM&T Metrology	5000 to 10,000 g	2.5%
SVA7	Time Interval Counter	Stanford Research Systems	±100 sec to 10 sec	±0.05% of reading
SVA8	Micrometer	Mitutoyo	1.000 to 2.000 in.	±0.0003 in. from nominal
SVA9	Standard Pistonphone	B and K	124 dB @ 250 Hz	0.5 dB

ENVIRONMENTAL, GAS, LIQUID

ENVIRONMENTAL, GAS, LIQUID

Temperature

Temperature measurements in Metrology are based both on the International Temperature Scale of 1990 (ITS-90) and the International Practical Temperature Scale of 1968 (IPTS-68). IPTS-68 capabilities will be maintained as long as older equipment is used. There are three primary standards at FM&T for temperature calibration: fixed point cells, the platinum resistance thermometer (PRT), and the platinum/10% rhodium versus platinum thermocouple (type S).

The PRT covers the range from -180 to 500°C and is certified to an accuracy of ±0.01 to 0.05°C. The type S thermocouple covers the range from 0 to 1450°C and is certified to an accuracy of 0.5°C or 0.2% of reading, whichever is greater.

Temperature environments for calibrations are created with two stirred baths, a horizontal tube furnace, and fixed point temperature cells. The first stirred bath contains Fluorinert and covers the range from -100 to +140°F. The second bath contains silicon oil and covers the range from 70 to 500°F. Both baths are used to calibrate thermocouples, PRTs, thermistors, liquid-in-glass thermometers, and some solid state sensors. The horizontal tube furnace covers the range from 73 to 2700°F and is used to calibrate different types of thermocouples in air. Fixed point temperature cells make possible very accurate single point temperature measurements for PRTs and thermocouples. These cells are (temperatures in ITS-90 scale) Mercury (-38.8344°C), Water (0.01°C), Gallium (29.7646°C), Indium (156.5985°C), Tin (231.928°C), and Zinc (419.527°C).

Humidity

Humidity calibrations are performed with two instruments. The first is a frost point generator capable of generating frost points from -75°C to 0°C ±0.5°C. The second is a two-pressure system that can generate humidity from 5% to 95% RH ±0.5% RH.

The dew/frost point temperature and the ambient air temperature of the moist air are measured to determine absolute and relative humidity. Air flow through the test chamber can be varied from 0 to 140 SLPM.

Pressure

Pressure gages are calibrated using dead weight piston gages. The effective area of the 0 to 500 psi reference is determined by NIST. The effective area of the 0 to 15,000 psi reference is determined by PSL. The effective area of the 0 to 100,000 psi reference is determined at FM&T with NIST traceable standards. True mass for each reference is determined using the NIST Mass MAP program.

Gas Flow

Gas flowmeters are calibrated by direct comparisons to PSL-certified flowmeters or volumetric displacement devices. Volume, time, pressure, and temperature measurements are combined to obtain a value of flow. All measurement parameters are certified and NIST traceable.

Vacuum

Vacuum calibrations at or below 10-3 mmHg are performed using a molecular drag gage, sometimes called a spinning rotor gage (SRG). The SRG is calibrated by NIST.

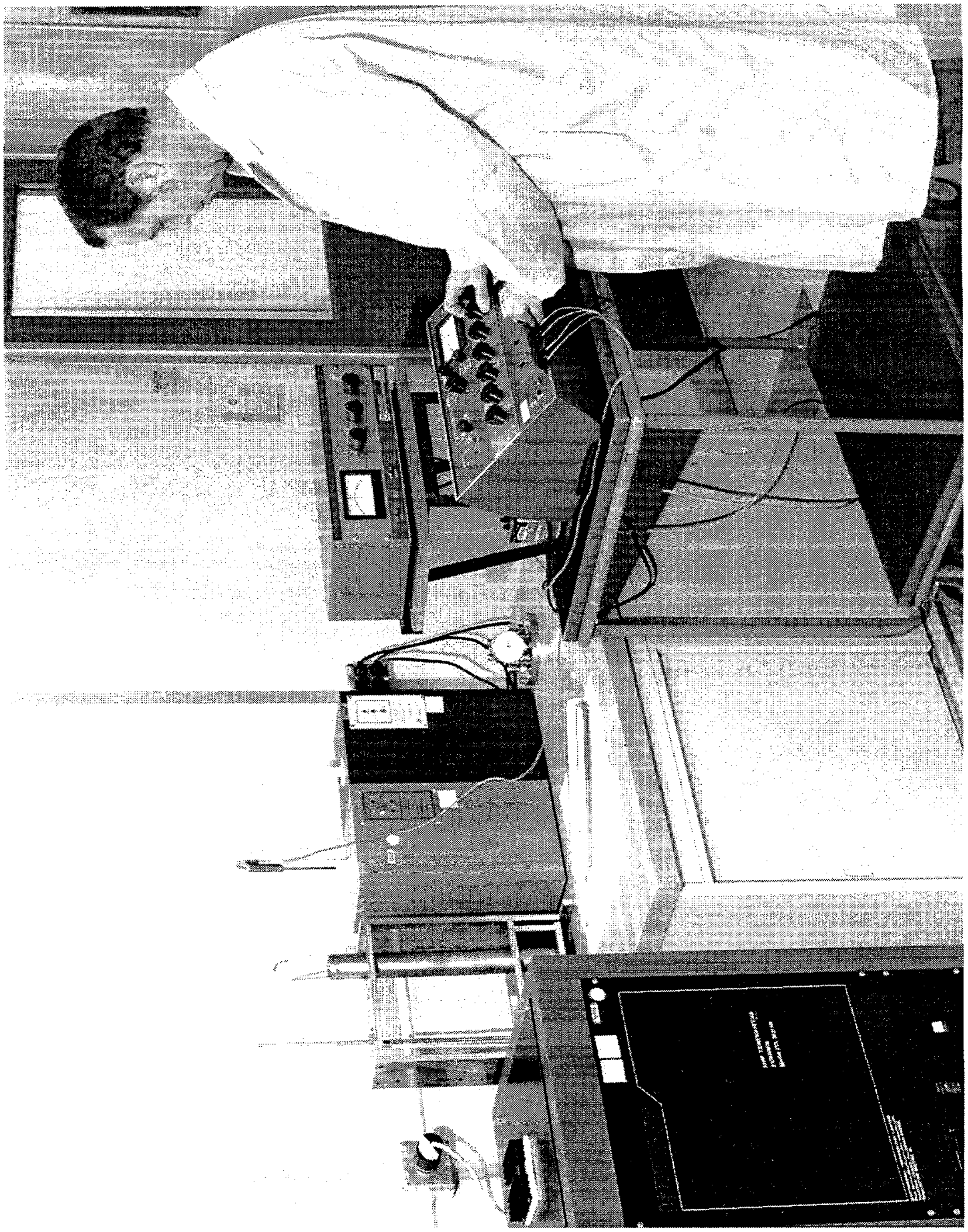
Vacuum calibrations above 10-3 mmHg are performed using either a capacitance manometer or digital Quartz manometer, depending upon the range of the gage. The manometers are calibrated using a PSL-certified dead weight piston gage.

Gas Leaks

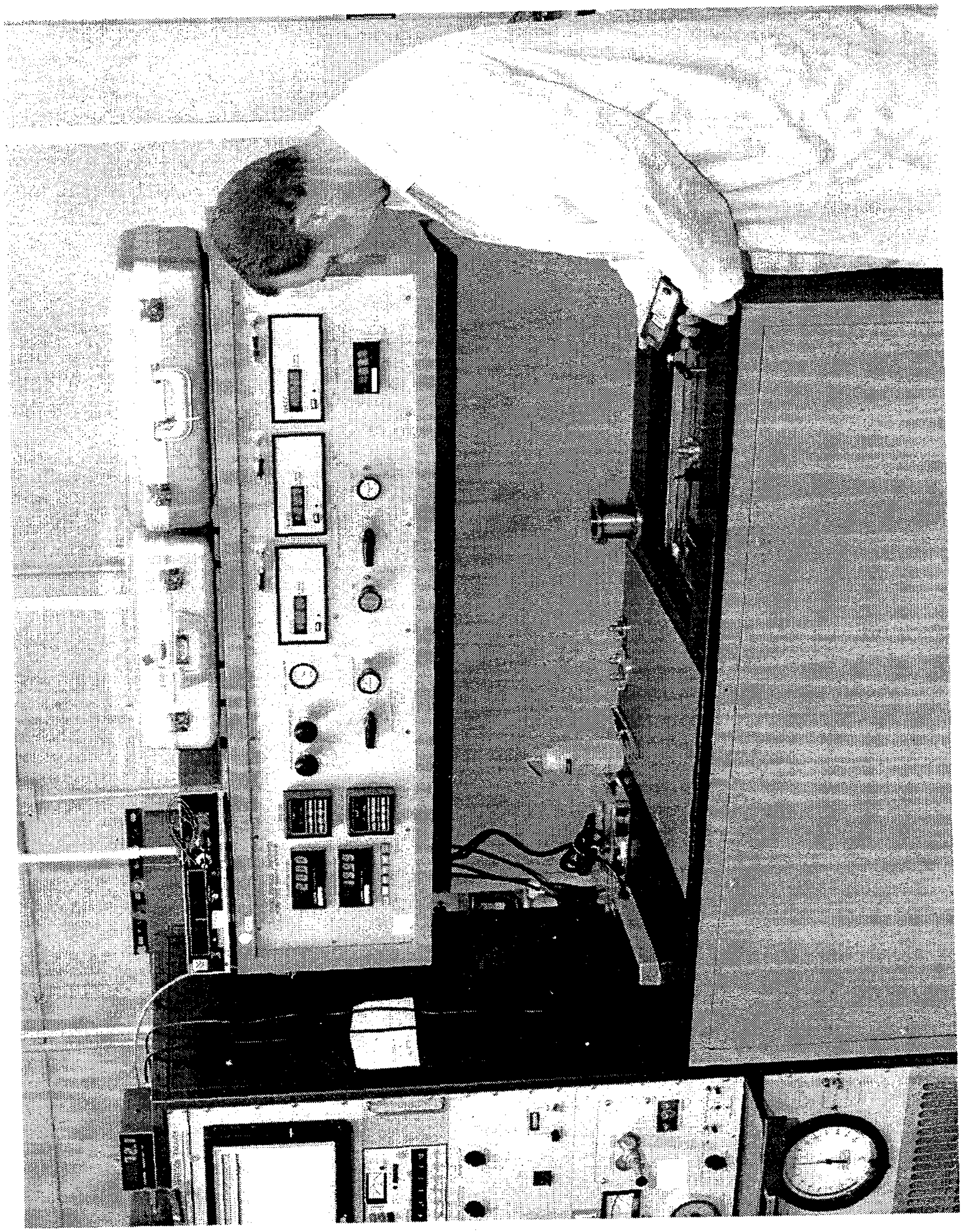
Gas leak devices are calibrated by making direct comparisons to PSL-certified leaks on a mass spectrometer or using the pressure, volume, temperature (PVT) technique. All measurement parameters of the PVT technique are certified and NIST traceable. A precision gas analyzer is used to evaluate the composition of the leak gas.

Viscosity

Viscometers are calibrated using standard viscosity oils obtained from the Cannon Instrument Company, a PSL-approved source.

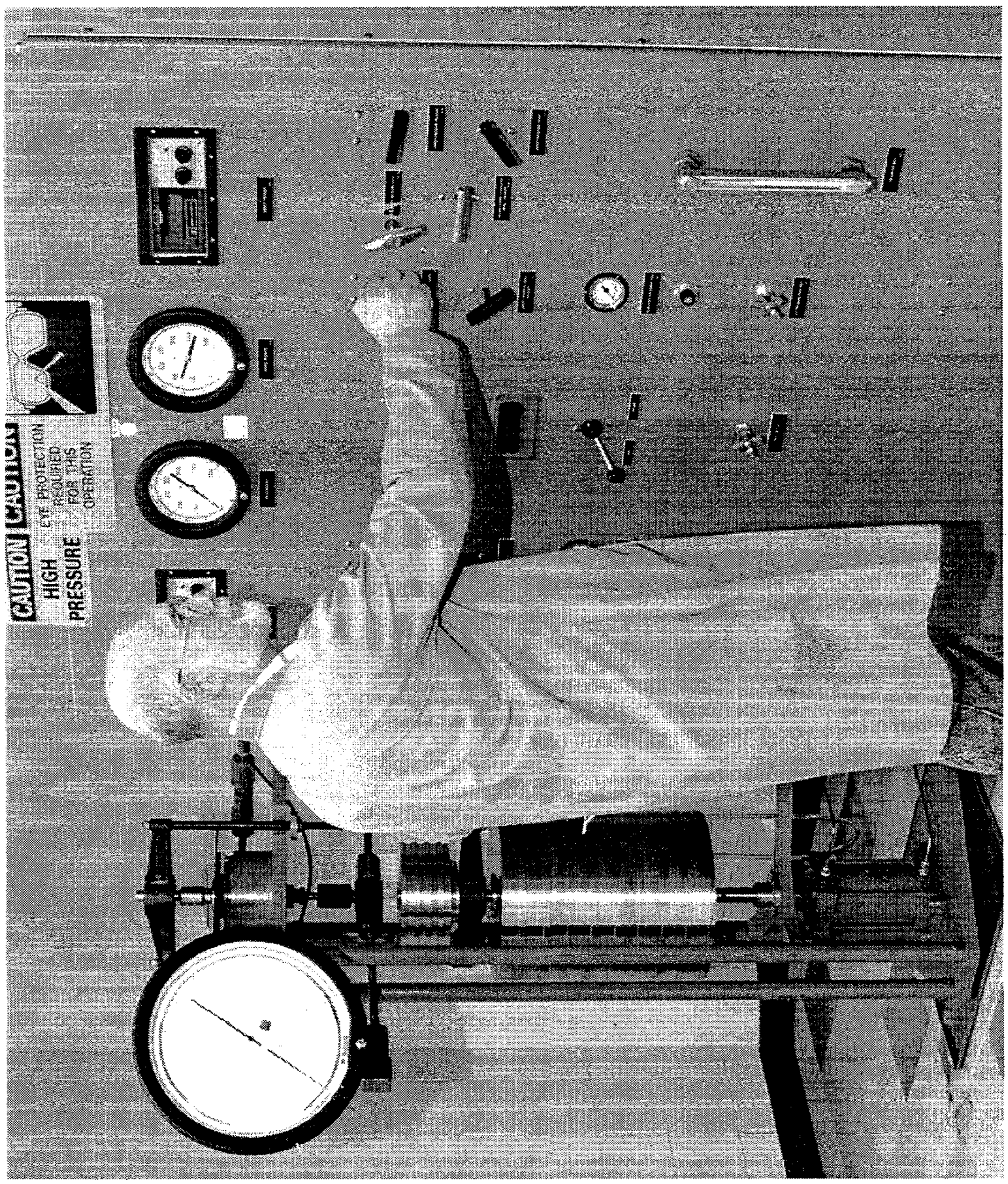


SPRT Calibration Using a Fixed Point Temperature Cell



Humidity Calibration Using the Two-Pressure Method

Standard Leak Calibration System



Pressure Calibration Using Controlled Clearance Dead Weight Piston Gage

Environmental Measurement Capability (Temperature, Humidity)

Type	Range	Accuracy (±)
Temperature	-183°C to +500°C 500°C to 1093°C	0.01°C to 0.05°C 0.4% of reading
Fixed Point	-38.8344°C 0.01°C 29.7646°C 156.5985°C 231.928°C 419.527°C	0.005°C 0.0005°C 0.0005°C 0.007°C 0.008°C 0.01°C
Humidity	-75°C to 0.0°C 5% RH to 95% RH	0.5°C 0.5% RH

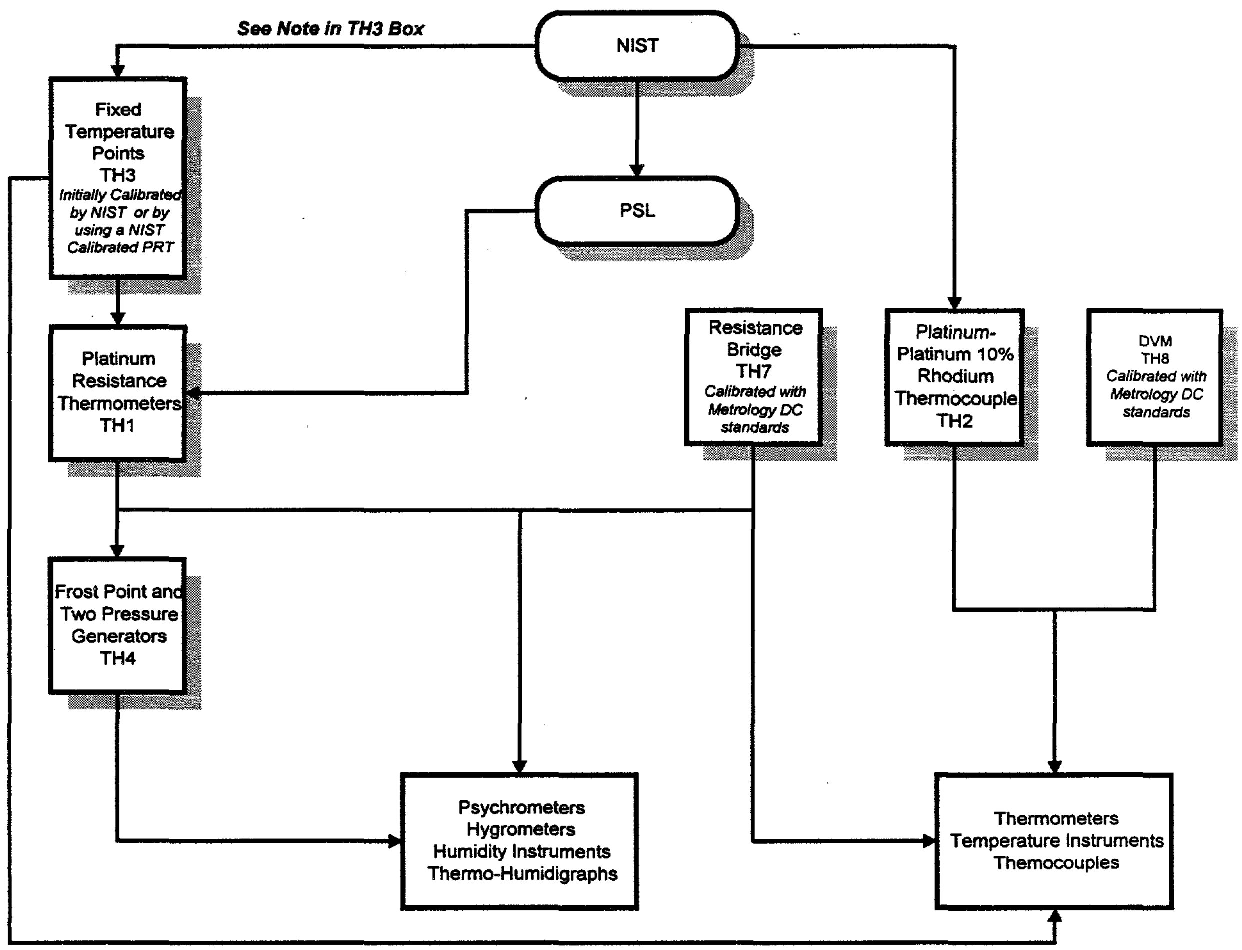


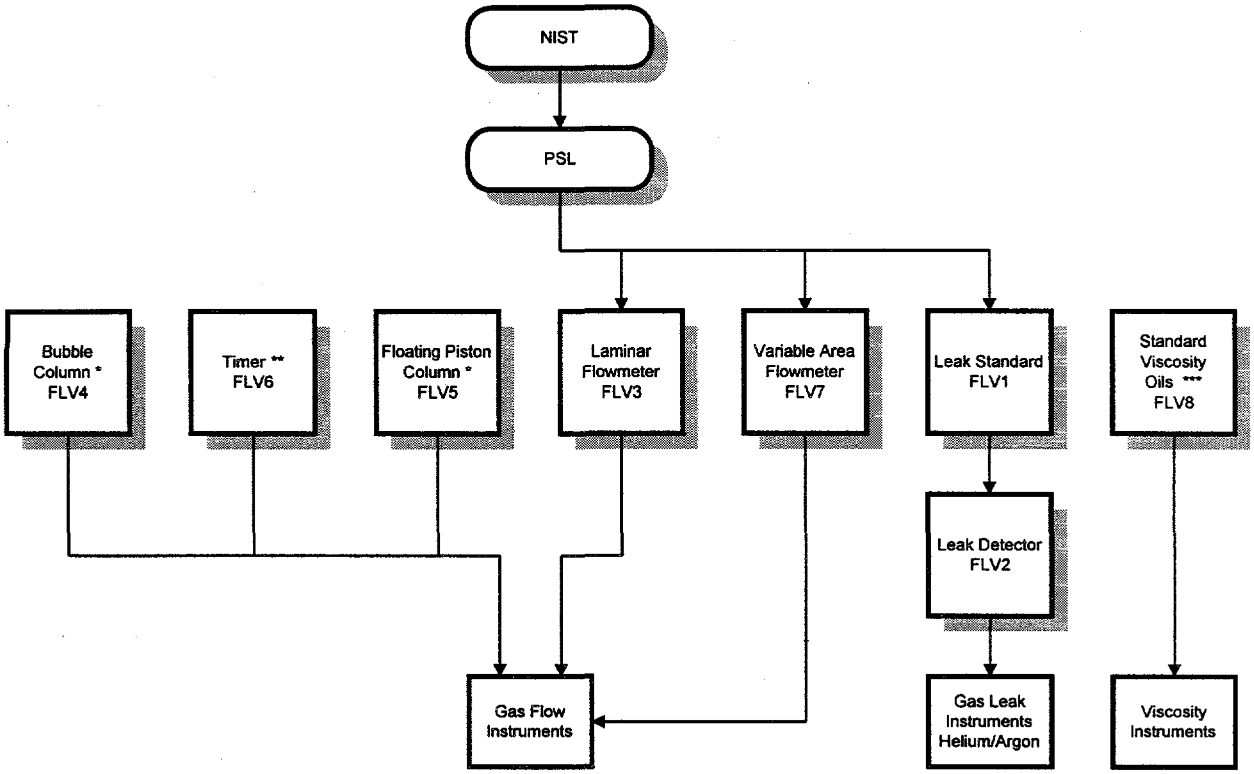
Figure 1B. Environmental Calibration Traceability (Temperature, Humidity)

Environmental Standards

Code	Description	Manufacturer	Range	Accuracy (±)
TH1	Platinum Resistance Thermometer	Leeds & Northrup	-186 to 0°C 0 to 100°C 100 to 500°C	0.05 to 0.02°C 0.02°C 0.02 to 0.05°C
TH2	Platinum - Platinum 10% Rhodium Thermocouple	Leeds & Northrup	0 to 1450°C	0.5°C or 0.2% of reading (whichever is greater)
TH3	Fixed Temperature Points			
	Mercury	Isotech	-38.8344°C	0.005°C
	TP Water	Jarrett	0.01°C	0.0005°C
	Gallium	Isotech	29.7646°C	0.0005°C
	Indium	Isotech	156.5985°C	0.007°C
	Tin	Isotech	231.928°C	0.008°C
	Zinc	Trans-sonics	419.527°C	0.01°C
TH4	Frost Point Generator	Thunder Scientific	-70 to 0°C	0.5°C
	Two-Pressure Generator	Thunder Scientific	5 to 95% RH	0.5% RH
TH7	Resistance Bridge	Leeds & Northrup	0 to 150 ohms	Resistance 0.004% or 0.0004 Ω with corrections Ratio 0.002% with corrections
TH8	DVM	Keithley	0 to 1000 Vdc	0.015% of reading + 4 digits

Gas, Liquid Measurement Capability

Type	Range	Accuracy (±)
Pressure	Absolute 10-6 to 10-4 torr 10-3 to 0.05 torr 0.05 to 1 torr 1 to 10 torr 10 to 350 torr 350 to 760 torr Gage 0.5 to 600 psig 600 to 15,000 psig 15,000 to 100,000 psig	 ±10% ±0.0005 torr ±(0.001 torr or 0.75% of reading, whichever is greater) ±0.2% of reading ±(0.01 + 0.00016 * reading) torr ±0.04 + 0.00016 * reading) torr 0.02% 0.03% 0.05%
Gas Flow	0.001 - 10 sccm 0.01 - 1800 slpm	±1% ±2%
Leak Rate	2 x 10-2 to 5 x 10-9 standard cm3/s 10-10 standard cm3/s	10 - 15% 25%
Viscosity	0.3 to 5,300,000 mPa•s	2 to 5%



*** Calibrated using Metrology mass and dimensional standards.**
**** Calibrated using Metrology AC standards**
***** Source: Cannon Instrument Co. (approved by PSL)**

Figure 2B. Environmental Calibration Traceability (Gas Leak and Flow Rates, Viscosity)

Gas Leak, Gas Flow Rates and Viscosity Standards

Code	Description	Manufacturer	Range	Accuracy (±)
FLV1	Leak Standard	Veeco/VIC	1 x 10-7 to 9 x 10-5 cm3/s STP 1 x 10-9 to 9.9 x 10-8 cm3/s STP 2 x 10-10 to 9.9 x 10-10 cm3/s STP	10% 15% 20%
FLV2	Leak Detector	Vactronic	1 x 10-1 to 1 x 10-6 cm3/s STP 1 x 10-6 to 1 x 10-9 cm3/s STP 1 x 10-9 to 2 x 10-10 cm3/s STP	5% 17% 25%
FLV3	Laminar Flowmeter	National Instrument Laboratories	2 - 250 SLPM	2%
		CME	180 - 1800 SLPM	18 SCFM
FLV4	Bubble Column	Matheson Scientific	Volume 50 cm3	0.05 cm3
FLV5	Floating Piston Column	George K. Porter	Volume 400 cm3 Volume 2000 cm3	0.3 cm3 0.2%
FLV6	Timer	Standard Electric	0 - 999 seconds	(0.1% + 1 count)
FLV7	Variable Area Flowmeter	Fisher & Porter	8 to 23 SCFM	0.3 SCFM
FLV8	Standard Viscosity Oils	Cannon Instrument	0.3 to 5,300,000 mPa•s	0.4 to 1.2%

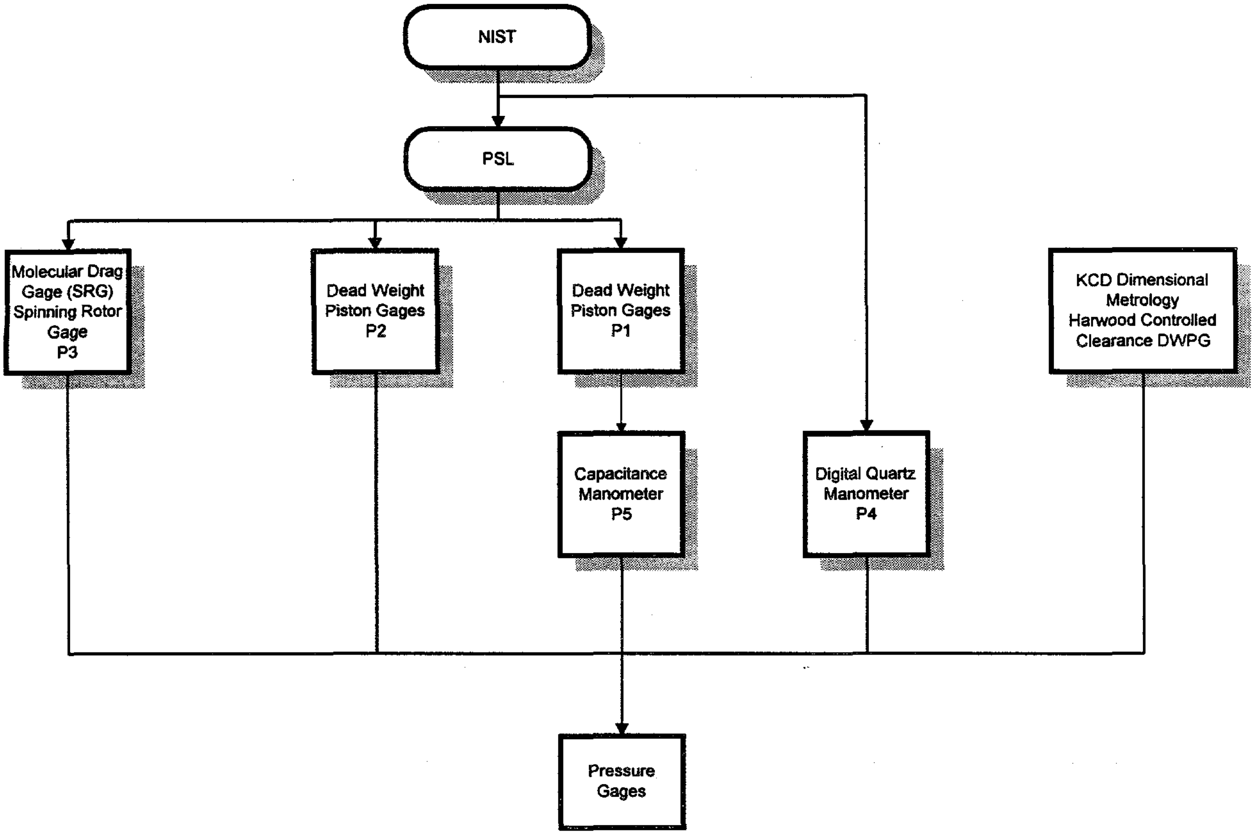


Figure 3B. Environmental Calibration Traceability (Pressure Calibration)

Pressure Standards

Code	Description	Manufacturer	Range	Accuracy (±)
P1	Piston Gage	CEC	0.2 to 600 psi	0.02%
P2	Piston Gages	Ruska Harwood	30 to 15,000 psig 20,000 to 100,000 psig	0.03% 0.05%
P3	Molecular Drag Gage	MKS	10-6 torr 10-5 torr 10-4 torr 10-3 torr 10-2 torr	5% 3% 3% 3% 3%
P4	Digital Quartz Manometer	Paroscientific	0.1 to 350 torr 350 to 1100 torr	(0.01 + 0.00016 * reading) (0.04 + 0.00016 * reading)
P5	Capacitance Manometer	MKS	10-3 to 0.05 torr 0.05 to 1 torr	0.0005 torr (0.001 torr or 0.75% of reading) whichever is greater
			1 to 1000 torr	0.2% of reading

ELECTRICAL

ELECTRICAL

DC Electrical Measurement

DC Voltage

The basic reference for DC voltage measurements consists of three groups of saturated standard cells maintained in temperature-controlled air baths. All three groups are re-certified by intercomparison tests with a voltage standard from the Primary Standards Laboratory. A precision potentiometer is used for voltage measurements to 1.5 volts. The potentiometer and a precision divider are used for measurements up to 1500 volts. High voltage dividers calibrated by the Primary Standards Laboratory or by NIST are used for measurements up to 100 kilovolts.

DC Current

Measurements of current up to 2 amperes are made using resistance and voltage standards. Shunts calibrated by the Primary Standards Laboratory are used for current measurements from 2 amperes to 300 amperes.

DC Resistance

The reference for resistance measurements is two groups of standard resistors, ranging from 0.001 ohm to 100 megohms, which are certified by the Primary Standards Laboratory. These resistors, a double ratio set and a precision bridge, are used for resistance measurements to 100 megohms. Above 100 megohms and up to 10 teraohms, resistance measurements are accomplished using either a wheatstone bridge or a teraohmmeter.

AC Electrical Measurement

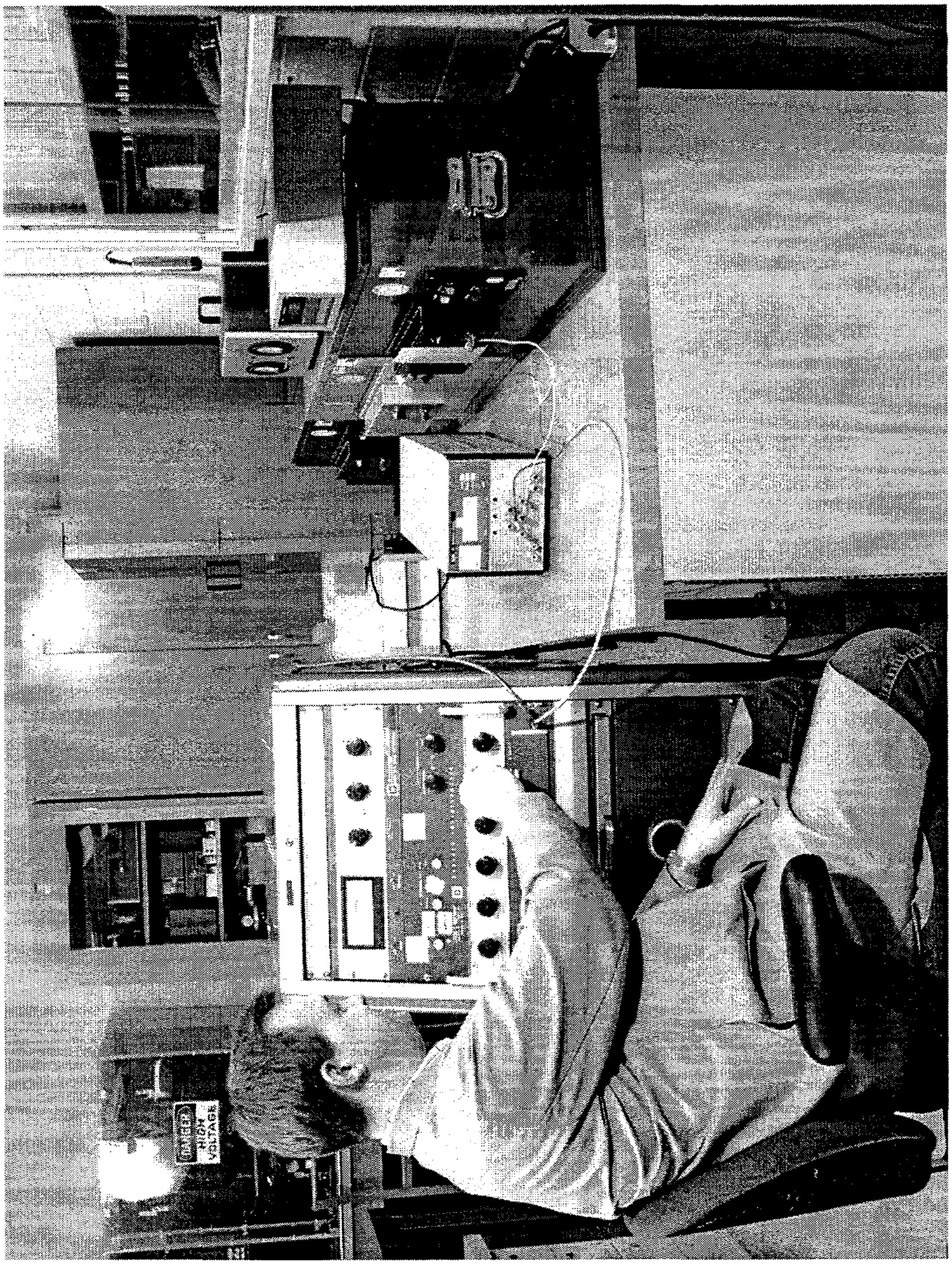
AC Voltage

AC voltage sources are calibrated using an Alternating Voltage Measurement Standard which is calibrated by a DC voltage standard and standard thermal voltage converter devices certified for AC-DC difference by the Primary Standards Laboratory.

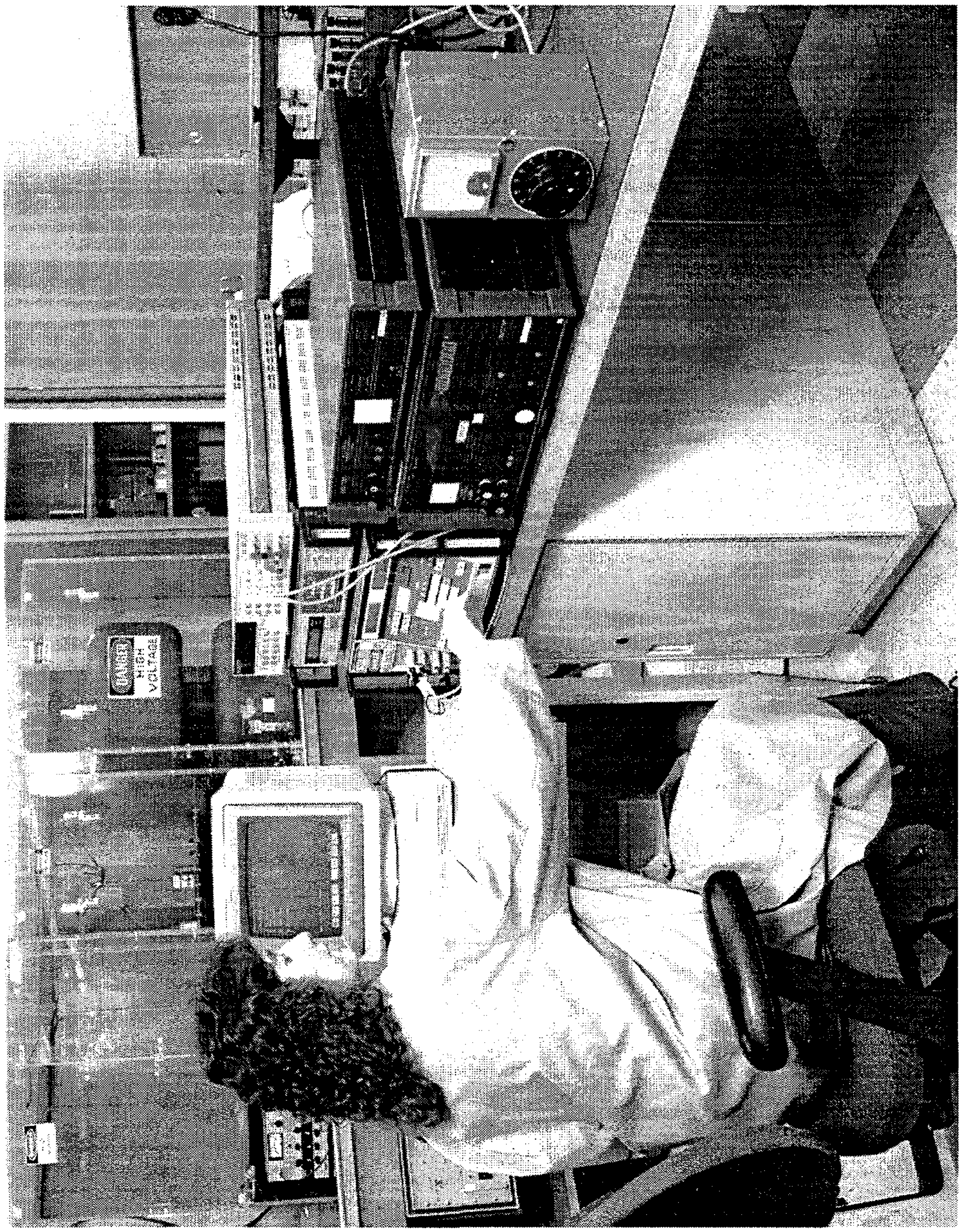
Test thermal voltage converter devices can be calibrated for AC-DC difference by direct comparison of their response to the response of the standard thermal voltage converter devices.

AC Current

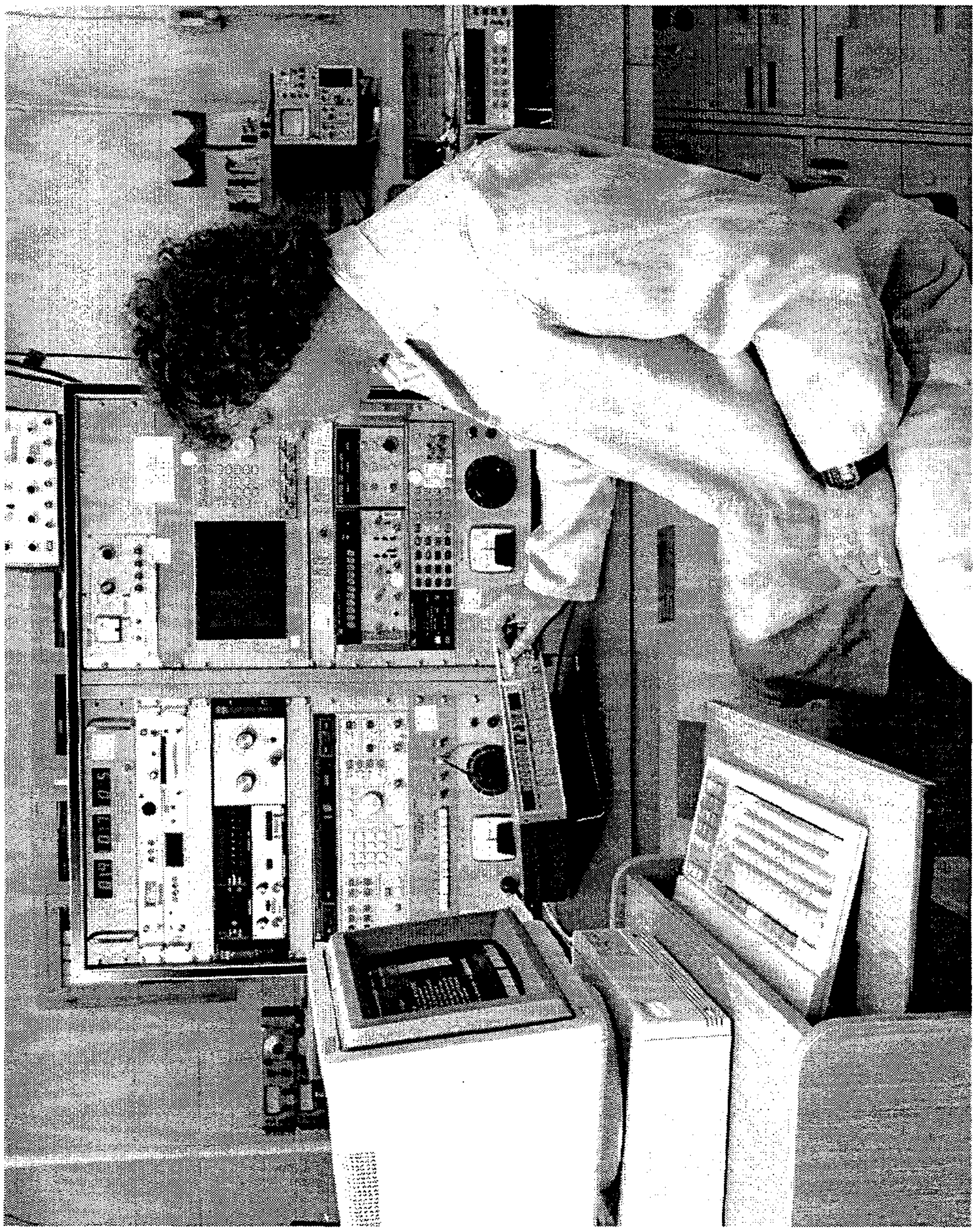
AC current sources are calibrated using a known DC current and standard current shunts certified by the Primary Standards Laboratory. Current levels lower than 10 mA are calibrated using standard AC resistors. The shunts are terminated with a standard thermal voltage converter certified for AC-DC difference by the Primary Standards Laboratory. The voltage across the AC resistor, which is directly proportional to the current through the resistor, is measured with an AC voltmeter.



DC Voltage Calibration



Automated DMM Calibration



Computer-Controlled Counter Calibration

AC Ratio

Decade voltage ratio transformers are calibrated by connecting a standard ratio transformer, certified by the Primary Standards Laboratory, and a test transformer to the same input signal and comparing their output signals.

Capacitance and Inductance

Calibration of capacitors and inductors is made by direct comparison of the unknown to a standard capacitor or standard inductor calibrated by the Primary Standards Laboratory. Depending on accuracy and frequency, the comparison is made on a transformer ratio arm bridge (for capacitance only) or on one of three different LCR meters.

The measurement uncertainties vary with value and frequency. Capacitance uncertainties range upward from ±0.02%; inductance uncertainties range upward from ±0.03%.

Frequency and Time

The output of a rubidium frequency standard is compared periodically with the frequency transmitted by NIST on radio station WWVB. The frequency standard is used to calibrate frequency counters and to drive a digital clock. An electronic counter is used to calibrate frequency sources and for time interval measurements.

A digital clock, displaying hours, minutes and seconds, is synchronized with time information transmitted by NIST on radio station WWVB.

RF/Microwave Electrical Measurement

Air Lines

Air lines are the most accurate impedance standards. They are calibrated using dimensional measurement techniques, such as air gages to measure the inner and outer conductors by comparison to plug gages of similar diameters. The length of the outer conductor is measured using one of two length measurement systems. Values from dimensional measurements are used in a computer program to determine the electrical impedance and length parameters.

Attenuators

Attenuators are used to verify receiver levels accurately and match impedances of systems. Attenuators calibrated by NIST are used to transfer standard values to attenuation measurement systems and to other fixed value attenuators.

Terminations

Terminations are measured by NIST and certified for use with impedance measuring systems. Terminations provide a reference for SWR, reflection coefficient, and phase delay measurements.

DC Calibrator

DC sources are used to simulate power to check instrumentation on power meters. The power meters use thermistor mounts to change resistance values of bridges which give an indication of the level of higher frequency power.

Rubidium Sources

Transmissions from NIST broadcast stations supply the reference frequency for receivers which are used to compare stabilized frequency sources such as rubidium. These rubidium sources are portable and may be used as a reference for testers at the customer's location.

Attenuation Systems

Automatic attenuation measurement systems are used to measure fixed values of attenuation as well as loop insertion loss and step attenuators. To determine the true value of attenuation or insertion loss in a specific impedance system, the change in attenuation due to the discontinuities between connections is determined and added to the measurement uncertainty.

Network Analyzers

Automatic network analyzers are computer controlled to facilitate the control and acquisition of data and to make calculations for corrections on line. Several techniques are used to calibrate and standardize different types of analyzers depending on the frequency and parameter to be measured.

Noise Source

Excess noise ratio (ENR) is the parameter which noise sources are compared against. The tests are automatically controlled and limited to specific frequencies. Some interpolation may be used between points, provided proper uncertainties are considered.

Thermistor Mounts

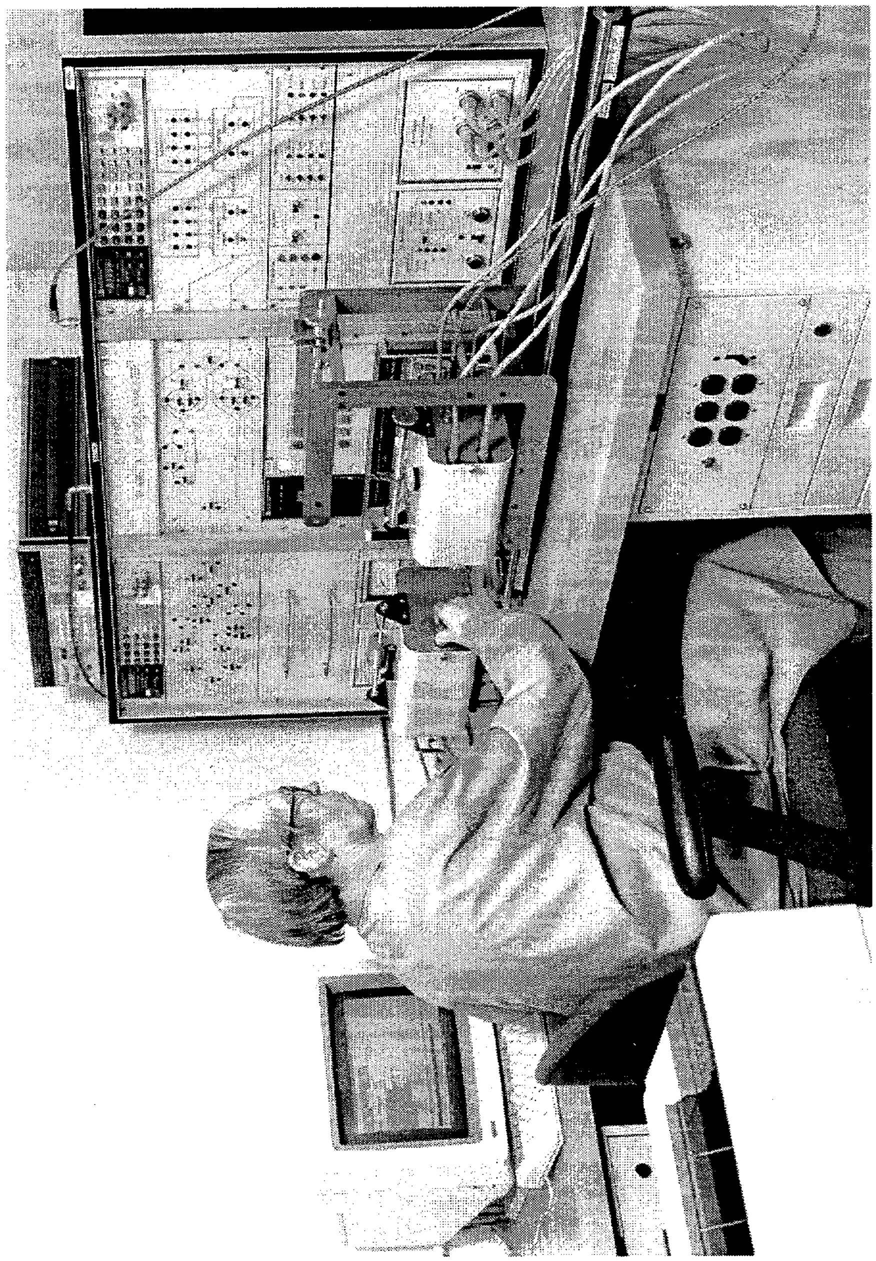
Thermistor mount calibration factors are computed by comparing a NIST-measured mount with another mount. Thermistor mounts are very stable and repeatable over a ten-dB range and are used in the calibration of step attenuators for attenuation measurement system calibration.

New Developments

A new semi-automatic probe station is in place for use in measuring components on wafers. The system may be connected to any of the MW calibration systems and computer controlled for probe placement and data acquisition.

General Information

Most systems in the MW calibration area are monitored using control standards. The daily, weekly, or monthly values are compared to previous values to determine the stability of the calibration systems.



Attenuator Calibration Using Dual 6-Port ANA

Electrical Direct Current Measurement Capability

Type	Range	Accuracy (±)
DC Voltage	0 to 0.016 V	(20 ppm + 0.1 µV)
	0.016 to 0.16 V	(15 ppm + 0.5 µV)
	0.16 to 1.6 V	(10 ppm + 5 µV)
	1.6 to 1500 V	0.0025%
	1.5 to 10 kV	0.04%
	>10 to 150 kV	0.075%
DC Current	10-9 A	0.5%
	10-8 A	0.4%
	10-7 - 10-6 A	0.2%
	10-5 to 0.3 A	0.005%
	>0.3 to 15 A	0.007%
	>15 to 100 A	0.02%
	>100 to 300 A	0.03%
DC Resistance	10-4 to 10-1 Ω	0.007%
	100 to 107 Ω	0.005%
	>107 to 108 Ω	0.01%
	>108 to 109 Ω	0.2%
	1010 to 1012 Ω	0.5%
	>1012 to 1013 Ω	1.0%
DC Magnetic Field Density	Transverse Probe:	
	20 to 10,000 Gauss	3% to 7.5%
	Axial Probe:	
	40 to 500 Gauss	3 % to 7.5%

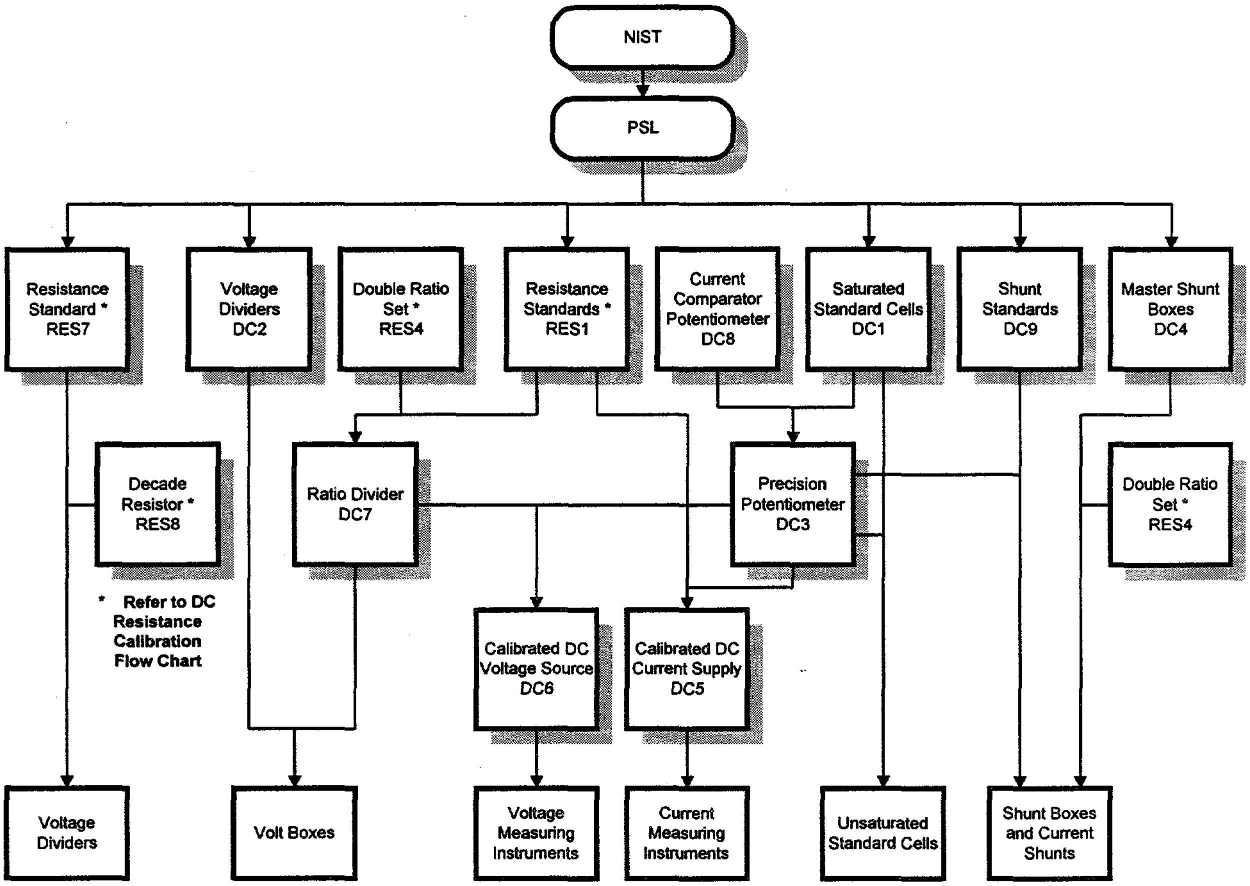


Figure 1C. DC Current and Voltage Traceability

DC Current and Voltage Standards

See Figure 1C

Code	Description	Manufacturer	Range	Accuracy (±)
DC1	Saturated Standard Cells	Eppley/Muirhead	1.018 V nominal	3 μV
DC2	Voltage Dividers	Julie	10 to 100 kV	0.05%
		Fluke	1 to 10 kV	0.025%
DC3	Precision Potentiometer	Leeds & Northrup	0 to 1.6 V	(15 ppm + 0.05 μV) to (5 ppm + 2 μV)
DC4	Master Shunt Boxes	Leeds & Northrup	0.015 to 15 A	0.005%
DC5	Calibrated DC Current Supply	FM&T Metrology	1.5 μA to 15 A (7 ranges)	(0.02% or 1 nA), whichever is greater
DC6	Calibrated DC Voltage Source	Fluke	1 to 1000 V	(0.0025% or 1 μV), whichever is greater
DC7	Ratio Divider	Guildline	1:1 to 10,000:1	0.001%
DC8	Current Comparator Potentiometer	Guildline	0 to 2 V 0 to 0.2 V 0 to 0.02 V	(1 ppm + 0.1 μV) (2 ppm + 0.02 μV) (4 ppm + 0.01 μV)
DC9	Shunt Standards	Leeds & Northrup Guildline	0 to 15 A 0 to 100 A 0 to 300 A 0 to 500 A	0.005% 0.01% 0.015% 0.010%

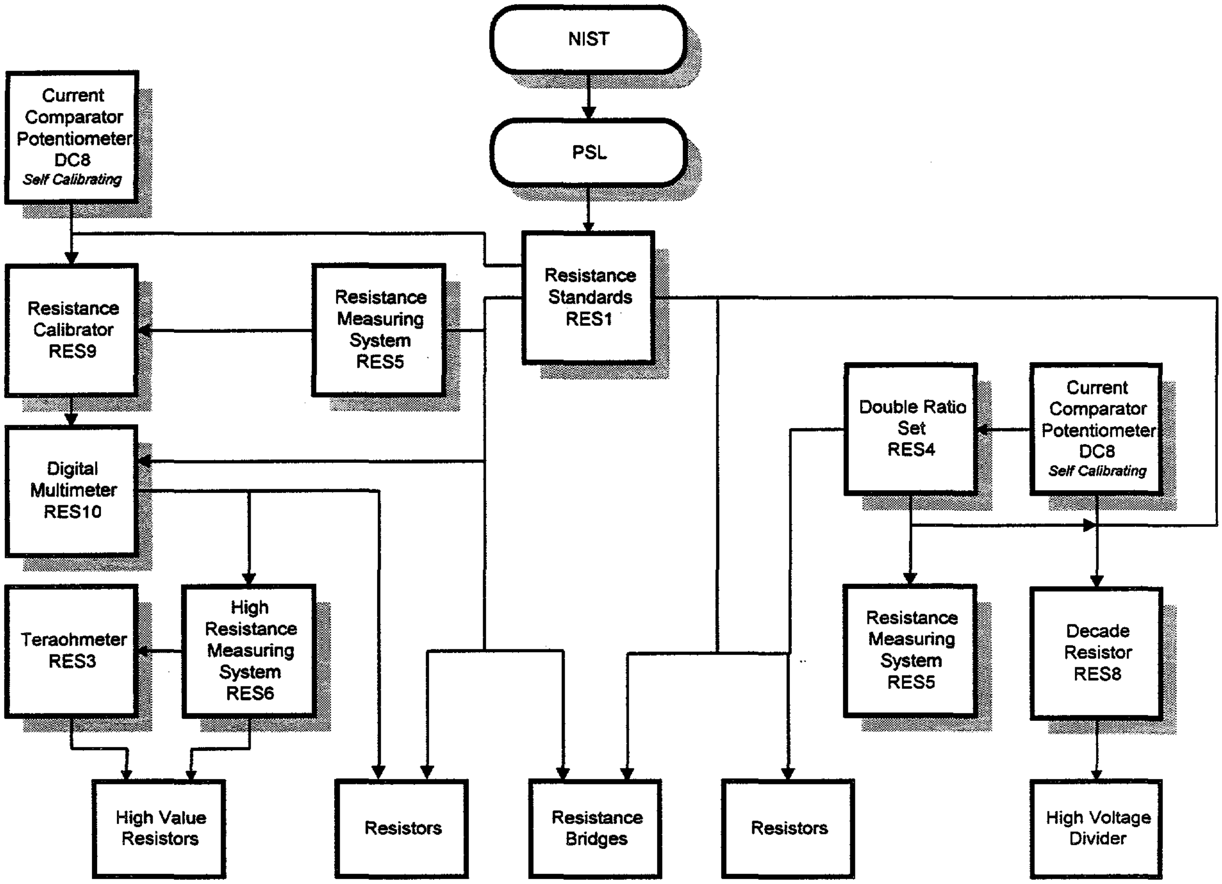


Figure 2C. DC Resistance and Ratio Traceability

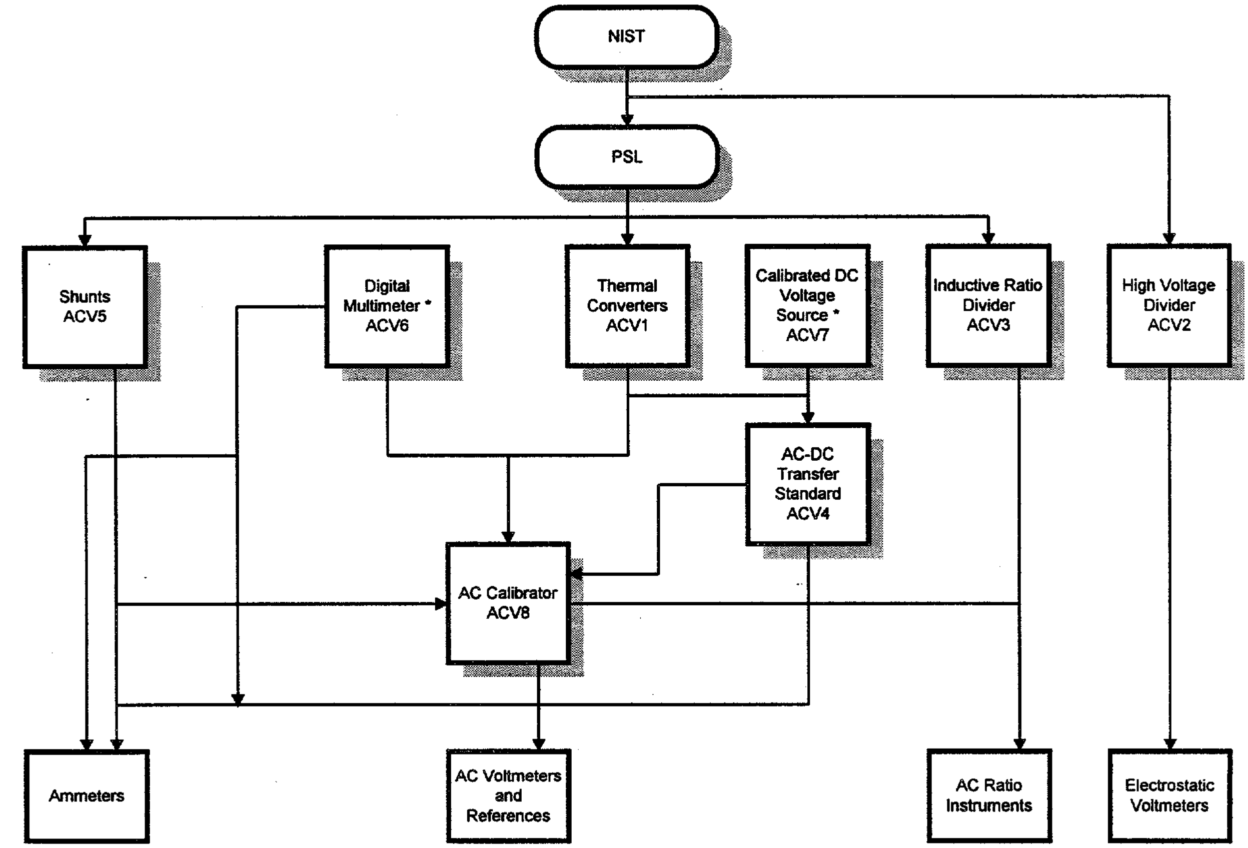
DC Resistance and Ratio Standards

Code	Description	Manufacturer	Range	Accuracy (±)
RES1	Resistance Standard	Leeds & Northrup, Julie, Guildline	0.001 Ω to 100 MΩ	0.002 to 0.01%
RES3	Teraohmmeter	Guildline	107 to 1013 MΩ	0.1 to 1%
RES4	Double Ratio Set/Direct Reading Ratio Set	Leeds & Northrup	0.0001 Ω to 1 MΩ	0.002% (DRS) 0.0002% (DRRS)
RES5	Resistance Measuring System	ESI	0.001 Ω to 10 MΩ	(0.005% + M x 0.005 Ω)
			10 to 100 MΩ	(0.01% + M x 0.005 Ω) M = range multiplier
RES6	High-Resistance Measuring System	Mid-Eastern	108 to 1013 Ω	0.3% to 0.5%
RES7	High Voltage Resistance Standard	Spellman	2000 x 106 Ω	0.03%
RES8	Decade Resistor	Guildline	0 to 100 kΩ	(0.005% of setting + 0.004 Ω)
RES9	Resistance Calibrator	Fluke	1 Ω to 100 MΩ	0.005% to 0.02%
RES10	Digital Multimeter	Hewlett Packard	10 Ω to 100 MΩ	(0.01% or 10 digits) whichever is greater (0.05% or 50 digits) whichever is greater

Electrical Alternating Current Measurement Capability

Type	Range	Frequency	Measuring Accuracy (±)
AC Voltage *	0.1 to 1000 V 0.1 to 1000 V 0.1 to 30 V 1 to 70 kV	10 Hz to 50 kHz 50 kHz to 100 kHz 100 kHz to 1 MHz 60 Hz	100 ppm 150 ppm 850 ppm 0.3%
AC Current	10 mA to 20 A	10 Hz to 50 kHz	0.05 to 0.07%
Capacitance	0.001 pF to 1 μF 1 to 10 μF 10 to 100 μF 1.0 to 1000 pF	1 kHz 1 kHz 1 kHz 1 MHz	(0.01% + 0.00005 pF) 0.02% 0.5% 0.1 to 0.2%
Inductance **	0.05 to 2 μH 2 to 100 μH 100 μH to 10 H	10 kHz to 1 MHz 10 kHz to MHz 1 kHz	0.7% to 12% 0.7% to 3% 0.04% to 0.4%
Frequency	1 Hz to 18 GHz		1 part in 109
Time of Day			0.5 ms

* Accuracy depending on range and frequency
** Accuracy depending on inductance and frequency



* Calibrated using Metrology DC Standards

Figure 3C. AC Current, Voltage, and Ratio Traceability

AC Current, Voltage, and Ratio Standards

Code	Description	Manufacturer	Range	Accuracy (±)
ACV1	Thermal Converters	Holt	0.5 V to 1000 V (10 Hz to 1 MHz)	25 ppm to 110 ppm
		Ballantine	1 V (10 Hz to 100 MHz)	0.02 to 1.2%
		Fluke	1.0 to 10 V (10 Hz to 100 MHz)	0.1 to 1.2%
		Holt	2 mV to 200 mV (20 Hz to 1 MHz)	25 ppm to 700 ppm
		Holt	0.5 V (10 Hz to 1 MHz)	10 ppm to 325 ppm
ACV2	High Voltage Divider	Julie	1 to 100 kV	0.25%
ACV3	Inductive Ratio Divider	ESI	Ratio only, 0.1 ppm resolution (50 Hz to 10 kHz)	1 to 150 ppm

ACV4	AC-DC Transfer Standard	Datron	100 mV to 1000 V (10 Hz to 50 kHz)	100 ppm
			100 mV to 1000 V (50 to 100 kHz)	150 ppm
			100 mV to 30 V (100 kHz to 1 MHz)	850 ppm
ACV5	Shunts	Holt	10 mA to 20 A (10 Hz to 50 kHz)	0.05 to 0.07%
ACV6	Digital Multimeter	Fluke	100 mV Range	0.005% or 5 digits, whichever is greater
			1 to 1000 V Ranges	0.005% or 8 digits, whichever is greater
ACV7	Calibrated DC Voltage Source	Fluke	10 to 1000 V three ranges	0.005% or 20 µV, whichever is greater
ACV8	AC Calibrator	Fluke	1 mV to 100 mV (10 Hz to 30 kHz)	(0.02% of setting + 0.005% FS + 10 µV)
			1 V to 100 V (10 Hz to 50 kHz)	(0.02% of setting + 0.005% FS +10 µV)
			1 mV to 100 mV (30 kHz to 100 kHz)	(0.06% of setting + 0.006% FS +10 µV)
			1 V to 10 V (50 kHz to 100 kHz)	(0.06% of setting + 0.006% FS +10 µV)
			1000 V range (50 Hz to 1 kHz)	(0.06% of setting + 0.006% FS +10 µV)
			1 mV to 100 mV (100 kHz to 1 MHz)	(0.6% of setting + 0.1% FS)
			1 V to 10 V (100 kHz to 1 MHz)	(0.4% of setting + 0.1% FS)
			100 V range (50 kHz to 100 kHz)	0.1% of setting
			Wideband output	
			10-30 Hz	0.3%
			>30 Hz - 1 MHz	0.25%
			>1 MHz - 20 MHz	0.75%
			>20 MHz - 30 MHz	1.0%
			0 - 2 A	(0.07% of setting + 0.01% of range)

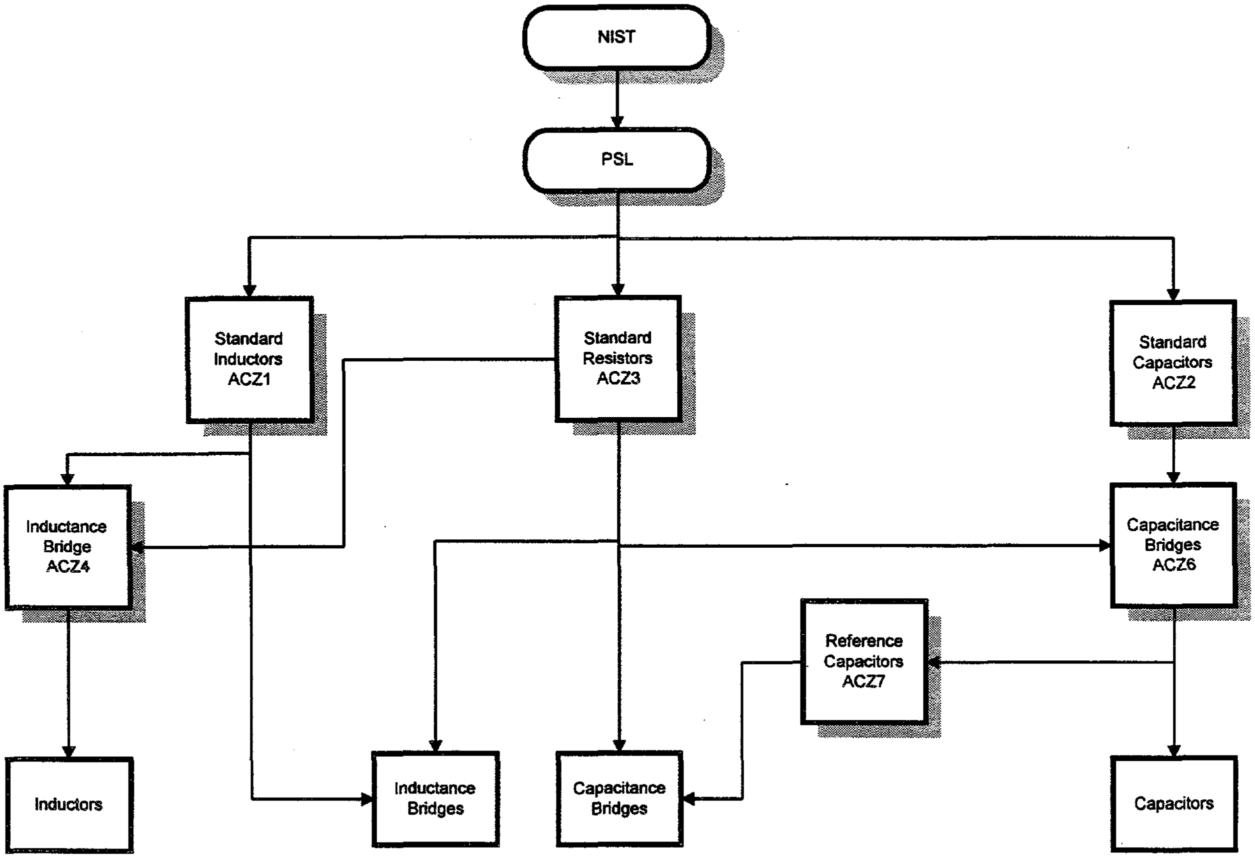


Figure 4C. Inductance and Capacitance Traceability

Inductance, Capacitance, and AC Resistance Standards

Code	Description	Manufacturer	Range	Accuracy (±)
ACZ1	Standard Inductors	General Radio, AlliedSignal,	50 μH to 10 H	0.03 to 0.3% *
		Hewlett-Packard, Boonton	50 nH to 100 μH	0.3 to 10% *
ACZ2	Standard Capacitors	General Radio	1000 pF, fixed	0.004% @ 1 kHz
ACZ3	Standard Resistors	Leeds & Northrup	1 to 20K Ω	0.015%
ACZ4	Inductance Bridge	Hewlett-Packard	100 μH to 5H	0.15 to 0.3% (direct measurement)
			0.05 μH to 10 μH	0.1 to 10% (comparison to standard inductors)
ACZ6	Capacitance Bridge	General Radio	0.001 pF to 1 μF 1 μF to 10 μF	(0.01% + 0.00005 pF) 0.02% (at 1 kHz)
		Hewlett Packard	0.1 to 1000 pF	0.1% at 1 kHz 0.2% at 1 MHz
ACZ7	Reference Capacitors	Boonton Electric General Radio	1 to 1000 pF	0.02% to 0.11% **
		FM&T Metrology	0.1 to 1000 pF	0.1 to 0.15% **
			0.001 to 1 μF	0.02% @ 1 kHz
			1 to 10 μF in 1 μF increments	0.1% @ 1 kHz
			10 to 100 μF in 10 μF increments	0.25% @ 1 kHz

* Accuracy depending on inductance value and frequency
** Accuracy depending on capacitance value and frequency

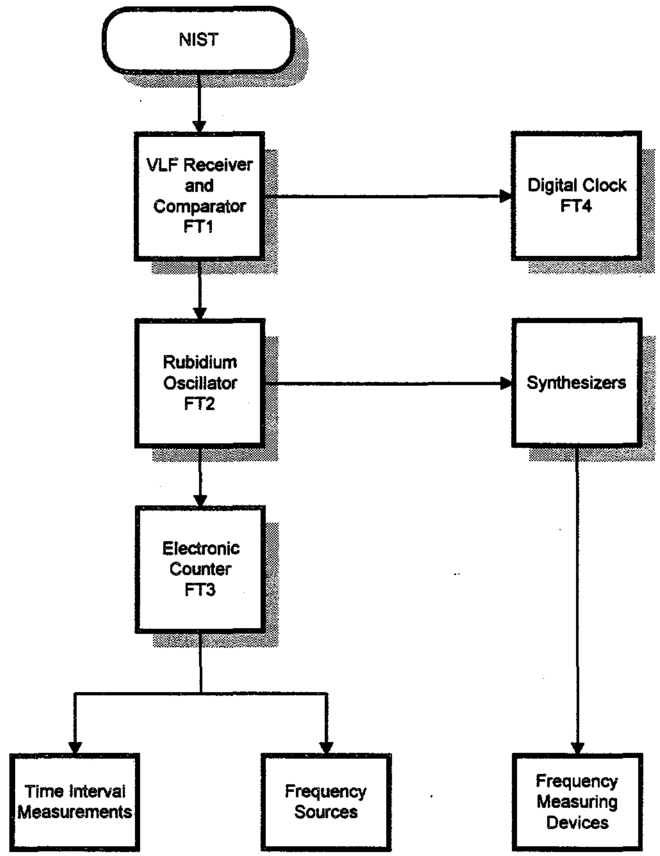


Figure 5C. Frequency and Time Traceability

Frequency and Time Standards

Code	Description	Manufacturer	Range	Accuracy (±)
FT1	VLF Receiver and Comparator	Kinemetrics	60 kHz	Comparison device
FT2	Rubidium Oscillator	Efratom	0.1 MHz to 10 MHz	1 part in 109
FT3	Electronic Counter	Hewlett-Packard	0 to 18 GHz	±(1 part in 109 + 2 counts)
FT4	Digital Clock	Truetime	24 hours	0.5 ms

Electrical Radio Frequency/Microwave Measurement Capability

Type	Range	Frequency	Measuring Accuracy (±)
Attenuation	0 to 80 dB 0 to 90 dB 0 to 100 dB 0 to 80 dB 0 to 60 dB 0 to 70 dB	0.01 to 1.999 GHz 0.01 to 1.0 GHz 0.01 to 0.03 GHz 2 to 8 GHz 8 to 18 GHz 300 kHz to 265 GHz	(0.03 dB or 0.03 dB/10 dB) * (0.03 dB or 0.03 dB/10 dB) * (0.03 dB or 0.03 dB/10 dB) * (0.04 dB or 0.04 dB/10 dB) * (0.06 dB or 0.06 dB/10 dB) * 0.01 to 1.10 dB * Whichever is greater plus mismatch
RF Power	10 microwatt to 100 mW 1 mW 1 nW to 100 mW 10 microwatt to 10 mW 30 mW to 12 W 10 mW to 1 kW	1 to 10 MHz 1 MHz to 8.5 GHz 10 MHz to 8.5 GHz 8.5 to 18 GHz 1.5 GHz to 2.3 GHz 2 MHz to 1.3 GHz	6 to 7% 1.0 to 2.5% 2.0 to 6.0% 4 to 8% 4.0% 5.0 to 15.0%
RF Reflection Coefficient	0.0 to 1.0	30 kHz to 26.5 GHz	0.002 to 0.05 Reflection coefficient magnitude (SWR calculated)

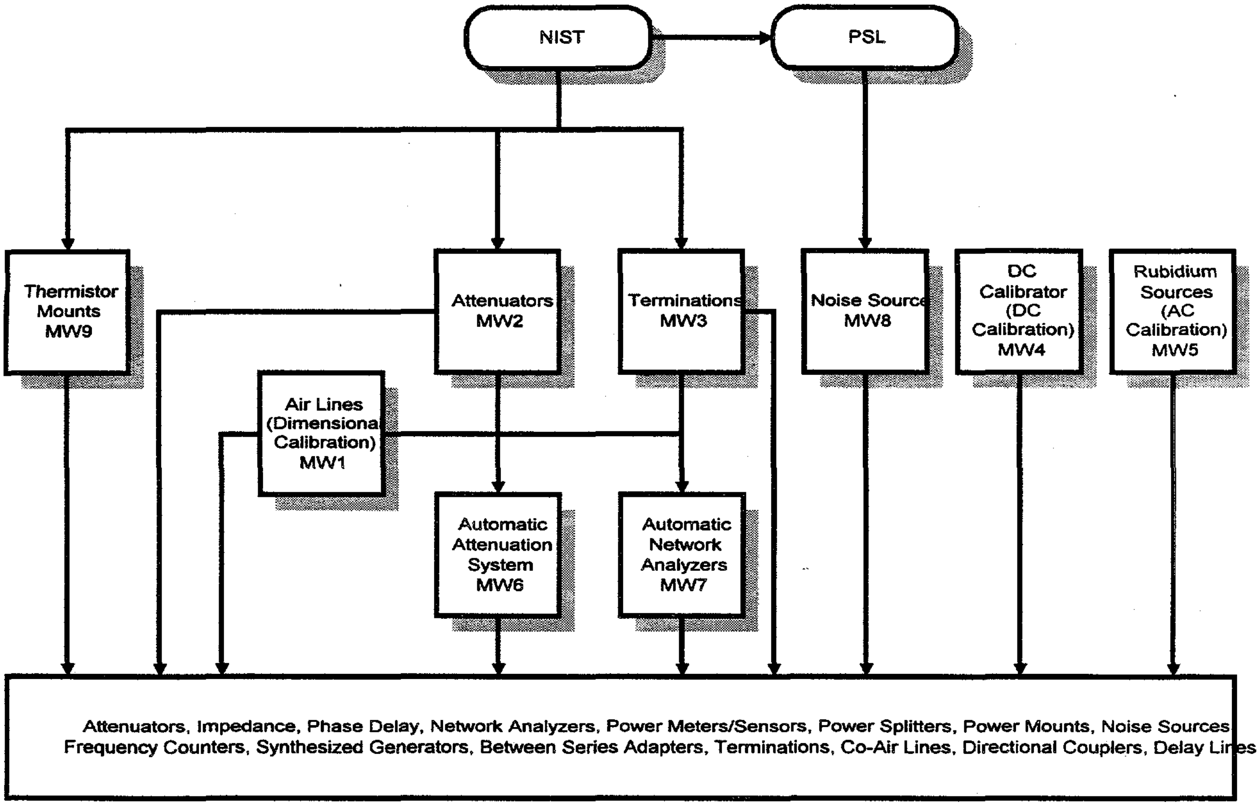


Figure 6C: Radio Frequency and Microwave Traceability

Radio Frequency and Microwave Standards

Code	Description	Manufacturer	Range	Accuracy (±)
MW1	Air Lines	General Radio Maury Microwave Hewlett-Packard	2.4 mm, 3.5 mm 7 mm, 14 mm 50 MHz to 50 GHz	$\|Z\|$ ± 0.050 to 3.75 Ω $\|\Gamma\| \leq$ 0.0008 to 0.036 EL ± 0.0031 to 0.0601 cm
MW2	Attenuators	Weinschel Engr. Hewlett-Packard	10 MHz to 50 GHz 0 dB to 120 dB	± 0.012 to 0.1 dB
MW3	Terminations	General Radio Maury Microwave Hewlett-Packard Wiltron	300 kHZ to 50 GHz	$\|\Gamma\|$ ±0.0005 to 0.0200 ϕ ± 0.0005 to 0.5°
MW4	DC Calibrator	Hewlett-Packard	1 nW to 100 mW	± 0.25%
MW5	Rubidium Source	Efratom	10 MHz	± 0.001 ppm
MW6	Automatic Attenuation System	Weinschel Engr.	10 MHz to 18 GHz 0 dB to 100 dB	± 0.03 to 1.0 dB
MW7	Automatic Network Analyzers	Hewlett-Packard FM&T Metrology	300 kHz to 50 GHz $\|\Gamma\|$ 0.0 to 1.0 ϕ 0.0 to 360° 512/521 Magn. (0 - 70 dB) 512/521 Phase (0 - 70 db)	$\|\Gamma\|$ ± 0.002 to 0.2 ϕ ± 0.8 to 180° ± 0.02 to 1.10 dB ± 0.5 to 3.0°
MW8	Noise Source	Hewlett-Packard	60 Hz to 3.55 GHz	± 0.1 to 0.35
MW9	Thermistor Mounts	Hewlett-Packard	1 MHz to 18 GHz	± 0.3 to 1.5%

OPTICAL AND RADIATION

OPTICAL AND RADIATION

Optical Radiometric Measurement

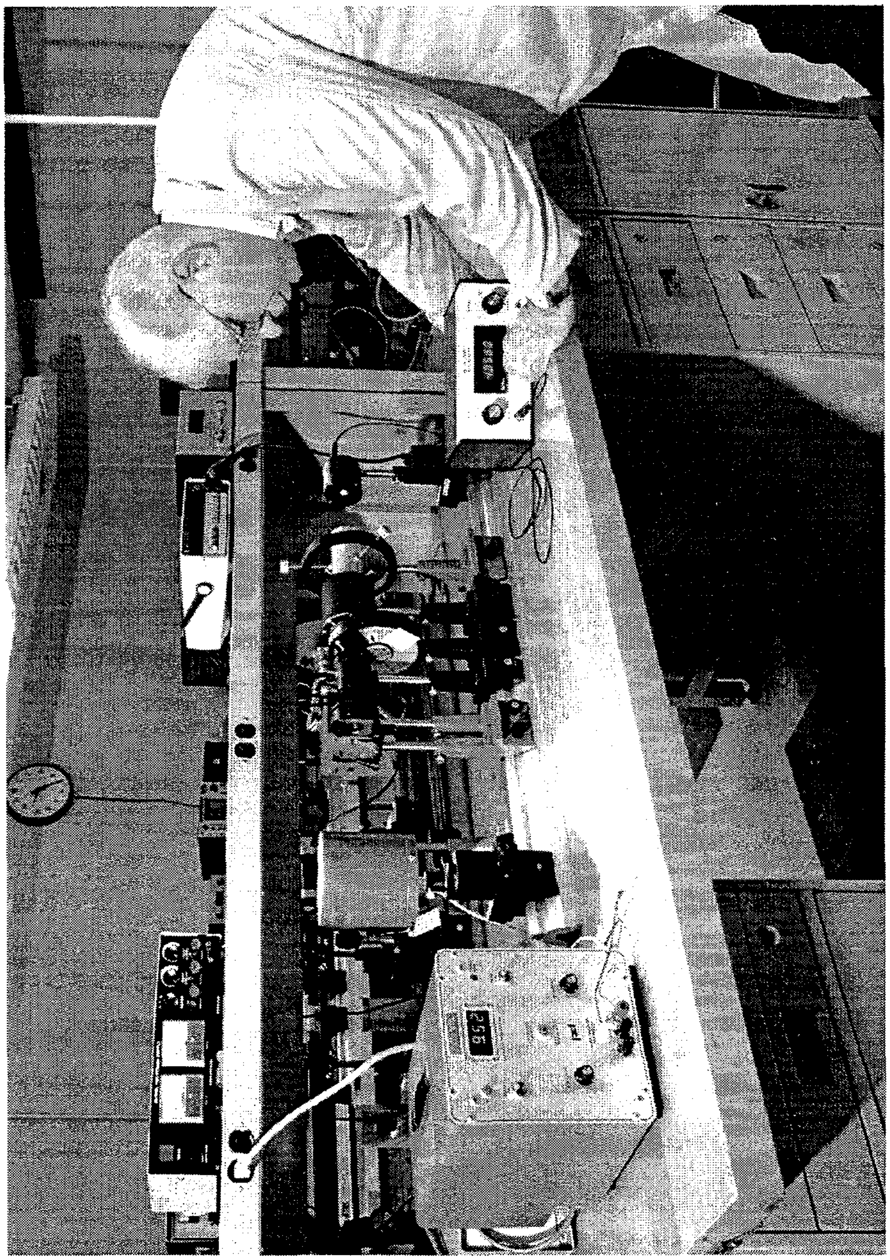
Radiometry is the measurement of radiation in the optical spectrum which includes ultraviolet, visible, and infrared light. The main radiometric reference standards at FM&T are heat-flow calorimeters and wavelength standards which include HeNe lasers and Hg lamps. The heat flow calorimeters are calibrated by the Primary Standards Laboratory. The wavelength standards do not require calibration because of their physical characteristics. Measurements performed include noncoherent measurement in the ultraviolet and visible regions of the optical spectrum and coherent measurements which consist of HeNe, laser diode, YAG and CO_2 lasers. Power levels of these measurements range from fractions of a microwatt to levels in excess of 1000 watts over wavelengths of 365 nm to 10.6 mm. Most of the radiometric calibration activity at FM&T is measuring the power output and characteristics of lasers in CW or pulsed modes of operation.

Optical Photometric Measurement

Photometry is the measurement of visible light intensity and energy as it affects the human eye. Photometric reference standards at FM&T are Luminous Intensity Standard Lamps. The Standard Lamps are calibrated in units of candelas and are normally used with an optical bench to calibrate light meters in units of foot candles. These lamps also are used as a stable source for calibration of an unknown photometer by comparison to a standard photometer that is calibrated at NIST.

Radiation Measurement

Radiation measurements are made using standards of alpha-particle emission rate from plutonium 239 and lead-probe neutron detectors. Alpha sources and lead probes are calibrated by the PSL. Accuracy of these standards ranges from ±3% to ±10%.



Photodiode Detector Calibration

Optical Radiometric Measurement Capability

Type	Range	Measuring Accuracy (±)
Optical Transmittance	λ = 350 to 400 nm λ = 400 to 500 nm λ = 500 to 1000 nm	2% 1% 0.5%
Optical Spectral Response	350 to 400 nm 400 to 500 nm 500 to 1000 nm	5% 1.5% 2%
Laser Average Power	λ = 516 nm to 1.064 μm 1 to 100 μW 100 μW to 1 mW 1 mW to 10 W λ = 1.064 μm 10 to 100 W λ = 10.6 μm 1 mW to 10 W 10 to 1000 W	 5% 4% 3% 6% 6% 6%
Laser Peak Power	λ = 450 to 950 nm Pulse width 50 ns to 1 ms 1 to 10 W λ = 1.064 μm Pulse width 50 ns to 1 ms 0.1 to 10 W 10 W to 10 kW	 7% 9% 20%
LED Power	λ = 570 to 910 nm 10 μW to 10 mW (CW) λ = 890 to 905 nm Pulse width 50 to 200 ns 1 to 75 W	 5% 8%
Ultraviolet Irradiance	λ = 365 nm 0.1 to 10 mW/cm2	 5%
X-Ray Film Density	0 to 4 Optical Density Units	(0.03 density units + 1% of reading)

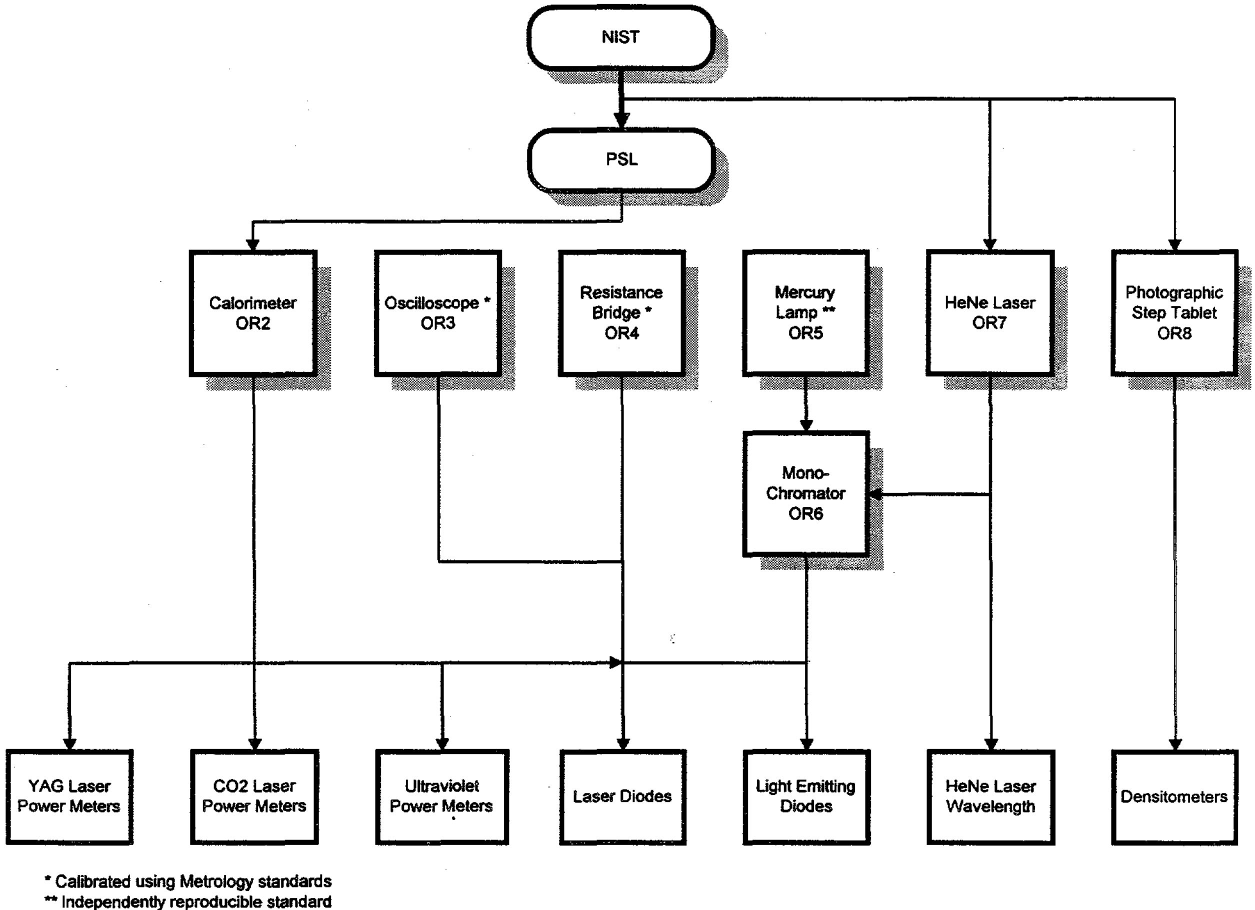


Figure 1D. Optical Traceability (Radiometric)

Optical Radiometric Measurement Standards

Code	Description	Manufacturer	Range	Accuracy (±)
OR2	Calorimeter	Scientech	10 μW to 10 W	1.1%
OR3	Oscilloscope	Hewlett-Packard	1 mV to 100 V 5 ns/div. to 0.1 s/div.	3%
OR4	Resistance Bridge	ESI	1 Ω to 100 MΩ	(0.01% + 0.005) times multiplier
OR5	Mercury Lamp	Oriel	237.8 to 1092.2 nm	0.1 nm
OR6	Monochromator	Various	237.8 to 1092.2 nm	1 nm
OR7	HeNe Laser	Various	632.8 nm	0.015 ppm
OR8	Photographic Step Tablet	NIST	0 to 4 density units	0.01 unit or 1% whichever is greater

Optical Photometric Measurement Capability

Type	Range	Measuring Accuracy (±)
Illuminance	2 to 750 foot-candle	1%
Luminous Intensity	98.8 to 739 candela	4.1%

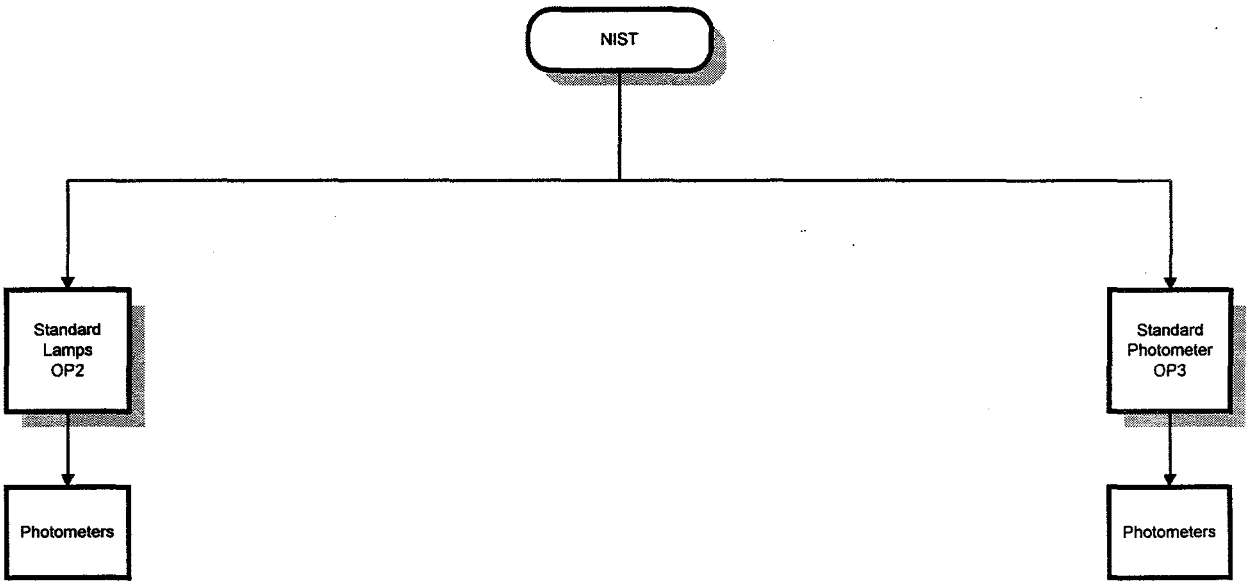


Figure 2D. Optical Traceability (Photometric)

Optical Photometric Measurement Standards

Code	Description	Manufacturer	Range	Accuracy (±)
OP2	Standard Lamps	NIST	98.8 to 739 candela	4.1%
OP3	Standard Photometer	NIST	1×10^{-2} to 2×10^{-3} foot-candle	1%

Radiation Measurement Capability

Type	Range	Measuring Accuracy (±)
Alpha Radiation	1.6×10^{3} to 1.5×10^{6} particles/minute	3%
Neutron	1.0×10^{6} to 5.0×10^{8} total neutrons	10%