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METROLOGY MEASUREMENT CAPABILITIES

Kermit Shroyer

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MASTER

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Introduction

During the past 36 years, the Kansas City Division's (KCD) 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.

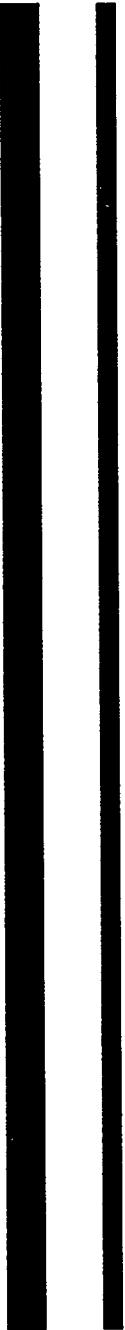
The capabilities developed include unique capabilities in many areas of measurement and engineering expertise to develop measurement techniques and resolve measurement problems in these major areas.

KCD Metrology was established in 1958 to provide a measurement base for the 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 19 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



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 μ in. 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 certified by NIST.

Vibration

Accelerometers used for vibration testing are calibrated on a computer-controlled shaker. Comparison is made to an NIST-certified 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 weighings on 1-2-3-5 decade progressions over the range from 1 mg to 5 kg.

Force Measurement

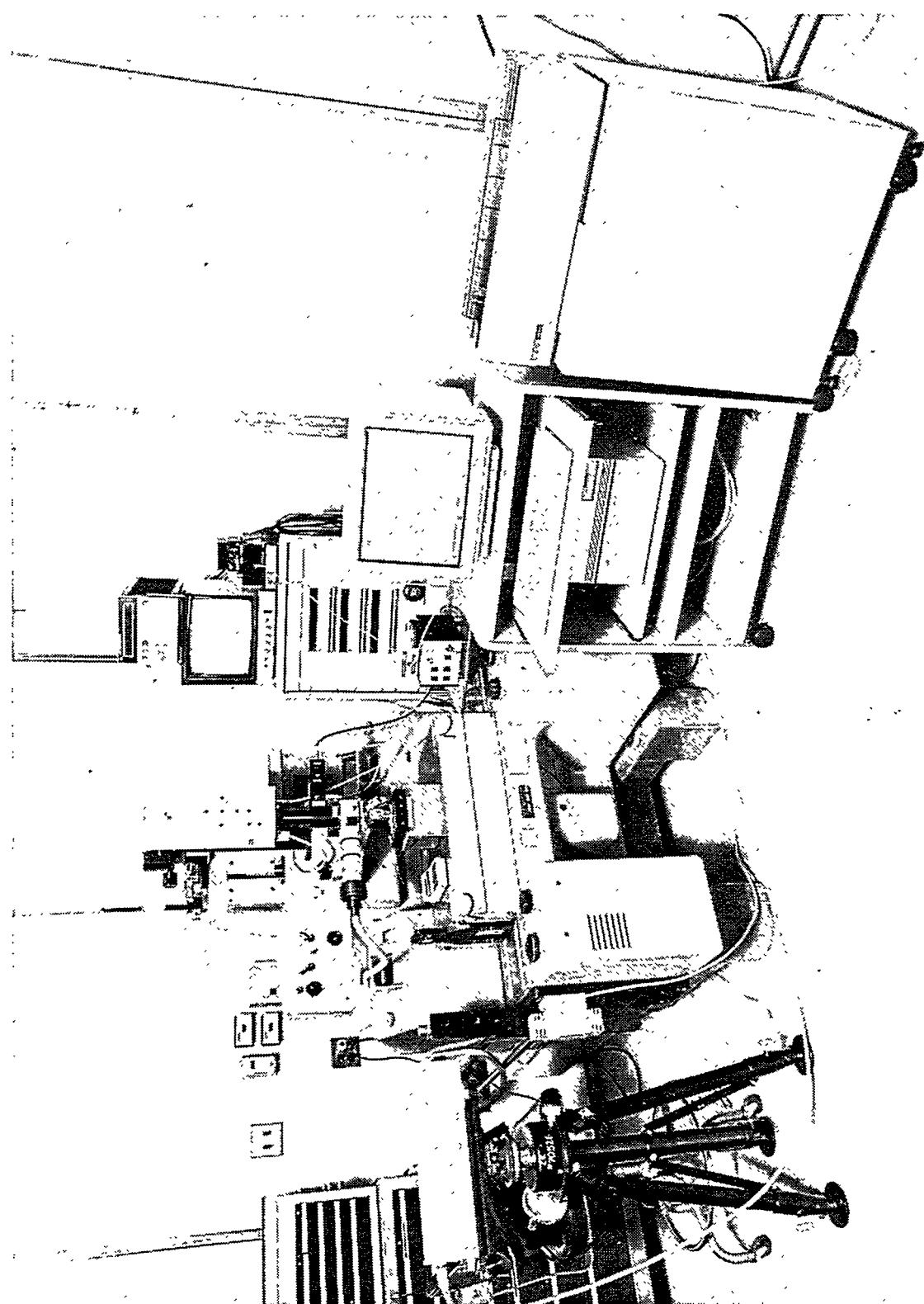
Force transducers up to 2400-lbf capacity are measured using weight sets or dead weight testers which are certified in force units in our Mass lab. Larger force devices are measured by comparison to NIST-certified proving rings using a universal force tester.

Torque Measurement

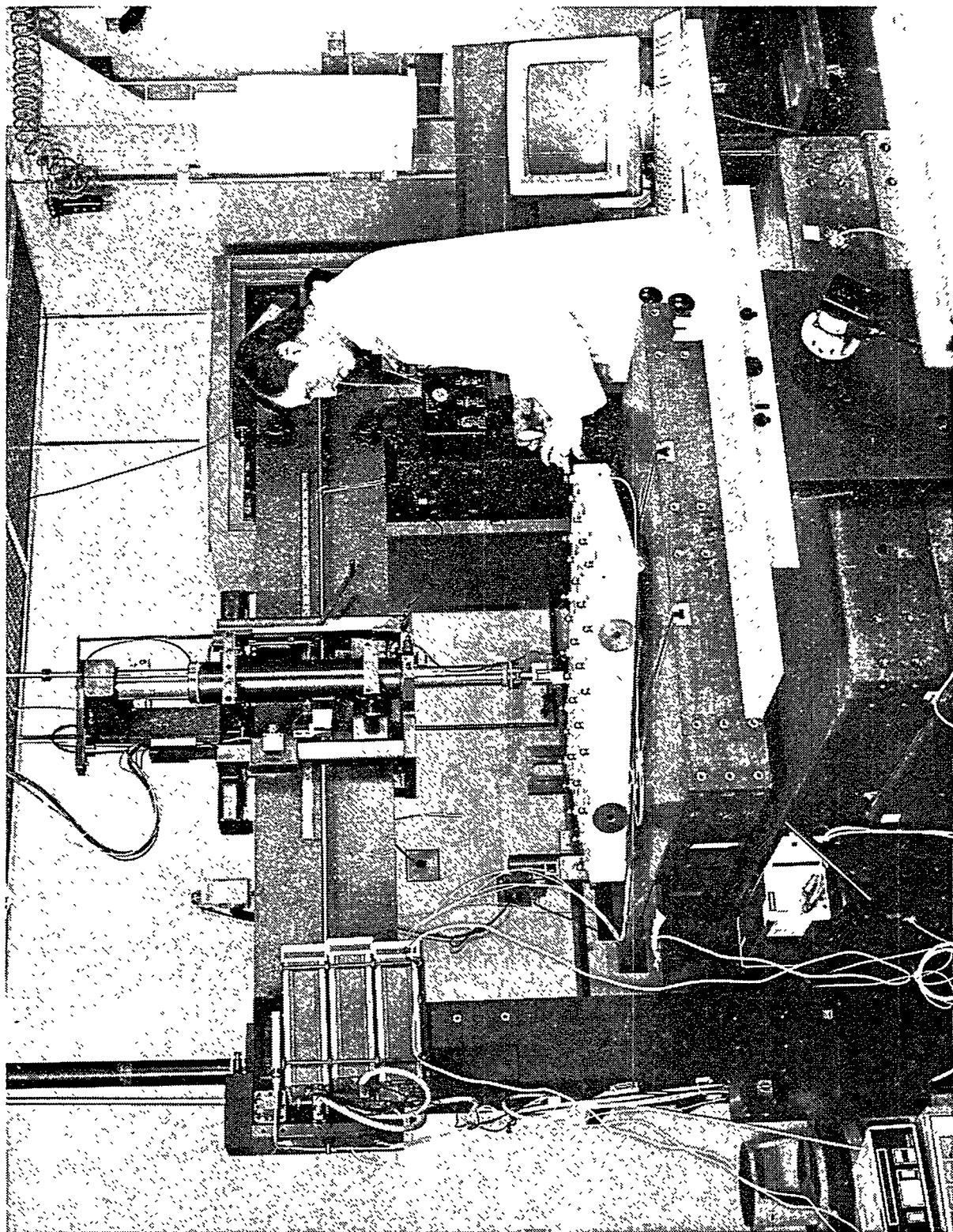
Torque transducers are measured using weights which are certified in force units in our Mass lab and lever arms of known length. The lever arms are calibrated on a coordinate measuring machine using a helium-neon laser as a standard.

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

Table 1A. Dimensional Measurement Capability

Type	Range (in.)	Accuracy (\pm) Measuring
Length-Gage Blocks	To 1	5 μ in.
	2	6 μ in.
	3	7 μ in.
	4	8 μ in.
	5 to 7	9 μ in.
	8 to 10	10 μ in.
	12	11 μ in.
	16	12 μ in.
	20	13 μ in.
Length-Coordinate Measurement*	Along an axis	$\pm(20 \mu\text{in.} + 2 \text{ ppm})$
	In a plane #	$\pm(30 \mu\text{in.} + 6 \text{ ppm})$
	In x-y-z space #	$\pm(30 \mu\text{in.} + 9 \text{ ppm})$
Internal Diameters	0.02 to 15 in.	4 ppm + 10 μ in.
Roundness	To 20-in. diameter	3 μ in.
Thread Wires	All standard pitches	8 μ in.

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

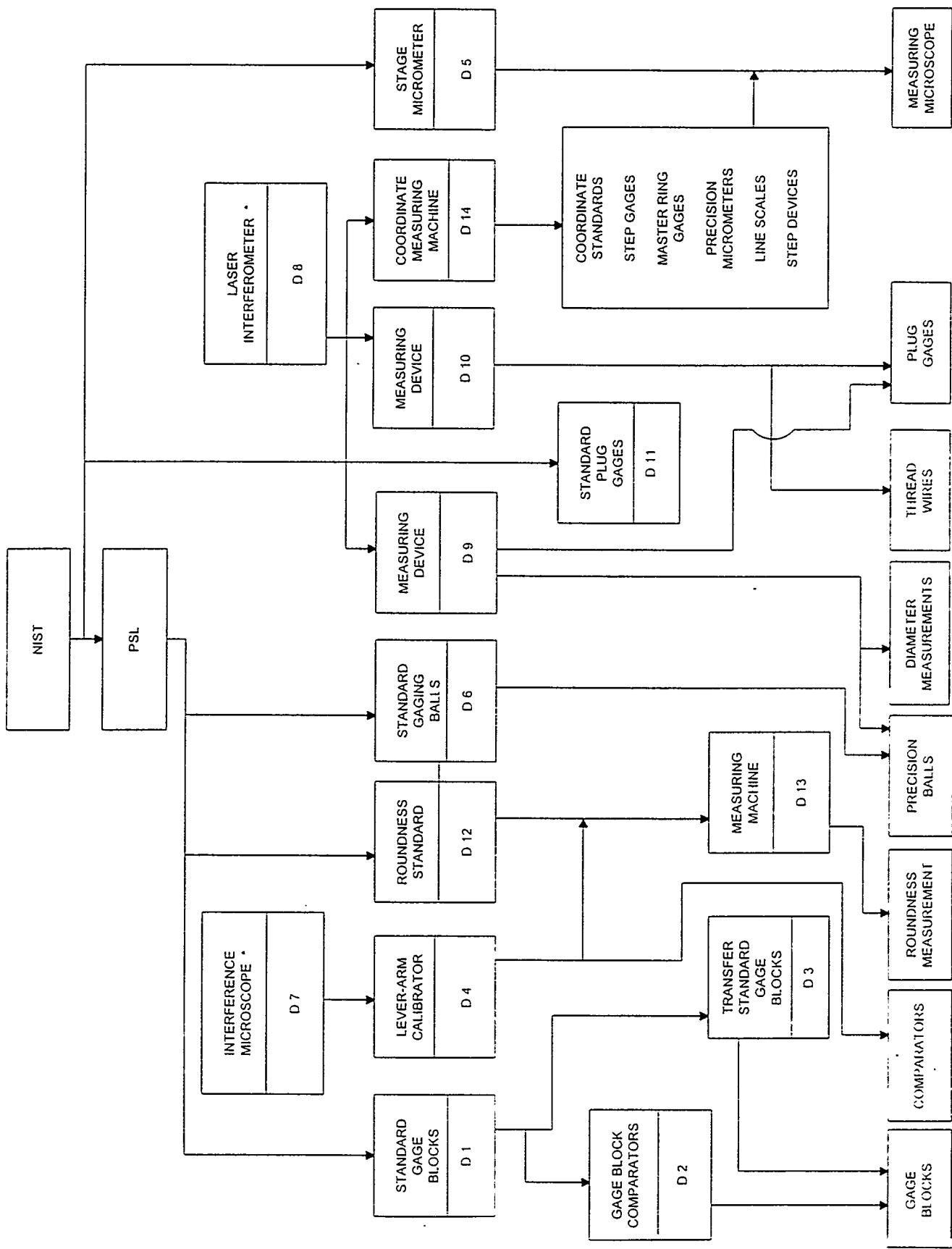


Figure 1A Dimensional Measurement Capability

* Independently reproducible standard

Table 2A. Dimensional Code Description

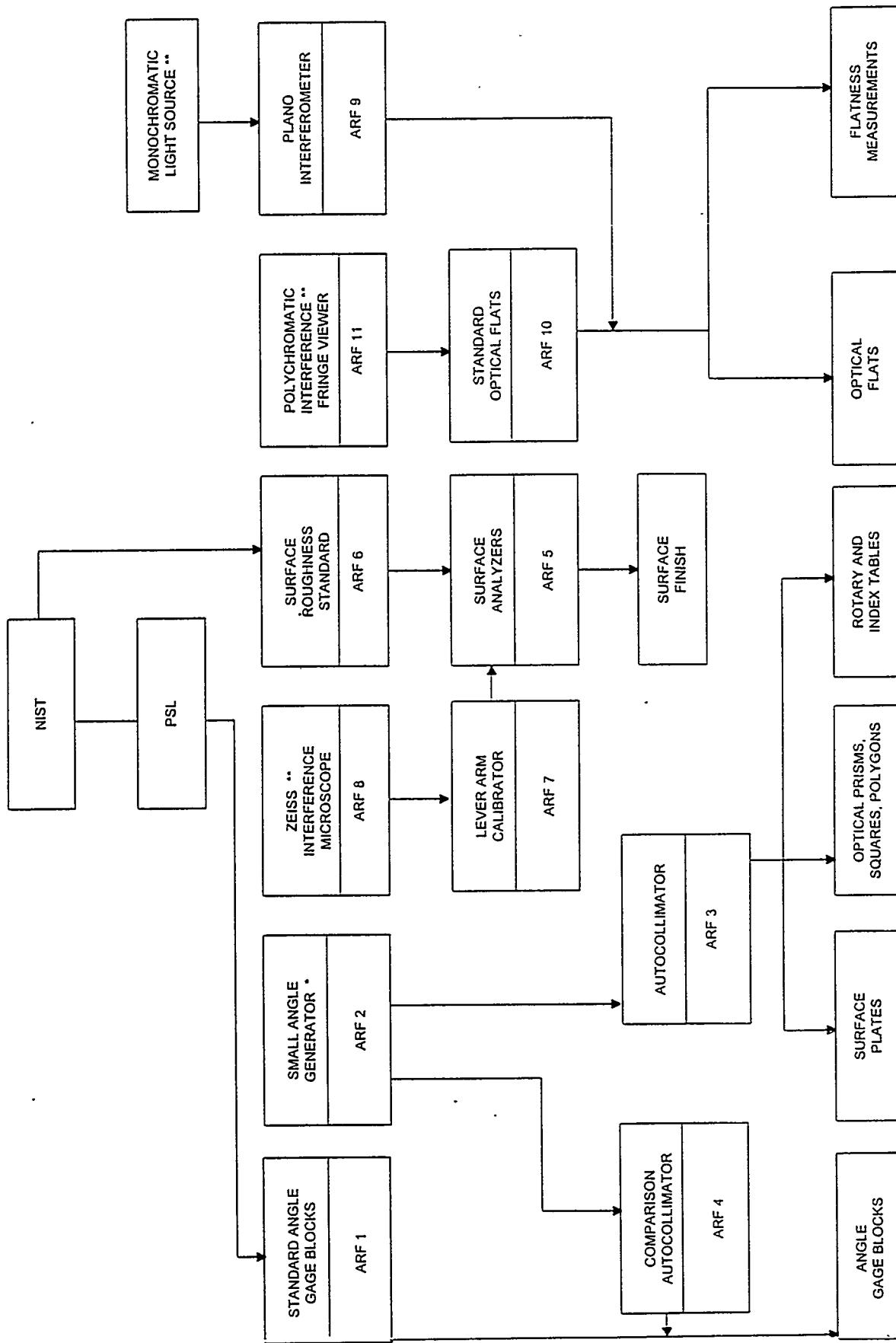
Code	Description	Manufacturer	Range	Accuracy (\pm)
D 1	Standard Gage Blocks	Do All	To 1 in.	3 μ in.
		Do All	2 in.	4 μ in.
		Do All	3 in.	5 μ in.
		Do All	4 in.	6 μ in.
		Pratt & Whitney	5 to 7 in.	7 μ in.
		Pratt & Whitney	8 to 10 in.	8 μ in.
		Pratt & Whitney	12 in.	9 μ in.
		Pratt & Whitney	16 in.	10 μ in.
		Pratt & Whitney	20 in.	11 μ in.
D 2	Gage Block Comparators	Link	0 to 2 in.	3 μ in.
		Federal	0 to 4 in.	3 μ in.
		Pratt & Whitney	0 to 20 in.	3 μ in.
D 3	Transfer Standard Gage Blocks	Do All	To 1 in.	5 μ in.
		Do All	2 in.	6 μ in.
		Do All	3 in.	7 μ in.
		Do All	4 in.	8 μ in.
		Pratt & Whitney	5 to 7 in.	9 μ in.
		Pratt & Whitney	8 to 10 in.	10 μ in.
		Pratt & Whitney	12 in.	11 μ in.
		Pratt & Whitney	16 in.	12 μ in.
		Pratt & Whitney	20 in.	13 μ in.
		KCD Metrology	0 to 0.0002 in.	0.2 μ in. + 0.5% of travel
D 4	Lever Arm Calibrator	Mitutoyo	0 to 0.05 in.	4 μ in. + 0.25% of travel
		American Optical 15680	0 to 25 mm 0 to 1 in.	0.15 μ m 4 μ in.
D 5	Stage Micrometer	AA Industries	1/16 to 1 in. (1/32-in. increments)	7 μ in.
D 6	Standard Gaging Balls	Zeiss	0 to 0.01 in.	1 μ in.
D 7	Laser Interferometer	Hewlett-Packard	NA	1 ppm
D 8	Measuring Device	Pratt & Whitney	1 in.	10 μ in.
D 9	Measuring Device	KCD Metrology	0 to 2 in.	8 μ in.

Table 2A Continued. Dimensional Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
D 11	Standard Plug Gages	Lincoln	0.050 to 1 in.	5 μ in.
D 12	Roundness Standard	Taylor Hobson	NA	3 μ in.
D 13	Roundness Measuring Machine	Bendix A & M	20-in. diameter	3 μ in.
D 14*	Coordinate Measuring Machine	Shelton	x axis y axis z axis x-y plane y-z plane x-z plane ** x-y-z space **	2 ppm + 20 μ in. 2 ppm + 20 μ in. 2 ppm + 20 μ in. 6 ppm + 30 μ in. 6 ppm + 30 μ in. 6 ppm + 30 μ in. 9 ppm + 30 μ in.

*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. 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 $\pm(30 \mu$ in. + 2 ppm).

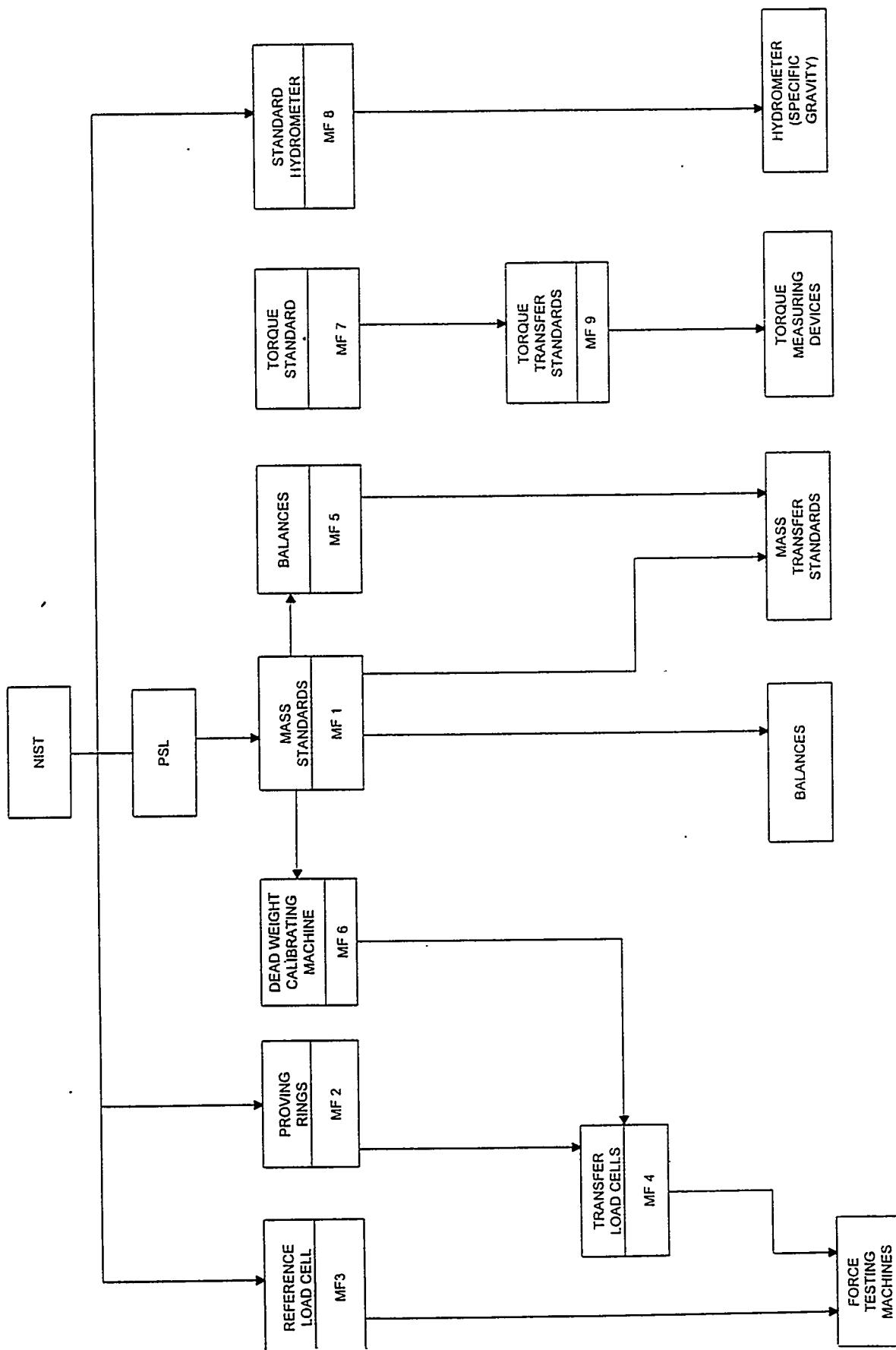


* Calibrated using laser Interferometer
 .. Independently reproducible standard
 ARF

Figure 2A Dimensional Code Description

Table 3A. Angle, Roughness, and Flatness Measurement Capability

Type	Range	Measuring Accuracy (\pm)
Angle	0 to 360°	1 arc second
Surface Roughness	0 μ in. to 0.008 in. R_a	1.2 to 400 μ in. R_a
Optical Surface Flatness	To 3-in. dia. 3 - 12-in. dia.	2 μ in. 4 μ in.
Surface Plate Flatness	1 by 1 ft. 4 by 6 ft. 5 by 10 ft.	50 μ in. 75 μ in. 100 μ in.

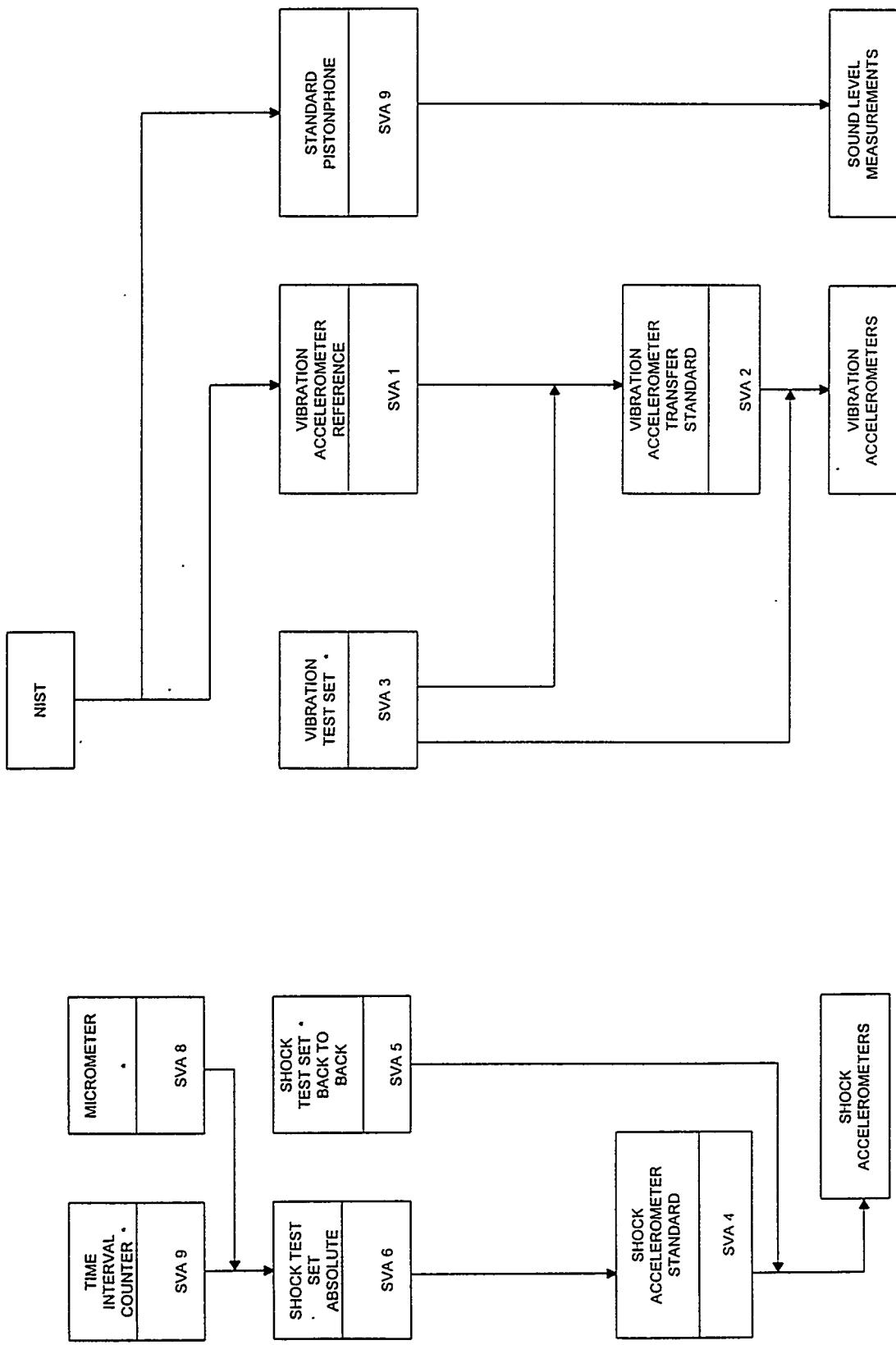


* Calibrated using Metrology dimensional and mass standards

Figure 3A Mechanical Calibration Flow Chart (Mass, Force, Torque, Specific Gravity)

Table 4A. Angle, Roughness, Flatness Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
ARF 1	Standard Angle Gage Blocks	Webber	1 arc second to 45° (16 blocks)	0.7 arc second
ARF 2	Small Angle Generator	Matrix	10 arc minutes	0.1 arc second
ARF 3	Autocollimator	Davidson	10 arc seconds	0.15 arc second
		Nikon	20 arc minutes	0.4 arc second +0.25% of measured angle
ARF 4	Comparison Autocollimator	Davidson	10 arc minutes	0.5 arc second +0.25% of measured angle
			120 arc seconds	0.3 arc second +0.5% of measured angle
ARF 5	Surface Analyzer	Federal	0 to 0.008 in. R_a (10 ranges)	1.2 to 400 μ in. R_a
ARF 6	Surface Roughness Standard	NIST	120 μ in. R_a	3.1 μ in. R_a
ARF 7	Lever-Arm Calibrator	KCD Metrology	0 to 0.0002 in.	0.2 μ in. +0.5% of travel
ARF 8	Interference Microscope	Zeiss	0 to 0.01 in.	1 μ in.
ARF 9	Plano Interferometer	Davidson	2 3/4-in. diameter	2 μ in.
ARF 10	Standard Optical Flats (set of 3)	Do All	12-in. diameter	Flat within 4 μ in.
ARF 11	Polychromatic Interference Fringe Viewer	Strang	NA	1 μ in.



• Indicates items certified using Metrology standards

Figure 4A Mechanical Calibration Flow Chart (Vibration, Shock, Sound Level)

Table 5A. Mass, Force, Torque, Specific Gravity, and Laboratory Glassware Volumetric Measurement Capability

Type	Range	Accuracy (\pm)
Mass (Direct Weighing)	To 15 mg	0.020 mg
	15 - 100 mg	0.025 mg
	100 mg - 1 g	0.035 mg
	1 - 3 g	0.055 mg
	3 - 20 g	4 ppm + 0.07 mg
	20 - 100 g	3 ppm + 0.4 mg
	100 - 1000 g	3 ppm + 0.5 mg
	1000 - 5000 g	3 ppm + 11.0 mg
	5000 - 60000 g	2 g
(Substitution Weighing)	1 - 100 mg	0.013 mg
	200 mg - 10 g	0.015 to 0.04 mg
	20 - 50 g	0.07 to 0.20 mg
	100 - 5000 g	3.5 ppm
	5 - 22 Kg	25 to 50 mg
(Calibration Design Using 1-2-3-5 Decade Progressions)	1 - 500 mg	0.004 to 0.006 mg
	1 - 5 g	0.006 to 0.011 mg
	10 - 50 g	0.018 to 0.030 mg
	100 - 5000 g	0.12 to 0.7 ppm
(1 Kg Design)	1 Kg	0.12 ppm
(Class Weights and Weight Sets)	1 mg to 20 Kg	ANSI/ASTM Class 1, 2, 3, 4, 5, 6 NIST Class M, S, S-1, P, Q, T, F, C
	1/16 oz to 50 lb	ANSI/ASTM Class 1, 2, 3, 4, 5, 6 NIST Class S, S-1, P, Q, T, F, C
Force	0.0625 - 5 lbf	0.1% of reading
	5 - 300 lbf	0.005% of reading
	300 - 2400 lbf	0.01% of reading
	750 - 3000 lbf	0.375 lbf
	3000 - 5000 lbf	0.625 lbf
	5000 - 10000 lbf	1.5 lbf
	10000 - 20000 lbf	2.5 lbf
	20000 - 30000 lbf	4.5 lbf
	30000 - 60000 lbf	7.5 lbf
	60000 - 100000 lbf	15.0 lbf
	100000 - 300000 lbf	150 lbf
	300000 - 500000 lbf	500 lbf

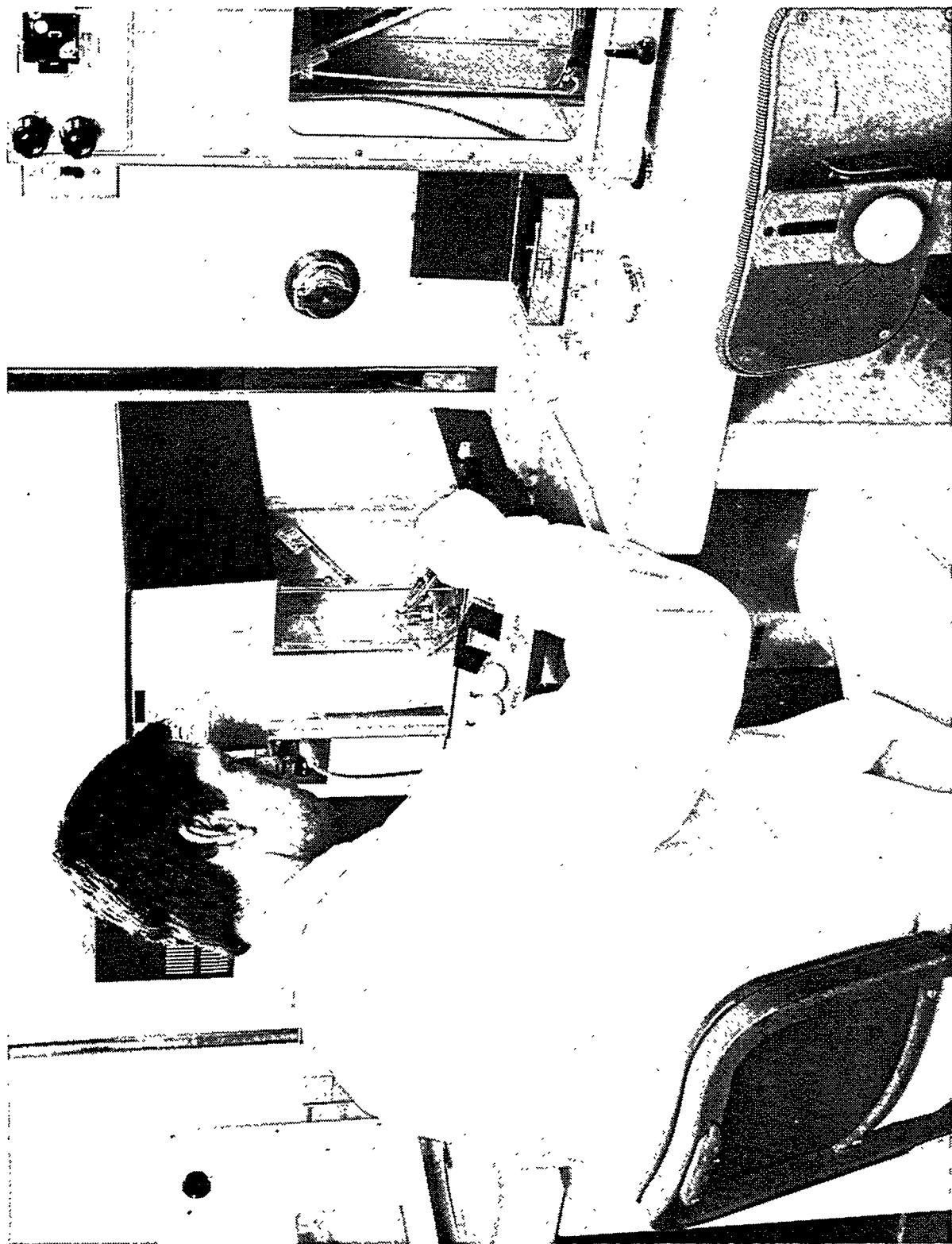
Table 5A Continued. Mass, Force, Torque, Specific Gravity, and Laboratory Glassware
Volumetric Measurement Capability

Type	Range	Accuracy (\pm)
Torque	1 - 160 oz-in.	0.175% of reading
	1 - 5 ft-lb	0.125% of reading
	5 - 50 ft-lb	0.15% of reading
	50 to 700 ft-lb	0.2% of reading
Specific Gravity	1.050 - 1.500	0.005 mg/cm ³
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	NIST Class A, B
	5 to 2000 mL	ASTM Class A, B
Graduated Cylinders	5 to 2000 mL	NIST or ASTM Class A, B

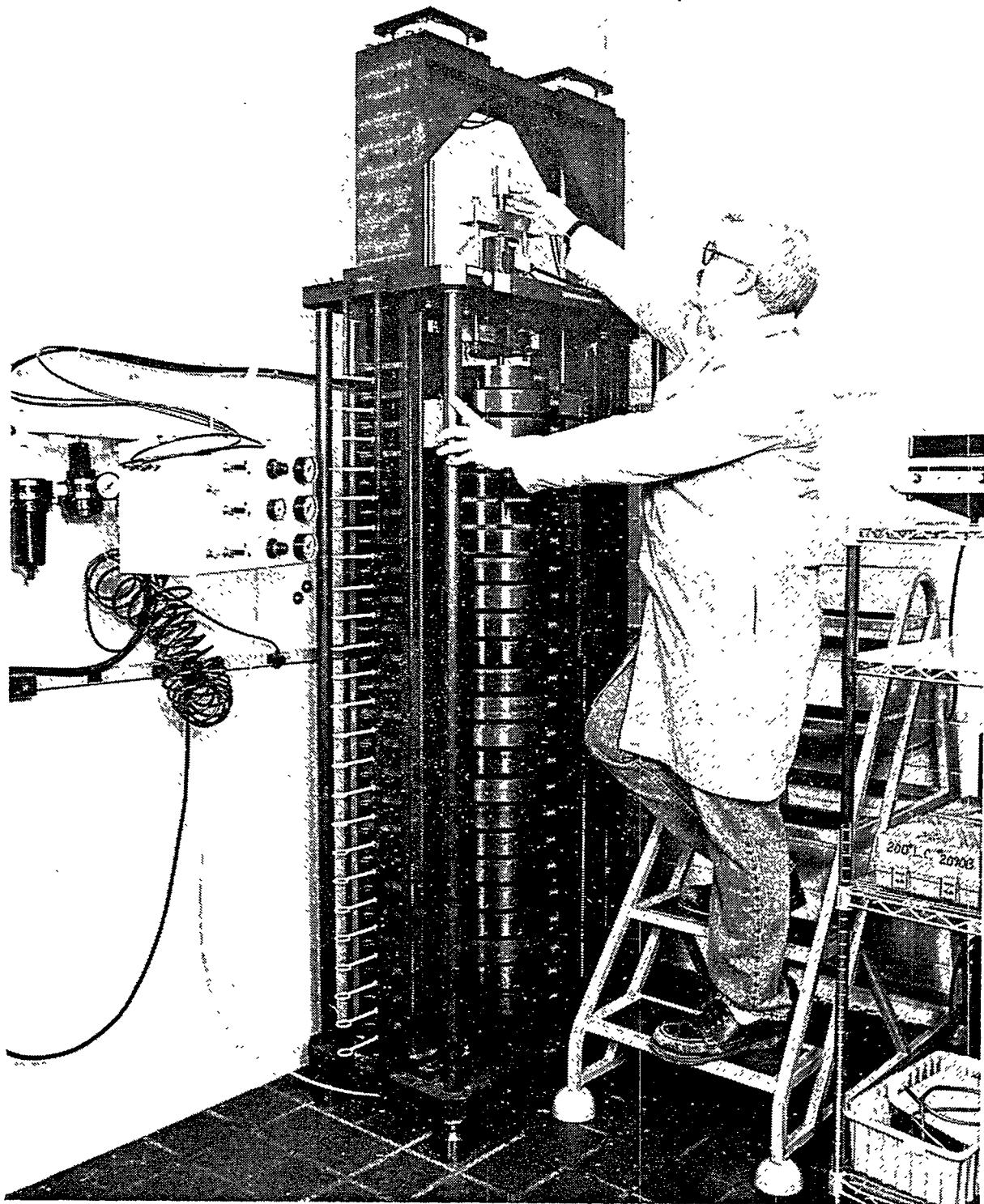
Table 6A. Mass, Force, Torque, Specific Gravity Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
MF 1	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
MF 2	Proving Rings	Morehouse	3000 to 100,000 lbf	0.0125 to 0.015% of range
			300,000 lbf	0.05% of range
MF 4	Transfer Load Cells	Various	0 to 240,000 lbf	0.05% F.S. +0.1% load
MF 5	Balances	Mettler*	0 to 3 g	0.020 to 0.055 mg
		Mettler*	0 to 20 g	4 ppm + 0.07 mg
		Sartorius*	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
MF 6	Dead Weight Calibrating Machine	Morehouse (modified)	5 to 300 lbf	0.005% of Reading
	Dead Weight Calibrating Machine	KCD Metrology	50 to 2400 lbf	0.01% of Reading
MF 7	Torque Standard	KCD Metrology	0 to 700 ft-lbf	0.125 to 0.2% of Reading
MF 8	Standard Hydrometer	H-B Instruments	1.050 to 1.500	0.005 mg/cm ³
MF 9	Transfer Torque Standard	Norbar	0 to 700 ft-lbf	0.3% of Range

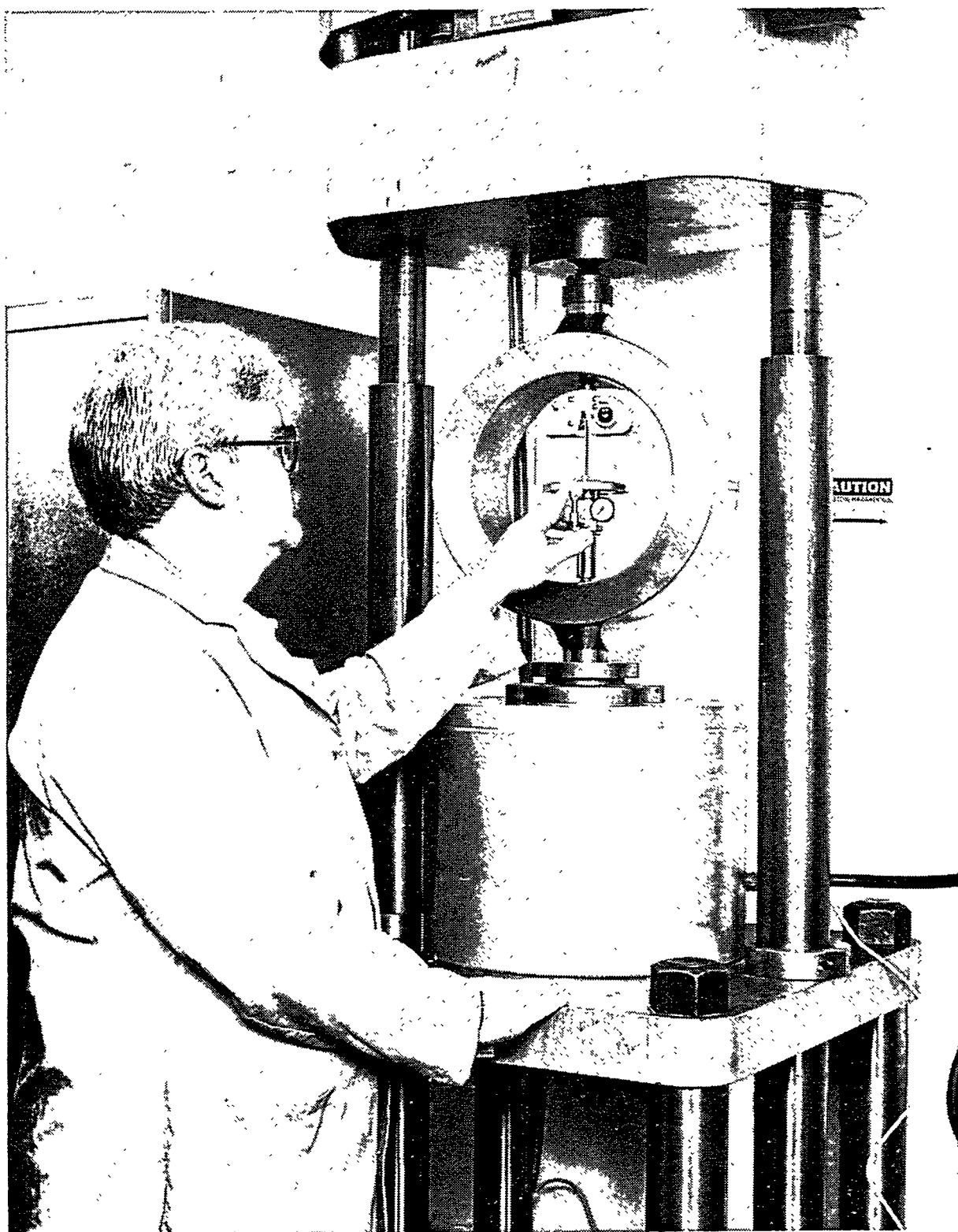
*Accuracy listed is for direct weighing.



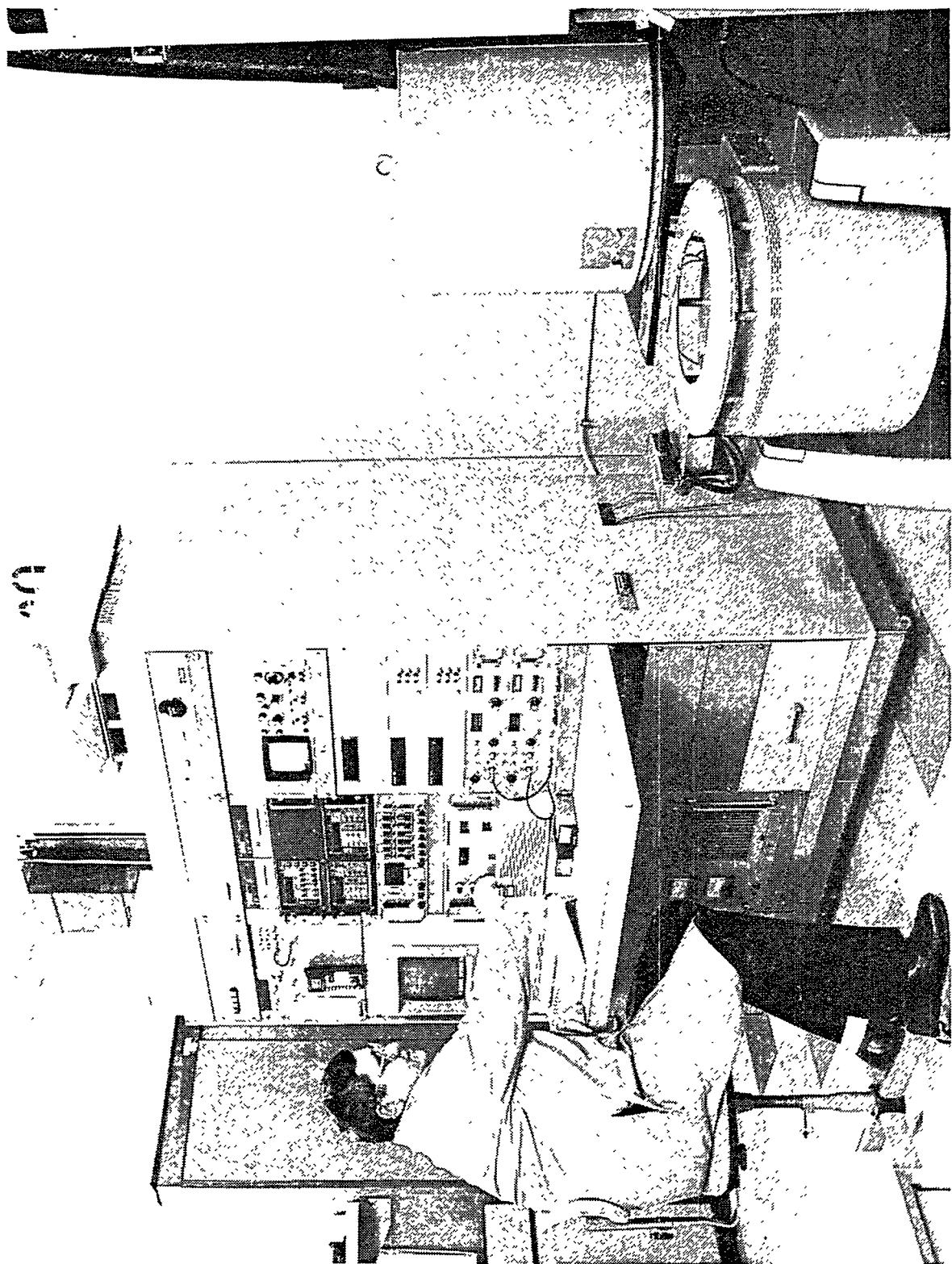
Mass Calibration



Dead Weight Force Calibration



Proving Ring Calibration



Accelerometer Vibration Calibration

Table 7A. Vibration, Acceleration, Shock, Sound Level Measurement Capability

Type	Range	Measuring Accuracy (\pm)
Vibration	0.3 to 75 g at 10 Hz to 10 kHz -65 to +125°C at 100 Hz to 4 kHz	2.5%
Shock	100 to 10,000 g at 0.1 to 10 ms -65 to +125°C at 0.25 to 10 ms	2.5 to 4.0%
Sound Level	124 dB at 250 Hz	0.5 dB

Table 8A. Vibration, Acceleration, and Shock Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
SVA 1	Vibration Accelerometer Reference	Endevco	0.3 to 75 g 10 Hz to 10 kHz	2%
SVA 2	Vibration Accelerometer Transfer Standard	Unholtz Dickie	0.3 to 75 g 10 Hz to 10 kHz	3%
SVA 3	Vibration Test Set	KCD	0.3 to 75 g 10 Hz to 10 kHz	Used only with other calibrated measuring standards
SVA 4	Shock Accelerometer Standard	Endevco	100 to 10,000 g	4%
SVA 5	Shock Test Set (back to back)	KCD Metrology	100 to 10,000 g	Used only with other calibrated measuring standards
SVA 6	Shock Test Set	KCD Metrology	5000 to 10,000 g	2.5%
SVA 7	Time Interval Counter	Stanford Research Systems	$\pm 100 \mu\text{sec}$ to 10 sec	$\pm 0.05\%$ of reading
SVA 8	Micrometer	Mitutoyo	1.000 to 2.000 in.	± 0.0003 in. from nominal
SVA 9	Standard Pistonphone	B and K	124 dB @ 250 Hz	0.5 dB



**ENVIRONMENTAL,
GAS, LIQUID**



Temperature

Temperature measurements in Metrology are based both on the International Practical Temperature Scale of 1990 (IPTS-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 KCD 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 1100°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 +200°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 IPTS-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 $\pm 0.5^\circ\text{C}$. The second is a two-pressure system that can generate humidities from 5% to 95% RH $\pm 0.5\%$ 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 1000 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 KCD 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.

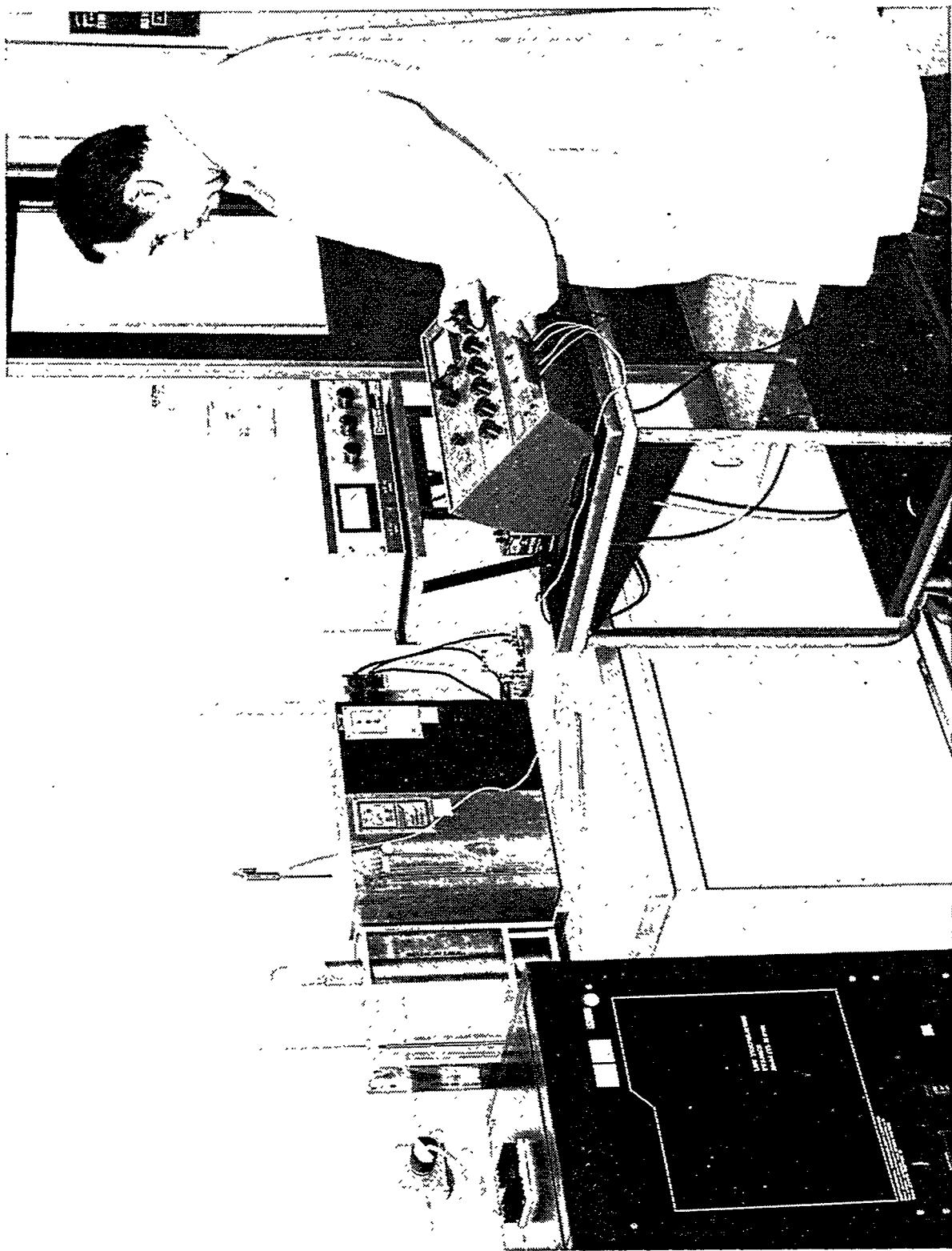
Vacuum calibrations above 10^{-3} mmHg are performed using either a capacitance manometer or digital Quartz manometer, depending upon the range of the gage. The manometers are calibrated using a PSL-certified dead weight piston gage.

Gas Leaks

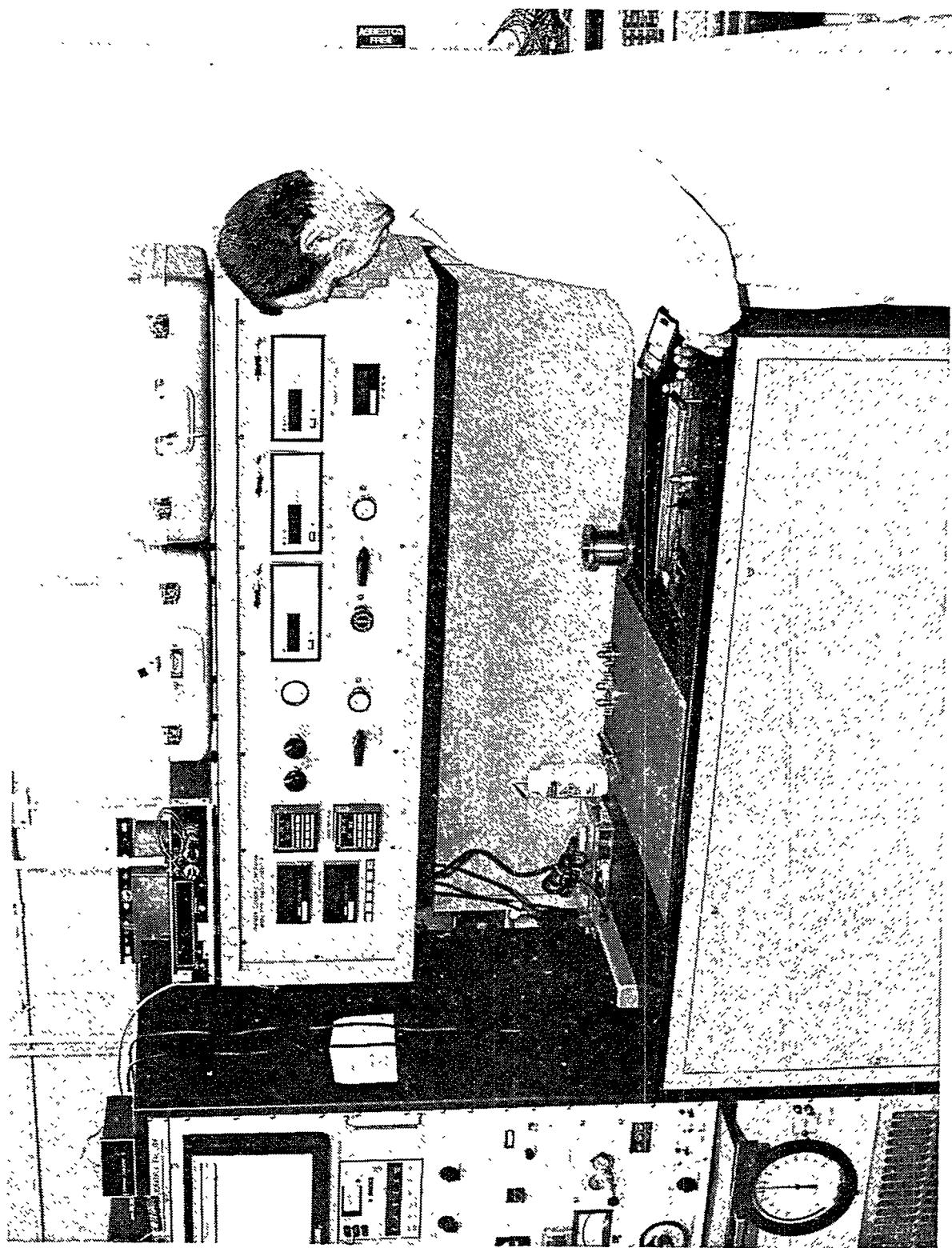
Gas leak devices are calibrated by making direct comparisons to PSL-certified leaks on a mass spectrometer or using the pressure, volume, temperature (PVT) technique. All measurement parameters of the PVT technique are certified and NIST traceable. A precision gas analyzer is used to evaluate the composition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

Viscosity

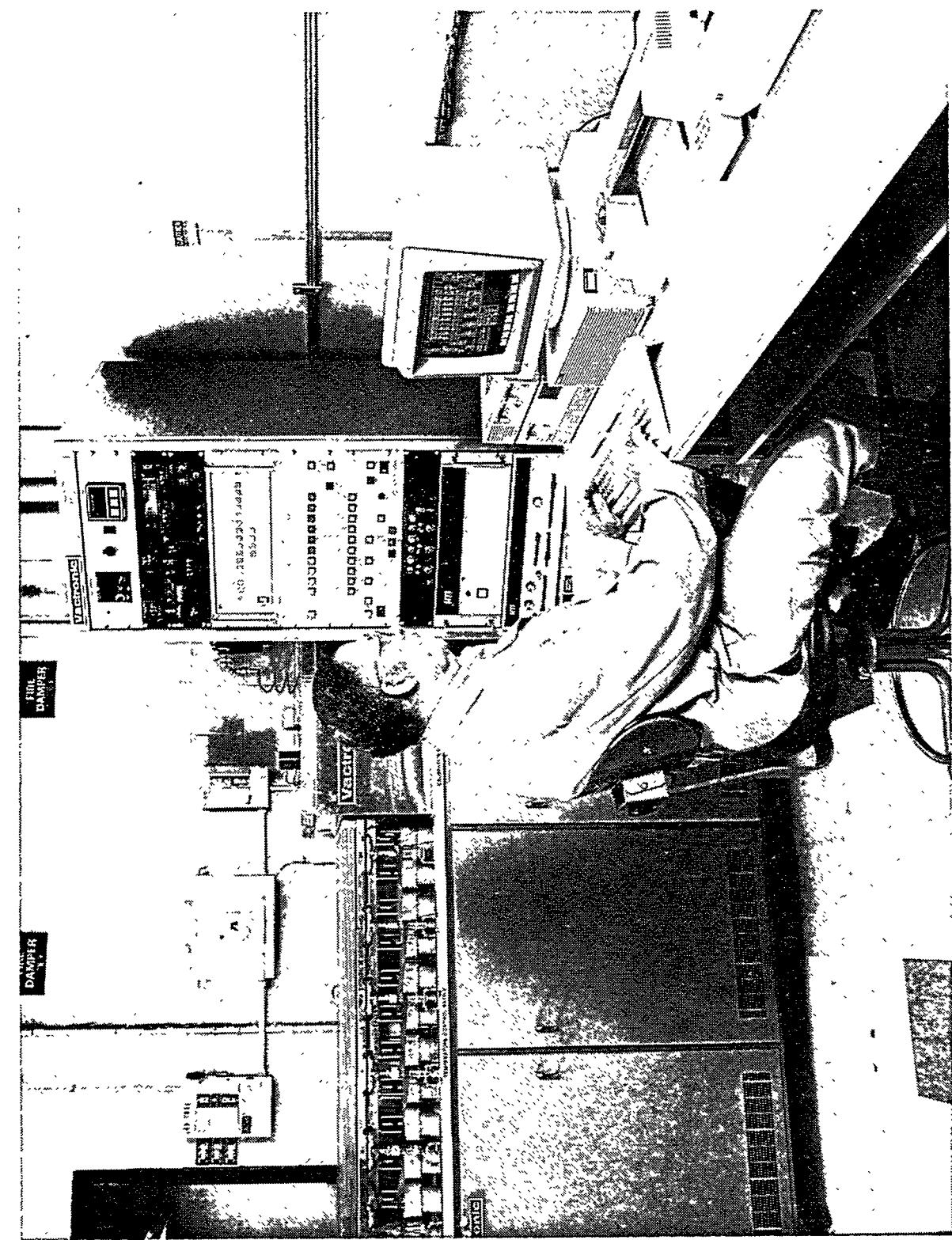
Viscometers are calibrated using standard viscosity oils obtained from the Cannon Instrument Company, a PSL-approved source



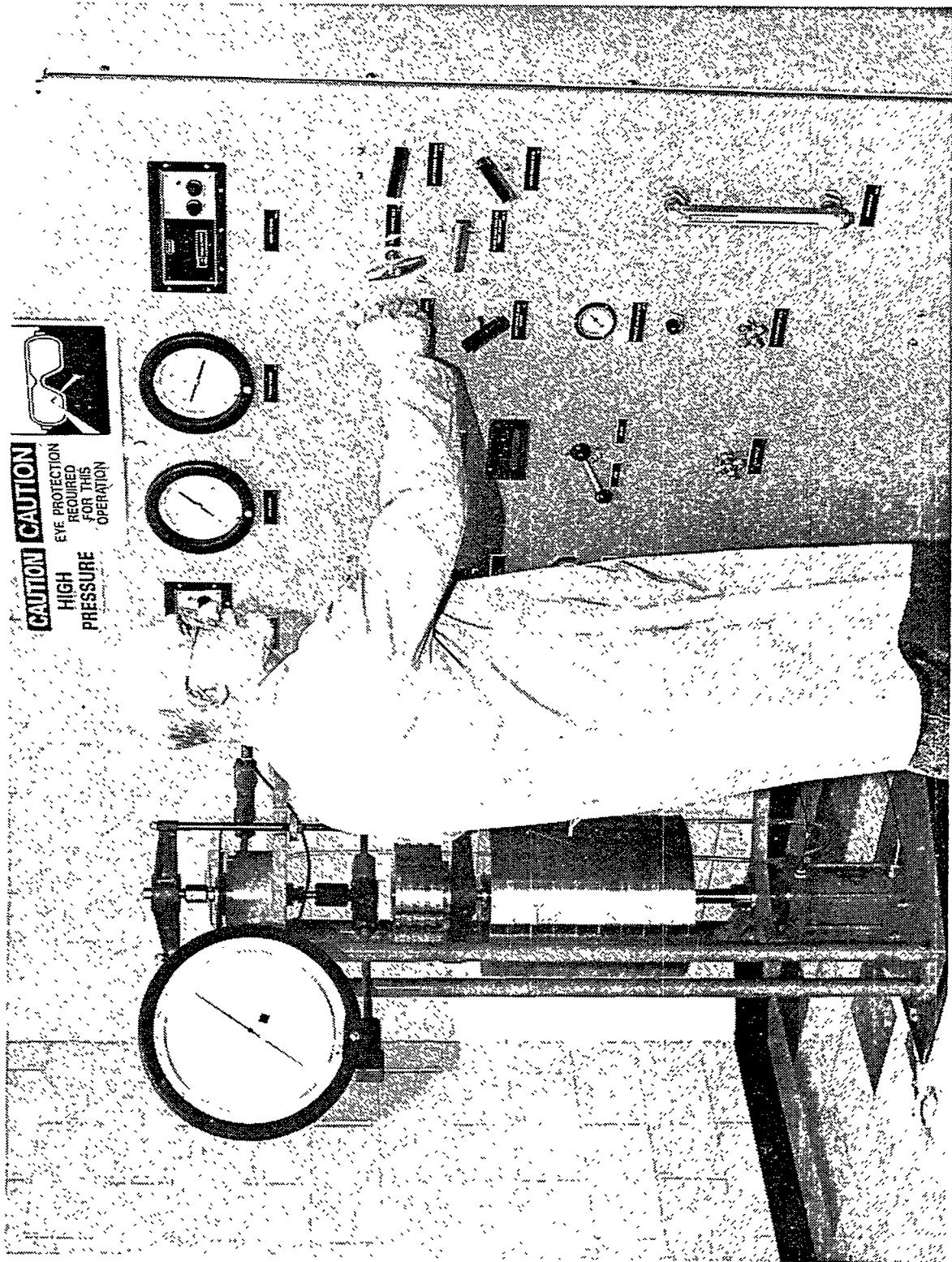
SPRT Calibration Using a Fixed Point Temperature Cell



Humidity Calibration Using the Two-Pressure Method



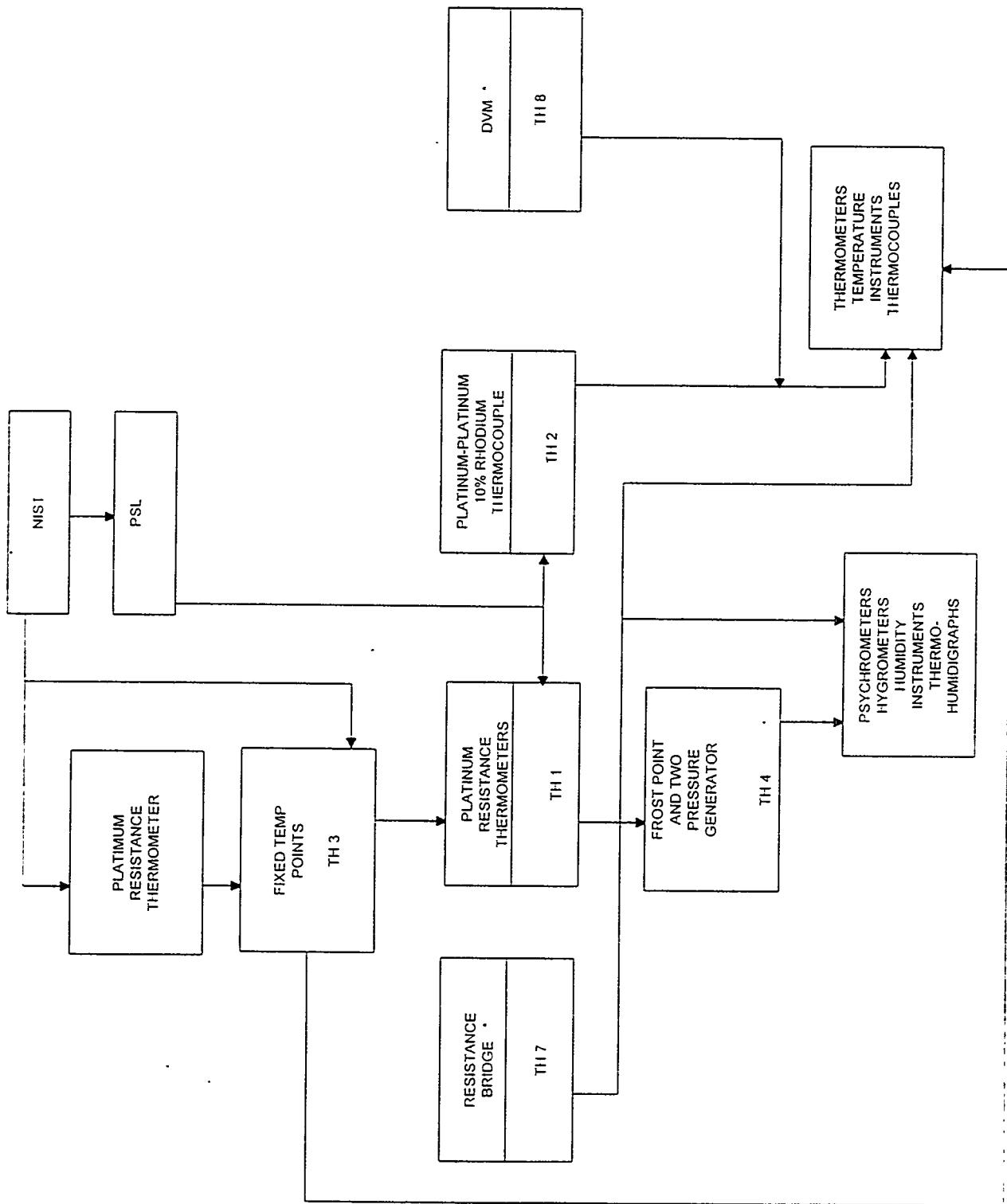
Standard Leak Calibration System



Pressure Calibration Using Controlled Clearance Dead Weight Piston Gage

Table 1B. Environmental Measurement Capability (Temperature, Humidity)

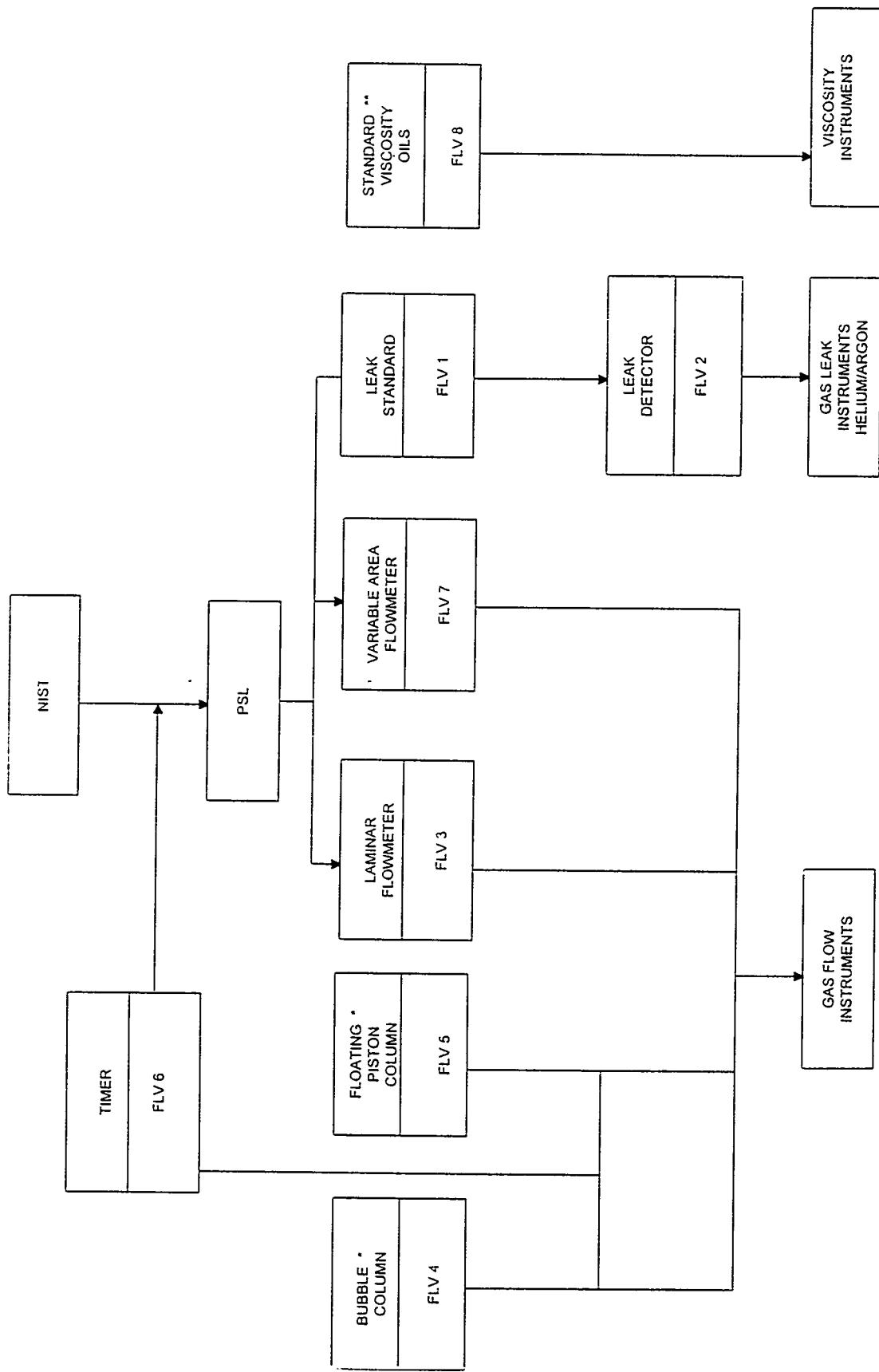
Type	Range	Accuracy (\pm)
Temperature	-183°C to +500°C	0.01°C to 0.05°C
	500°C to 1093°C	0.4% of reading
Fixed Point	-38.8344°C	0.005°C
	0.01°C	0.0005°C
	29.7646°C	0.0005°C
	156.5985°C	0.007°C
	231.928°C	0.008°C
	419.527°C	0.01°C
Humidity	-70°C to 0.0°C	0.5°C
	5% RH to 95% RH	0.5% RH



* Calibrated using Metrology DC voltage, current and resistance standards
 Figure 1B Environmental Calibration Flow Chart

Table 2B. Environmental Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
TH 1	Platinum Resistance Thermometer	Leeds & Northrup	-186 to 0°C	0.05 to 0.02°C
			0 to 100°C	0.02°C
			100 to 500°C	0.02 to 0.05°C
TH 2	Platinum - Platinum 10% Rhodium Thermocouple	Leeds & Northrup	0 to 1100°C	0.5°C or 0.2% of reading (whichever is greater)
TH 3	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
TH 4	Frost Point Generator	Thunder Scientific	-70 to 0°C	0.5°C
	Two-Pressure Generator	Thunder Scientific	5 to 95% RH	0.5% RH
TH 7	Resistance Bridge	Leeds & Northrup	0 to 150 ohms	Resistance 0.004% or 0.0004 Ω with corrections Ratio 0.002% with corrections
TH 8	DVM	Keithley	0 to 1000 Vdc	0.015% of reading + 4 digits



*Calibrated using Metrology mass and dimensional standards

** Source Cannon Instrument Co (approved by PSL)

Figure 2B Gas Leak and Flow Rates, Viscosity Calibration Flow Chart

Table 3B. Gas, Liquid Measuring Capability

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

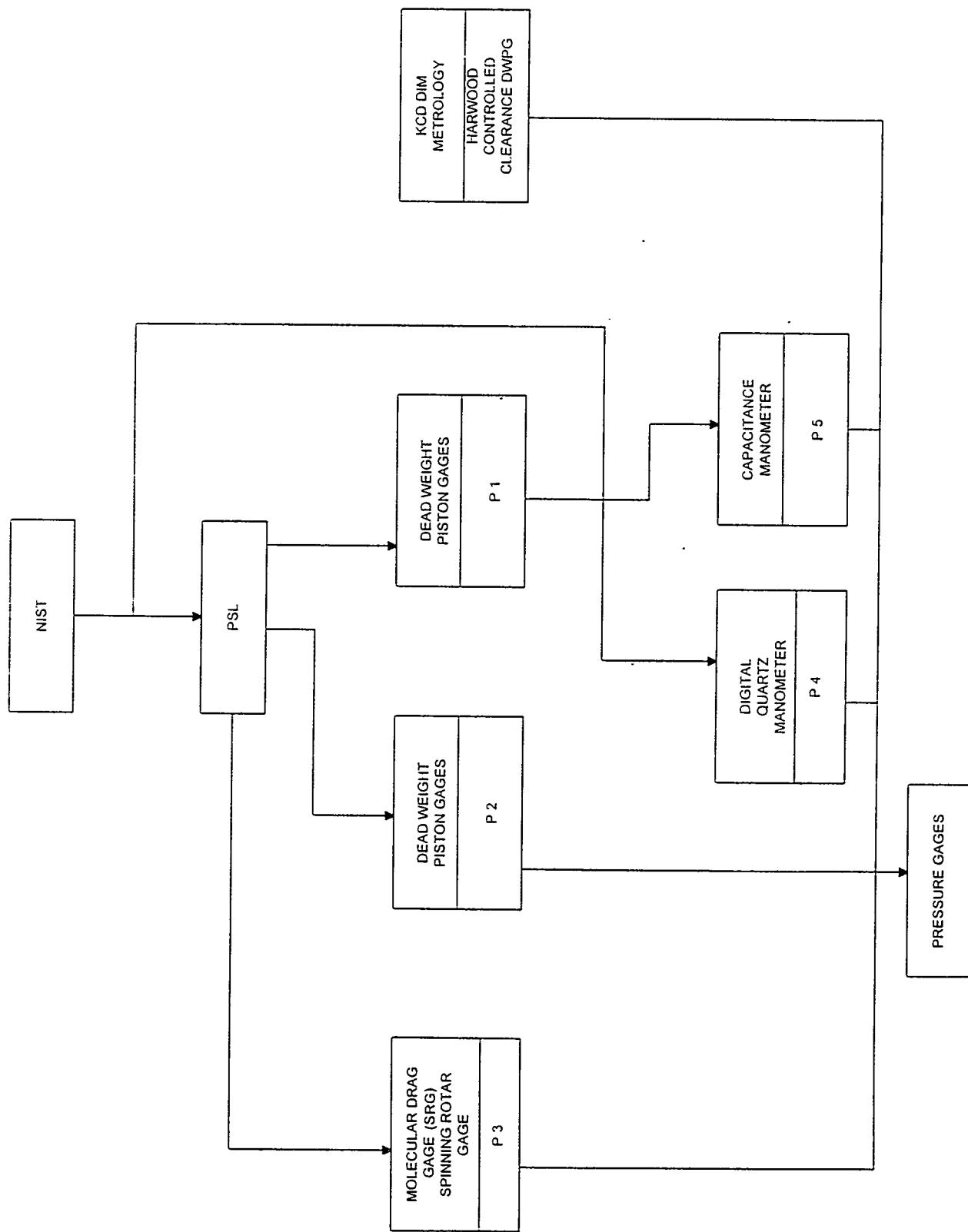


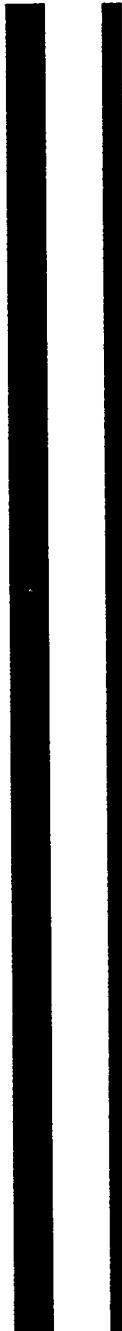
Figure 3B Pressure Calibration Flow Chart

Table 4B. Gas Leak, Gas Flow Rates and Viscosity Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
FLV 1	Leak Standard	Veeco/VIC	1×10^{-7} to 9×10^{-5}	10%
			1×10^{-9} to 9.9×10^{-8}	15%
			2×10^{-10} to 9.9×10^{-10}	20%
FLV 2	Leak Detector	Vactronic	1×10^{-1} to 1×10^{-6} cm^3/s STP	$\pm 5\%$
			1×10^{-6} to 1×10^{-9} cm^3/s STP	$\pm 17\%$
			1×10^{-9} to 2×10^{-10} cm^3/s STP	$\pm 25\%$
FLV 3	Laminar Flowmeter	National Instrument Laboratories CME	4 - 40 SLPM	$\pm 3\%$
			20 - 115 SLPM	$\pm 2\%$
			180 - 1800 SLPM	± 18 SCFM
FLV 4	Bubble Column	Matheson Scientific	Volume 50 cm^3	$\pm 0.05 \text{ cm}^3$
FLV 5	Floating Piston Column	George K. Porter	Volume 400 cm^3	$\pm 0.3 \text{ cm}^3$
			Volume 2000 cm^3	$\pm 0.2\%$
FLV 6	Time	Standard Electric	0 - 999 seconds	$\pm (0.1\%$ $+ 1 \text{ count})$
FLV 7	Variable Area Flowmeter	Fisher & Porter	8 to 23 SCFM	± 0.3 SCFM
FLV 8	Standard Viscosity Oils	Cannon Instrument	0.3 to 5,300,000 $\text{mPa}\cdot\text{s}$	0.4 to 1.2%

Table 5B. Pressure Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
P 1	Piston Gage	CEC	0.2 to 600 psi	0.02%
P 2	Piston Gages	Ruska Harwood	30 to 15,000 psig 20,000 to 200,000 psig	0.03% 0.05%
P 3	Molecular Drag Gage	MKS	10^{-6} torr 10^{-5} torr 10^{-4} torr	10% 6% 10%
P 4	Paroscientific	Paroscientific	0.1 to 350 torr 350 to 1100 torr	$\pm(0.01 + 0.00016 * \text{reading})$ $\pm(0.04 + 0.00016 * \text{reading})$
P 5	Capacitance Manometer	MKS	10^{-3} to 0.05 torr 0.05 to 1 torr 1 to 1000 torr	± 0.0005 torr ± 0.001 torr $\pm 0.2\%$ of reading



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 15 amperes are made using resistance and voltage standards. Shunts calibrated by the Primary Standards Laboratory are used for current measurements from 15 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

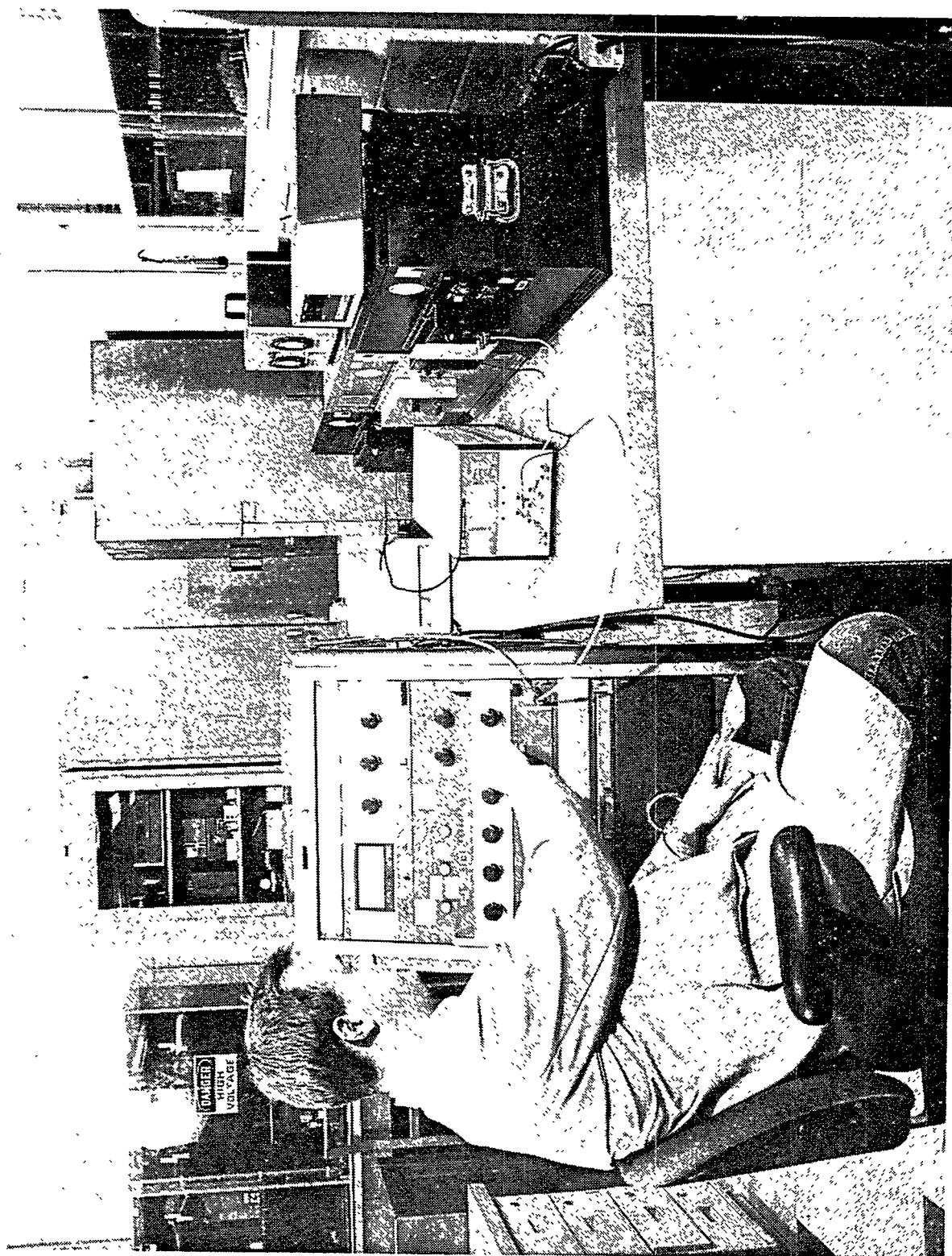
AC Voltage

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.

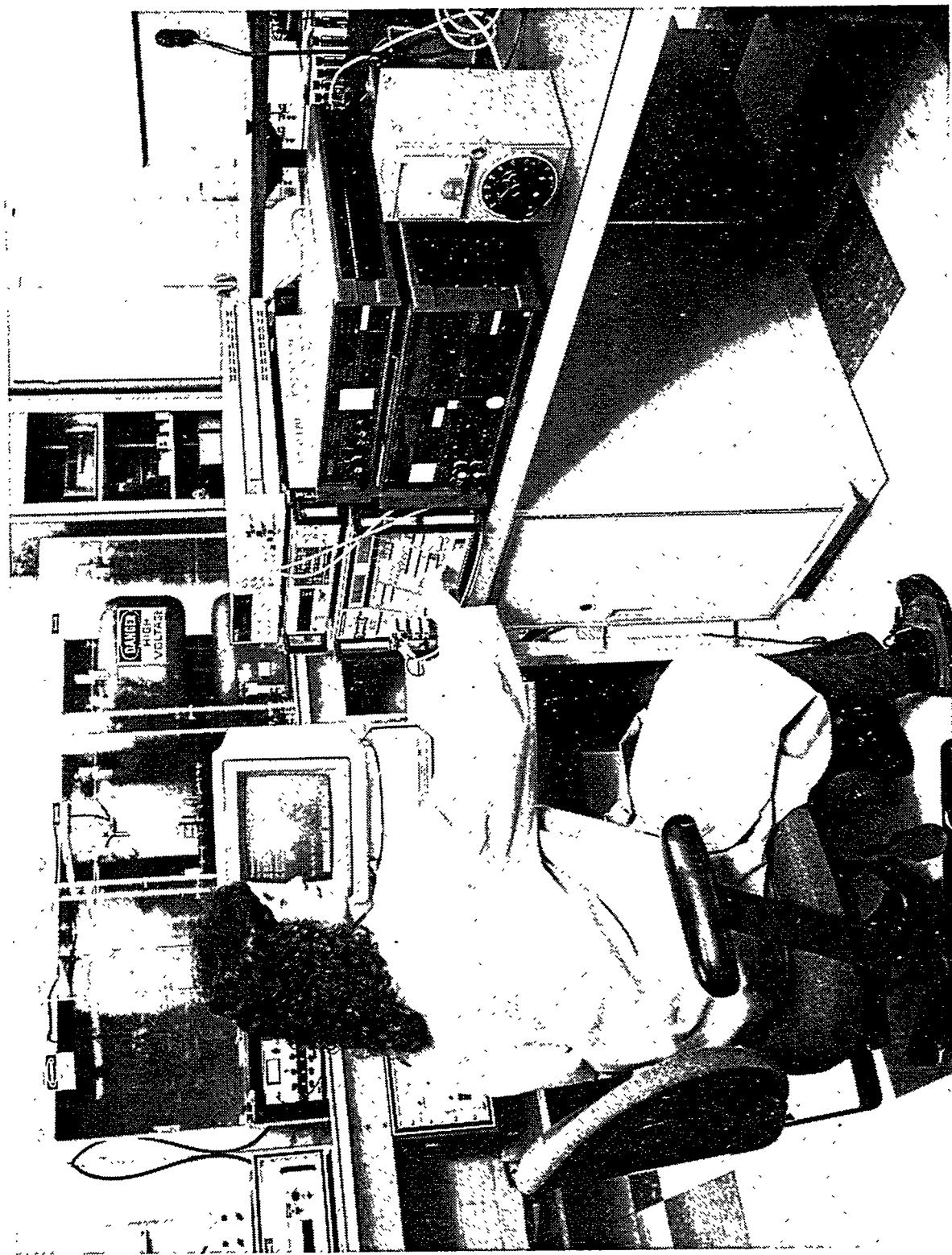
Test thermal voltage converter devices can be calibrated for AC-DC difference by direct comparison of their response to the response of the standard thermal voltage converter devices.

AC Current

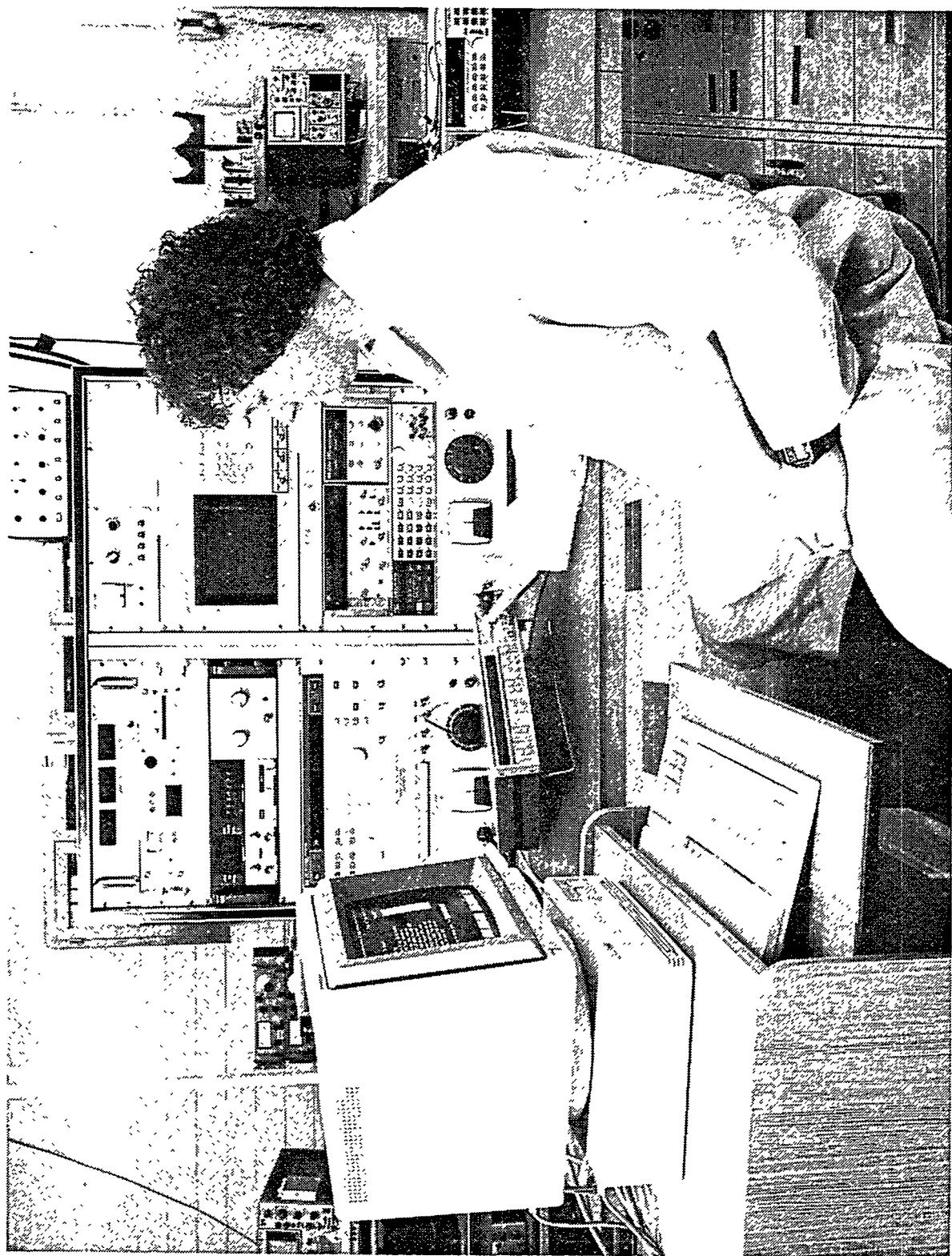
AC current sources are calibrated using a known DC current and standard current shunts certified by Primary Standards Laboratory. Current levels lower than 10 mA are calibrated using standard AC resistors. The shunts are terminated with a standard thermal voltage converter certified for AC-DC difference 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 $\pm 0.02\%$; inductance uncertainties range upward from $\pm 0.03\%$.

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 checked periodically for accuracy 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 certified 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 PSL-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

Table 1C. Electrical Direct Current Measurement Capability

Type	Range	Accuracy (\pm)
DC Voltage	0 to 0.016 V	20 ppm + 0.1 μ V
	0.016 to 0.16 V	15 ppm + 0.5 μ V
	0.16 to 1.6 V	10 ppm + 5 μ V
	1.6 to 1500 V	0.0025%
	1.5 to 10 kV	0.04%
	>10 to 100 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 10 A	0.007%
	>10 to 100 A	0.03%
	>100 to 300 A	0.05%
DC Resistance	10^{-4} to 10^{-1} ohms	0.007%
	10^0 to 10^7 ohms	0.005%
	> 10^7 to 10^8 ohms	0.01%
	> 10^8 to 10^9 ohms	0.2%
	10^{10} to 10^{12} ohms	0.5%
	> 10^{12} to 10^{13} ohms	1.0%
DC Magnetic Field Density	Transverse Probe: 20 to 10,000 Gauss	3 - 7.5%
	Axial Probe: 40 to 500 Gauss	3 - 7.5%

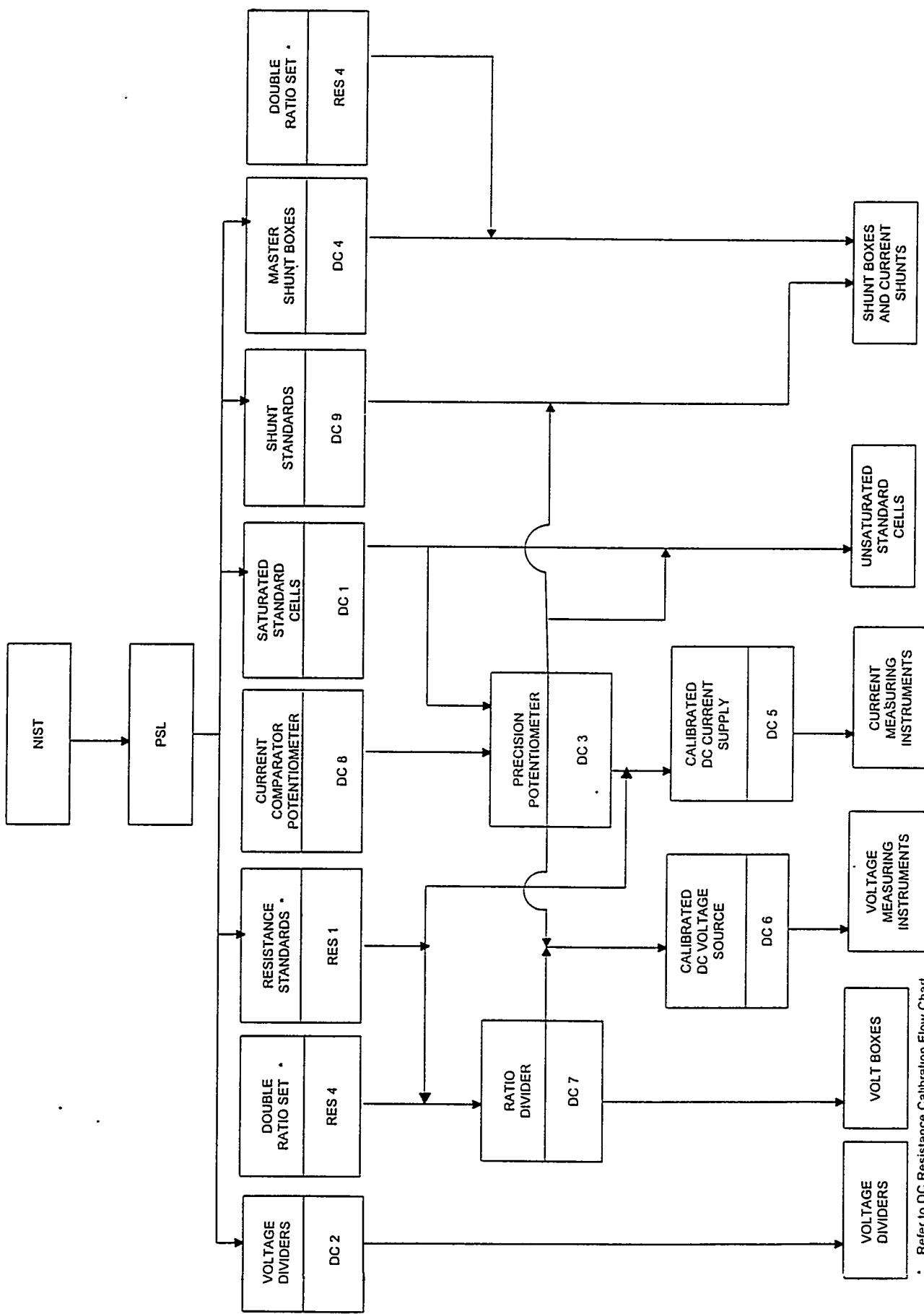


Figure 1C. DC Current and Voltage Calibration Flow Chart

Refer to DC Resistance Calibration Flow Chart

Table 2C. DC Current and Voltage Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
DC 1	Saturated Standard Cells	Eppley/Muirhead	1.018 V nominal	6 μ V
DC 2	Voltage Dividers	Julie Fluke	10 to 100 kV 1 to 10 kV	0.05% 0.025%
DC 3	Precision Potentiometer	Leeds & Northrup	0 to 1.6 V	15 ppm + 0.05 μ V to 5 ppm + 2 μ V
DC 4	Master Shunt Boxes	Leeds & Northrup	0.015 to 15 A	0.005%
DC 5	Calibrated DC Current Supply	KCD Metrology	1.5 μ A to 15 A (7 ranges)	0.02% + 1 nA
DC 6	Calibrated DC Voltage Source	Fluke	1 to 1000 V (3 ranges)	0.005% or 20 μ V, whichever is greater
DC 7	Ratio Divider	Guildline	1:1 to 10,000:1	0.001%
DC 8	Current Comparator Potentiometer	Guildline	X 1 Range X 0.1 Range X 0.01 Range	1 ppm + 0.1 μ V 2 ppm + 0.02 μ V 4 ppm + 0.01 μ V
DC 9	Shunt Standards	Leeds & Northrup	0 to 100 A 0 to 300 A	0.02% 0.03%

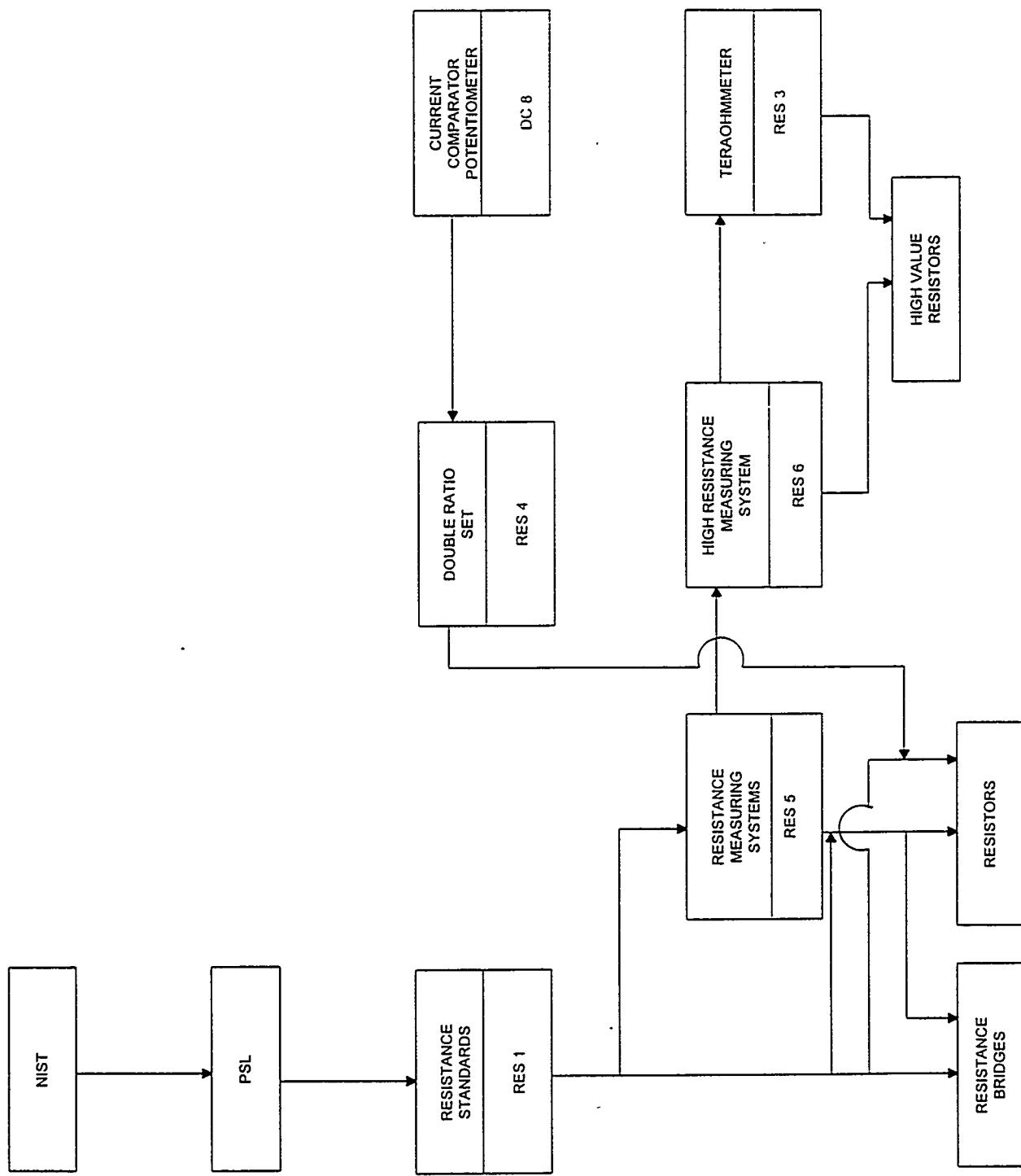


Figure 2C DC Resistance and Ratio Calibration Flow Chart

Table 3C. DC Resistance and Ratio Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
RES 1	Resistance Standard	Leeds & Northrup Julie, Guildline	0.001 ohm to 100 megohm	0.002 to 0.01%
RES 3	Teraohmmeter	Guildline	10^7 to 10^{13} megohm	0.1 to 1%
RES 4	Double Ratio Set/Direct Reading Ratio Set	Leeds & Northrup	0.0001 ohm to 1 megohm	0.002% (DRS) 0.0002% (DRRS)
RES 5	Resistance Measuring System	ESI	0.001 ohm to 10 megohm 10 to 100 megohm	0.005% + M x 0.005 ohm 0.01% + M x 0.005 ohm (M = range multiplier)
RES 6	High-Resistance Measuring System	Mid-Eastern	10^8 to 10^{13} ohms	0.3% to 0.5%

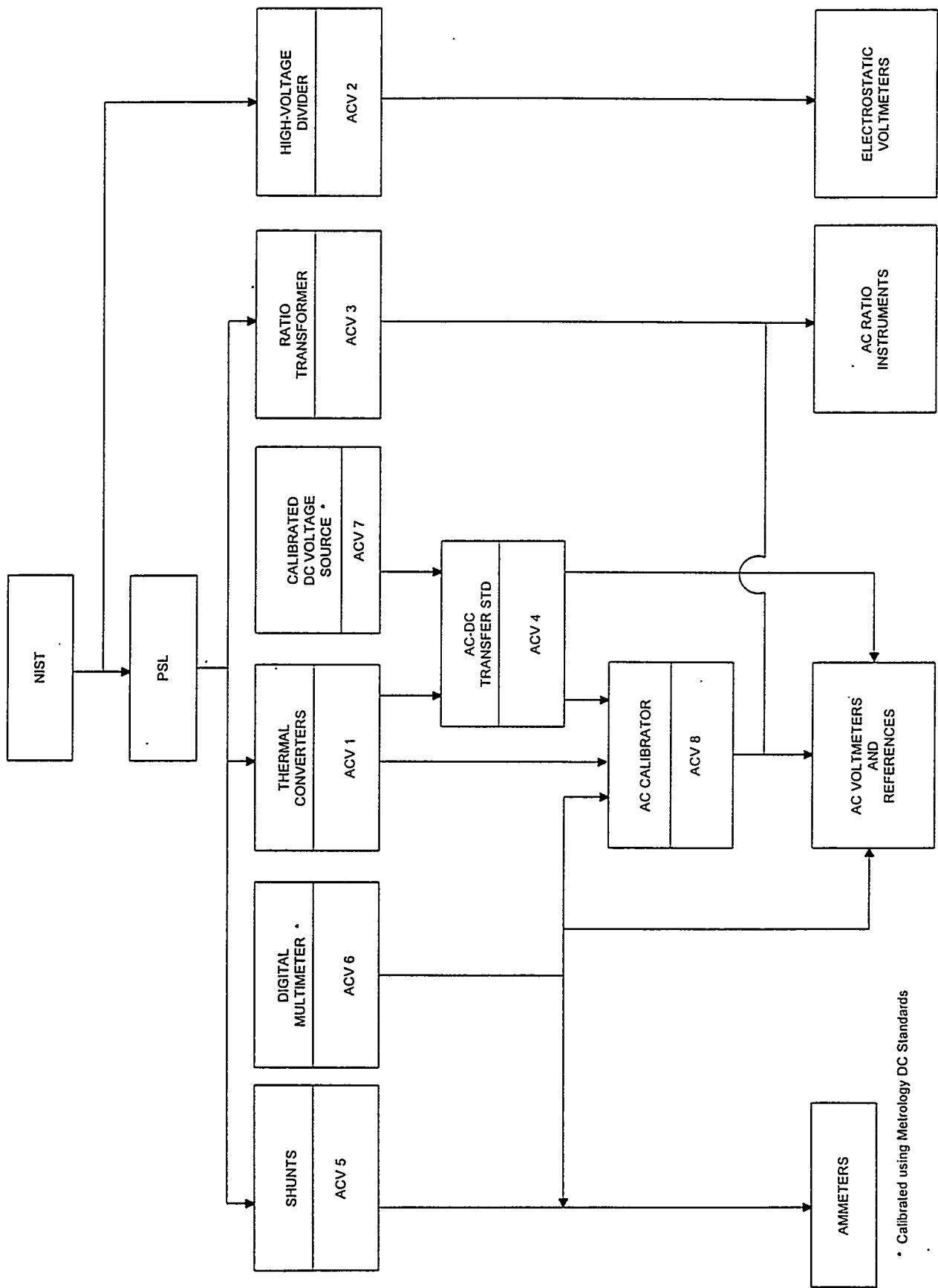


Figure 3C. AC Current and voltage, and Ratio Calibration Flow Chart

• Calibrated using Metrology DC Standards

Table 4C. Electrical Alternating Current Measurement Capability

Type	Range	Frequency	Measuring Accuracy (\pm)
AC Voltage*	0.1 to 1000 V	10 Hz to 50 kHz	100 ppm
	0.1 to 1000 V	50 kHz to 100 kHz	150 ppm
	0.1 to 30 V	100 kHz to 1 MHz	850 ppm
	1 to 70 kV	60 Hz	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 μ F	1 kHz	0.01 + 0.00005 pF
	1 to 10 μ F	1 kHz	0.02%
	10 to 100 μ F	1 kHz	0.5%
	1.0 to 1000 pF	1 MHz	0.1 to 0.2%
Inductance**	0.05 to 2 μ H	10 kHz to 1 MHz	0.7% to 12%
	2 to 100 μ H	10 kHz to MHz	0.7% to 3%
	100 μ H to 10 H	1 kHz	0.04% to 0.4%
Frequency	1 Hz to 18 GHz		1 part in 10^9
Time of Day			1.0 second

*Accuracy depending on range and frequency

**Accuracy depending on inductance and frequency

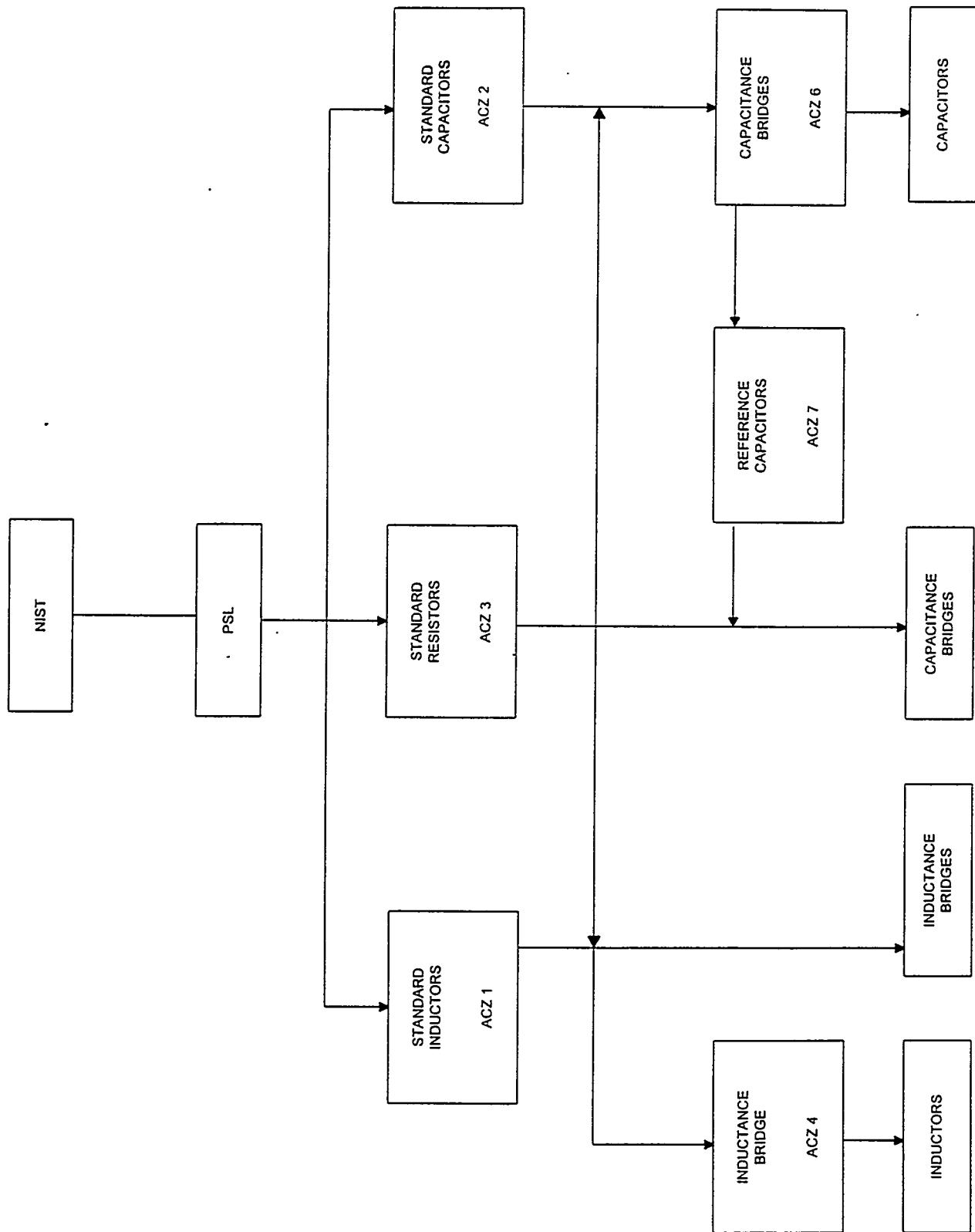


Figure 4C Inductance and Capacitance Calibration Flow Chart

Table 5C. AC Current, Voltage, and Ratio Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
ACV 1	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%
ACV 2	High Voltage Dividers	Julie	1 to 100 kV	0.25%
ACV 3	Inductive Ratio Divider	ESI	Ratio only, 0.1 ppm resolution 50 Hz to 10 kHz	1 to 150 ppm
ACV 4	AC-DC Transfer Standard	Datron	100 mV to 1000 V 10 Hz to 50 kHz	100 ppm
			100 mV to 1000 V 50 kHz to 100 kHz	150 ppm
			100 mV to 30 V 100 kHz to 1 MHz	850 ppm
			10 mA to 20 A 10 Hz to 50 kHz	0.05 to 0.07%
ACV 5	Shunts	Holt	100 mV Range	0.005% or 5 digits, whichever is greater
			1 to 1000 V Ranges	0.005% or 8 digits, whichever is greater
ACV 6	Digital Multimeter	Fluke	10 to 1000 V three ranges	0.005% or 20 μ V, whichever is greater
ACV 7	Calibrated DC Voltage Source	Fluke		

Table 5C Continued. AC Current, Voltage, and Ratio Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
ACV 8	AC calibrator	Hewlett-Packard	1 mV to 100 V Range 10 to 20 Hz	0.2% of setting + 0.005% of range + 50 μ V
			20 to 50 Hz	0.05% of setting + 0.005% of range + 50 μ V
			50 Hz to 20 kHz	0.02% of setting + 0.002% of range + 10 μ V
			20 to 110 kHz	0.05% of setting + 0.005% of range + 50 V
			1000 V Range 10 to 20 Hz	0.2% of setting + 0.005% of range
			20 to 50 Hz	0.08% of setting
			50 Hz to 20 kHz	0.04% of setting
			20 kHz to 50 kHz	0.08% of setting
			50 kHz to 110 kHz	0.15% of setting

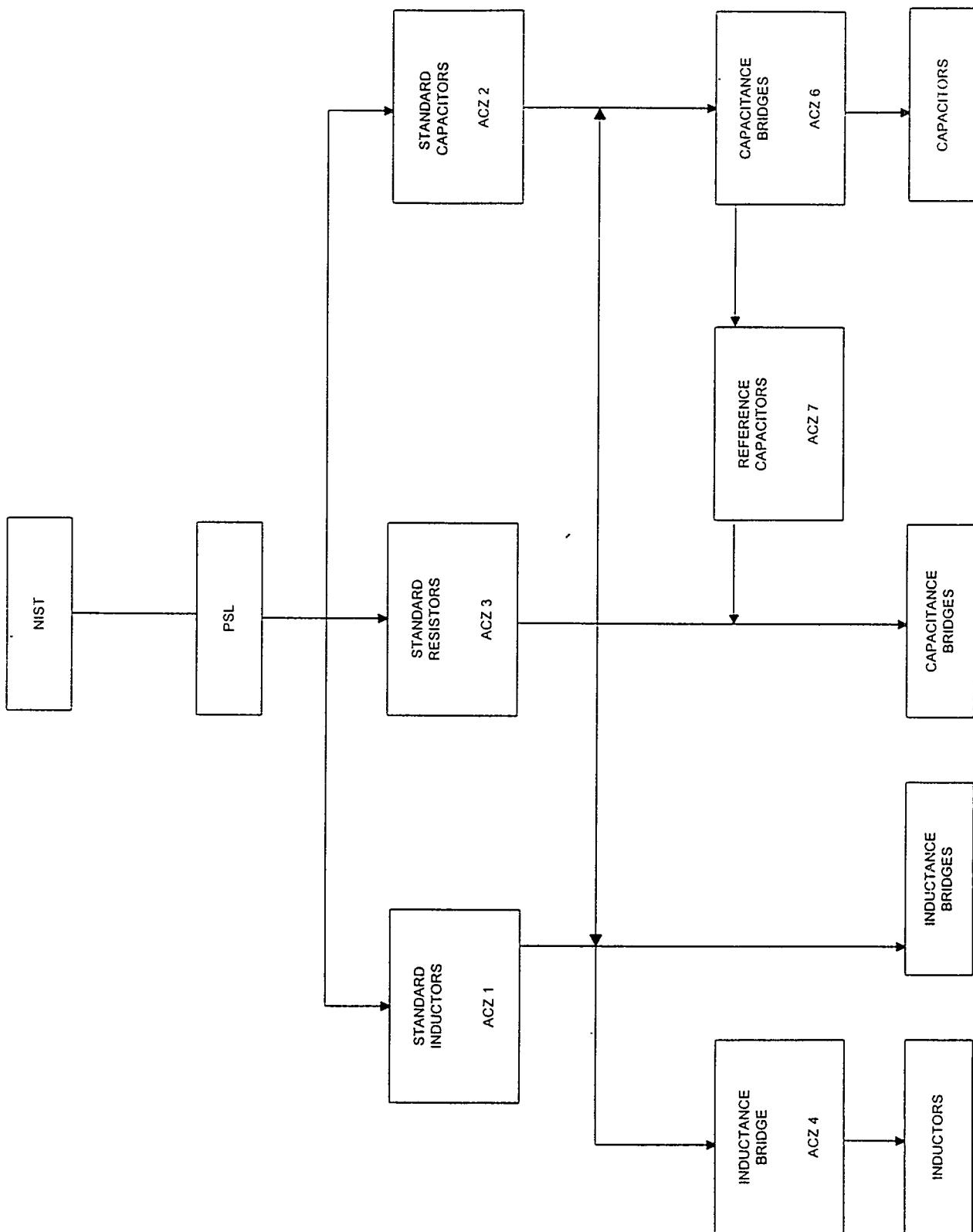


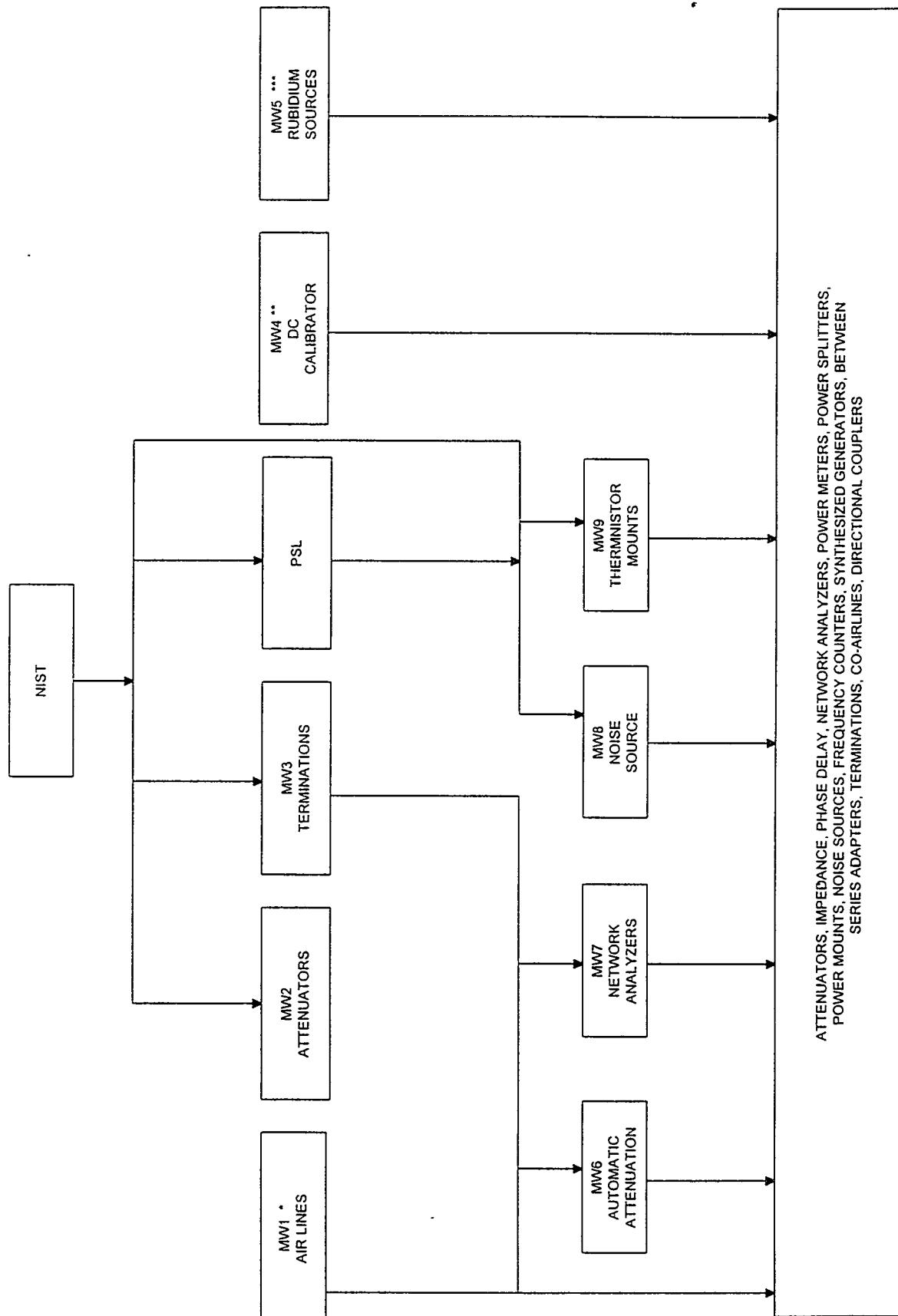
Figure 5C Frequency and Time Calibration Flow Chart

Table 6C. Inductance, Capacitance, and AC Resistance Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
ACZ 1	Standard Inductors	General Radio, AlliedSignal, Hewlett-Packard, Boonton	50 μ H to 10 H 50 nH to 100 μ H	0.03 to 0.3%* 0.3 to 10%*
ACZ 2	Standard Capacitors	General Radio	1000 pF, fixed	0.004% @ 1 kHz
ACZ 3	Standard Resistors	Leeds & Northrup	1 to 20K ohms	0.015%
ACZ 4	Inductance Bridge	Hewlett-Packard	100 μ H to 5H 0.05 μ H to 10 μ H	0.15 to 0.3% (direct measurement) 0.1 to 10% (comparison to standard inductors)
ACZ 6	Capacitance Bridge	General Radio Hewlett Packard	0.001 pF to 1 μ F 1 μ F to 10 μ F 0.1 to 1000 pF	0.01% + 0.00005 pF 0.02% (at 1 kHz) 0.1% at 1 kHz 0.2% at 1 MHz
ACZ 7	Reference Capacitors	General Radio General Radio KCD Metrology	0.1 to 1000 pF 0.001 to 1 μ F 1 to 10 μ F in 1 μ F increments 10 to 100 μ F in 10 μ F increments	0.1 to 0.15%** 0.02% @ 1 kHz 0.1% @ 1 kHz 0.25% @ 1 KHz

*Accuracy depending on inductance value and frequency

**Accuracy depending on capacitance value and frequency



- * Dimensional Calibration
- ** DC Calibration
- *** AC Calibration

Figure 6C Radio Frequency/Microwave Calibration Flow Chart

Table 7C. Frequency and Time Code Description

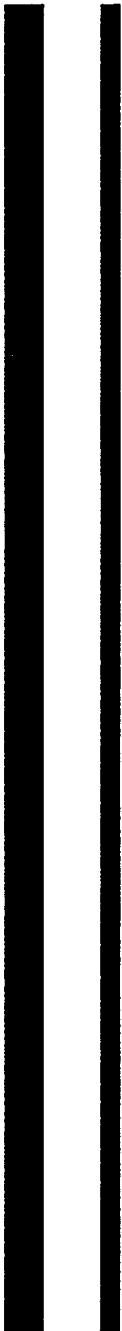
Code	Description	Manufacturer	Range	Accuracy (\pm)
FT 1	WWV Receiver	Kinematics	5, 10, 15 MHz	Comparison device
FT 2	VLF Receiver and Comparator	Kinematics	60 kHz	Comparison device
FT 3	Rubidium Oscillator	Efratom	0.1 MHz to 10 MHz	1 part in 10^9
FT 4	Electronic Counter	Hewlett-Packard	0 to 18 GHz	\pm (1 part in 10^9 + 2 counts)
FT 5	Digital Clock	AlliedSignal KCD	24 hours	1 second

Table 8C. Electrical Radio Frequency/Microwave Measurement Capability

Type	Range	Frequency	Measuring Accuracy (\pm)
Attenuation	0 - 80 dB	0.01 - 1.999 GHz	(0.03 dB or 0.03 dB/10 dB)*
	0 - 90 dB	0.01 - 1.0 GHz	(0.03 dB or 0.03 dB/10 dB)*
	0 - 100 dB	0.01 - 0.03 GHz	(0.03 dB or 0.03 dB/10 dB)*
	0 - 80 dB	2 - 8 GHz	(0.04 dB or 0.04 dB/10 dB)*
	0 - 60 dB	8 - 18 GHz	(0.06 dB or 0.06 dB/10 dB)*
			*Whichever is greater plus mismatch
RF Power	10 microwatt - 100 mW	1 - 10 MHz	6 - 7%
	1 mW	1 MHz - 8.5 GHz	1.0 - 2.5%
	10 microwatt - 10 mW	10 MHz - 8.5 GHz	2.3 - 3.0%
	1 nW - 10 microwatt	10 MHz - 8.5 GHz	3.8 - 6.0%
	10 mW - 100 mW	10 MHz - 8.5 GHz	6 - 7%
	10 microwatt - 10 mW	10, 12, 15, 18 GHz	4 - 5%
	30 mW - 12 W	1509.5 MHz and 2.2 - 2.3 GHz	4.0%
RF Reflection Coefficient	0.0 - 1.0	1 - 1000 MHz	0.005 - 0.012**
	0.0 - 0.8	0.5 - 8.5 GHz	0.0021 - 0.05**
	0.0 - 0.333	8 GHz - 18 GHz	0.001 - 0.2**
			**Reflection coefficient magnitude (SWR calculated)

Table 9C. Radio Frequency and Microwave Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
MW 1	Air Lines	General Radio Maury Microwave Hewlett-Packard Alford	2.4 mm, 3.5 mm 7 mm, 14 mm 50 MHz to 50 GHz	$ Z \pm 0.050$ to 0.35Ω $ \Gamma \leq 0.0008$ to 0.0045 $EL \pm 0.0036$ to 0.0211 cm
MW 2	Attenuators	Weinschel Engr. Hewlett-Packard	30 MHz to 50 GHz 0 dB to 120 dB	± 0.03 to 1.0 dB
MW 3	Terminations	General Radio Maury Microwave Hewlett-Packard Wiltron	300 KHz to 50 GHz	$ \Gamma \pm 0.005$ to 0.3000 $\phi \pm 0.20$ to 180°
MW 4	DC Calibrator	Hewlett-Packard	1 nW to 100 mW	$\pm 0.25\%$
MW 5	Rubidium Source	Efratom	10 MHz	± 0.001 ppm
MW 6	Automatic Attenuation System	Weinschel Engr. Hewlett-Packard	10 MHz to 50 GHz 0 dB to 100 dB	± 0.03 to 1.0 dB
MW 7	Automatic Network Analyzers	Hewlett-Packard KCD Metrology	1 MHz to 50 GHz $ \Gamma 0.0$ to 1.0 $\phi 0.0$ to 360°	$ \Gamma \pm 0.002$ to 0.2 $\phi \pm 0.8$ to 180°
MW 8	Noise Source	Hewlett-Packard	60 Hz to 3.55 GHz	± 0.1 to 0.35
MW 9	Thermistor Mounts	Hewlett-Packard	1 MHz to 18 GHz	± 0.3 to 3.0%



OPTICAL AND RADIATION

Optical Radiometric Measurement Capability

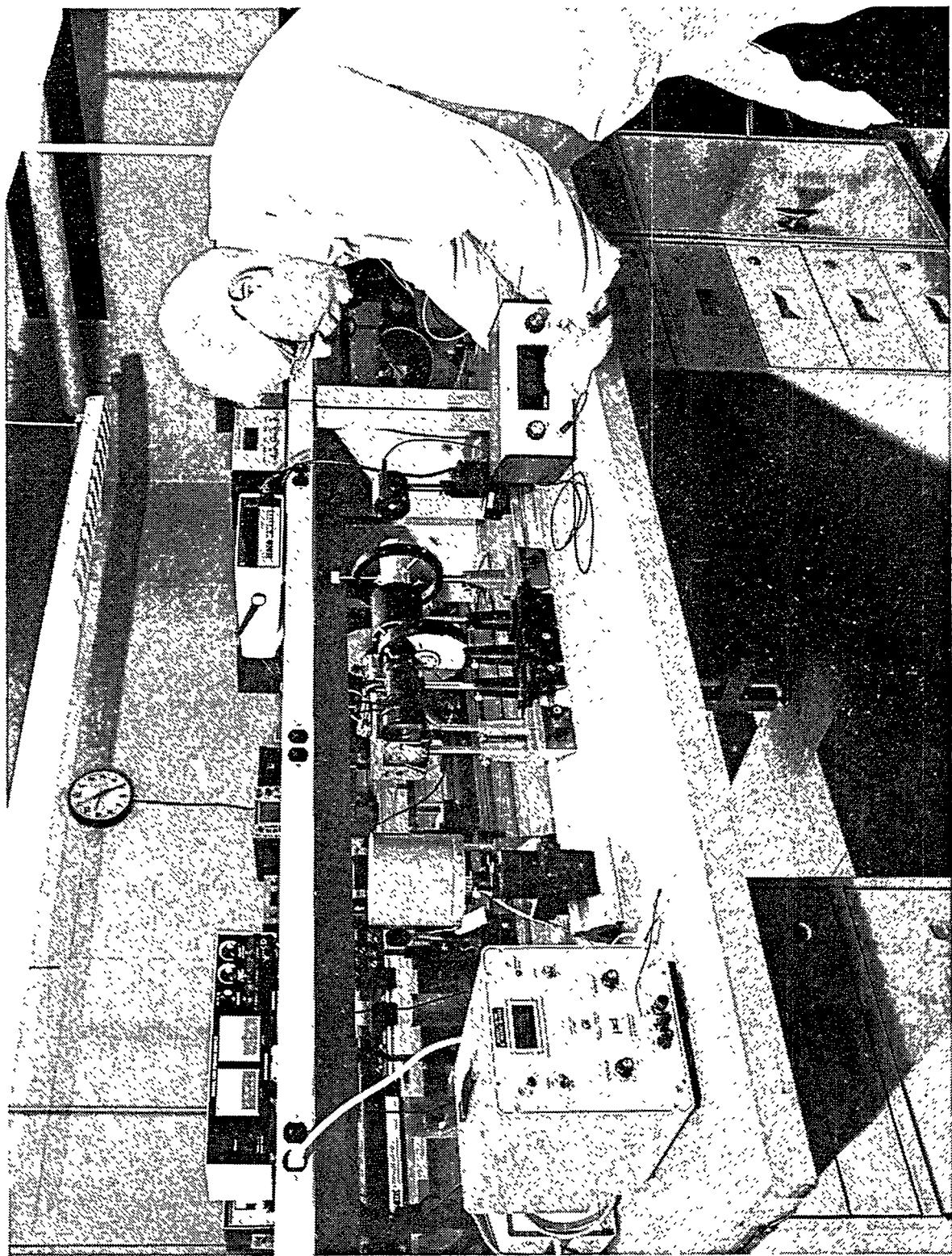
Radiometry is the measurement of radiation in the optical spectrum which includes ultraviolet, visible, and infrared light. The main radiometric reference standards at KCD are heat-flow calorimeters and wavelength standards which include HeNe lasers and Hg lamps. The heat flow calorimeters are calibrated 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 CO₂ 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 μ m. Most of the radiometric calibration activity at AlliedSignal Inc., Kansas City Division, is measuring the power output and characteristics of lasers in CW or pulsed modes of operation.

Optical Photometric Measurement Capability

Photometry is the measurement of visible light intensity and energy as it affects the human eye. Photometric reference standards at KCD 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 Capability

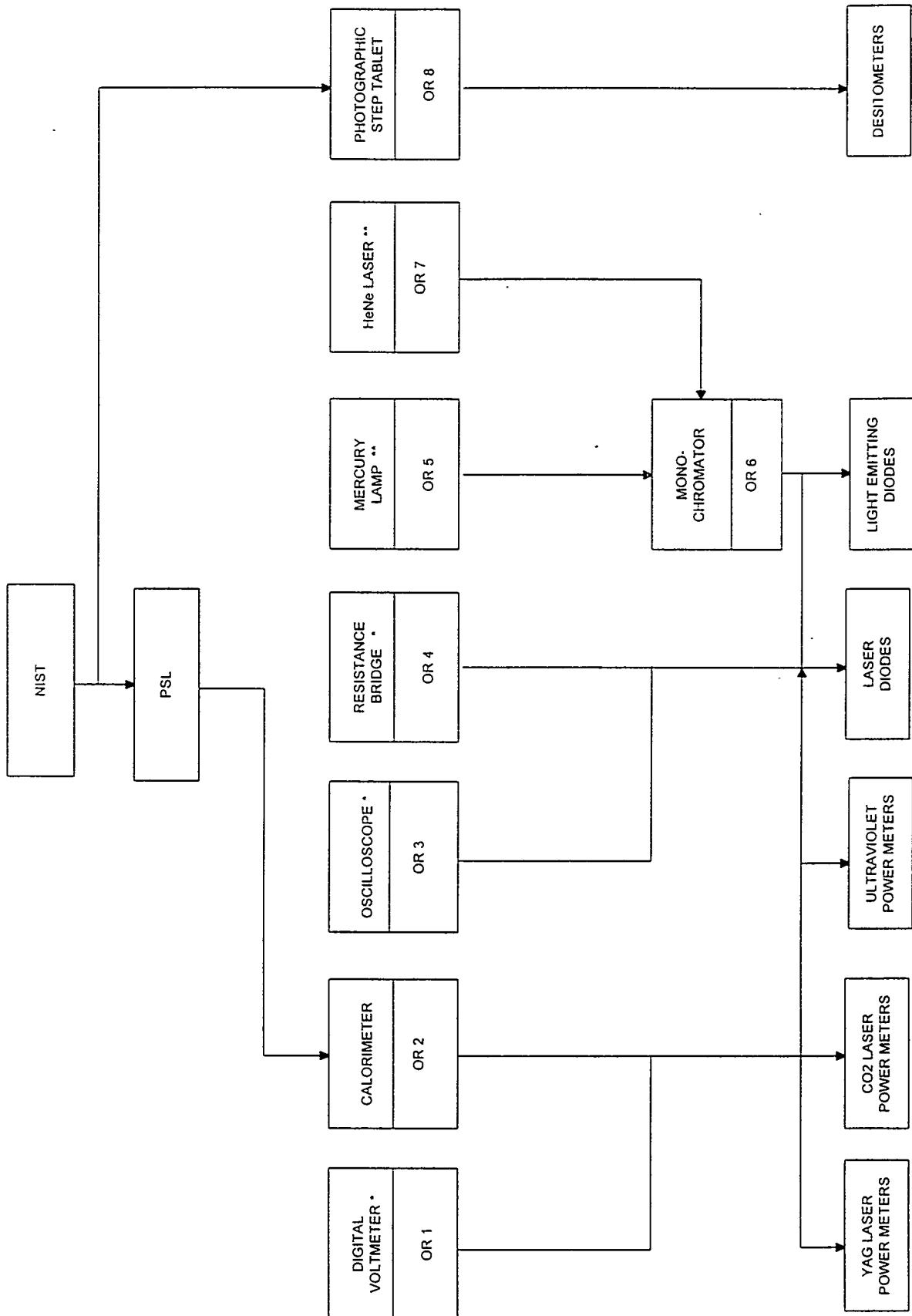
Radiation measurements are made using standards of alpha-particle emission rate from plutonium 239 and lead-probe neutron detectors. Alpha sources and lead probes are calibrated by the PSL. Accuracy of these standards ranges from $\pm 3\%$ to $\pm 10\%$.



Photodiode Detector Calibration

Table 1D. Optical Radiometric Measurement Capability

Type	Range	Measuring Accuracy (\pm)
Optical Transmittance	$\lambda = 350$ to 400 nm	2%
	$\lambda = 400$ to 500 nm	1%
	$\lambda = 500$ to 1000 nm	0.5%
Optical Spectral Response	350 to 400 nm	5%
	400 to 500 nm	1.5%
	500 to 1000 nm	2%
Laser Average Power	$\lambda = 516$ nm to 1.064 μ m	
	1 to 100 μ W	5%
	100 μ W to 1 mW	4%
	1 mW to 10 W	3%
	$\lambda = 1.064$ μ m	
	10 to 100 W	6%
	$\lambda = 10.6$ μ m	
	1 mW to 10 W	
	10 to 1000 W	6%
Laser Peak Power	$\lambda = 514$ to 633 nm	
	Pulse width 50 ns to 1 ms	
	1 to 10 W	7%
	$\lambda = 1.064$ μ m	
	Pulse width 50 ns to 1 ms	
LED Power	0.1 to 10 W	9%
	10 W to 10 kW	20%
	$\lambda = 570$ to 910 nm	
X-Ray Film Density	10 μ W to 10 mW (CW)	5%
	$\lambda = 890$ to 905 nm	
	Pulse width 50 ns to 200 ns	8%
Ultraviolet Irradiance	1 to 75 W	
	$\lambda = 365$ nm	5%
X-Ray Film Density	0.1 to 10 mW/cm ²	
	0 to 4 Optical Density Units	(0.03 density units + 1% of reading)



- Calibrated using Metrology standards
- Independently Reproducible Standard

Figure 1D Optical Calibration Flow Chart (Radiometric)

Table 2D. Optical Radiometric Measurements Code Description

Code	Description	Manufacturer	Range	Accuracy (\pm)
OR 1	Digital Voltmeter	Various	1 mV to 1000 V	0.01% to 5 digits
OR 2	Calorimeter	Scientech	10 μ W to 10 W	1.1%
OR 3	Oscilloscope	Hewlett-Packard	1 mV to 100 V 5 ms/div. to 0.1 s/div.	3%
OR 4	Resistance Bridge	ESI	1 ohm to 100 megohm	(0.01% + 0.005) times multiplier
OR 5	Mercury Lamp	Oriel	365 to 1092.2 nm	< 1 nm
OR 6	Monochromator	Jarrell Ash	365 to 1092.2 nm	1 nm
OR 7	HeNe Laser	Various	6328 angstroms	< 1 angstrom
OR 8	Photographic Step Tablet	NIST	0 to 4 density units	0.01 unit or 1% whichever is greater

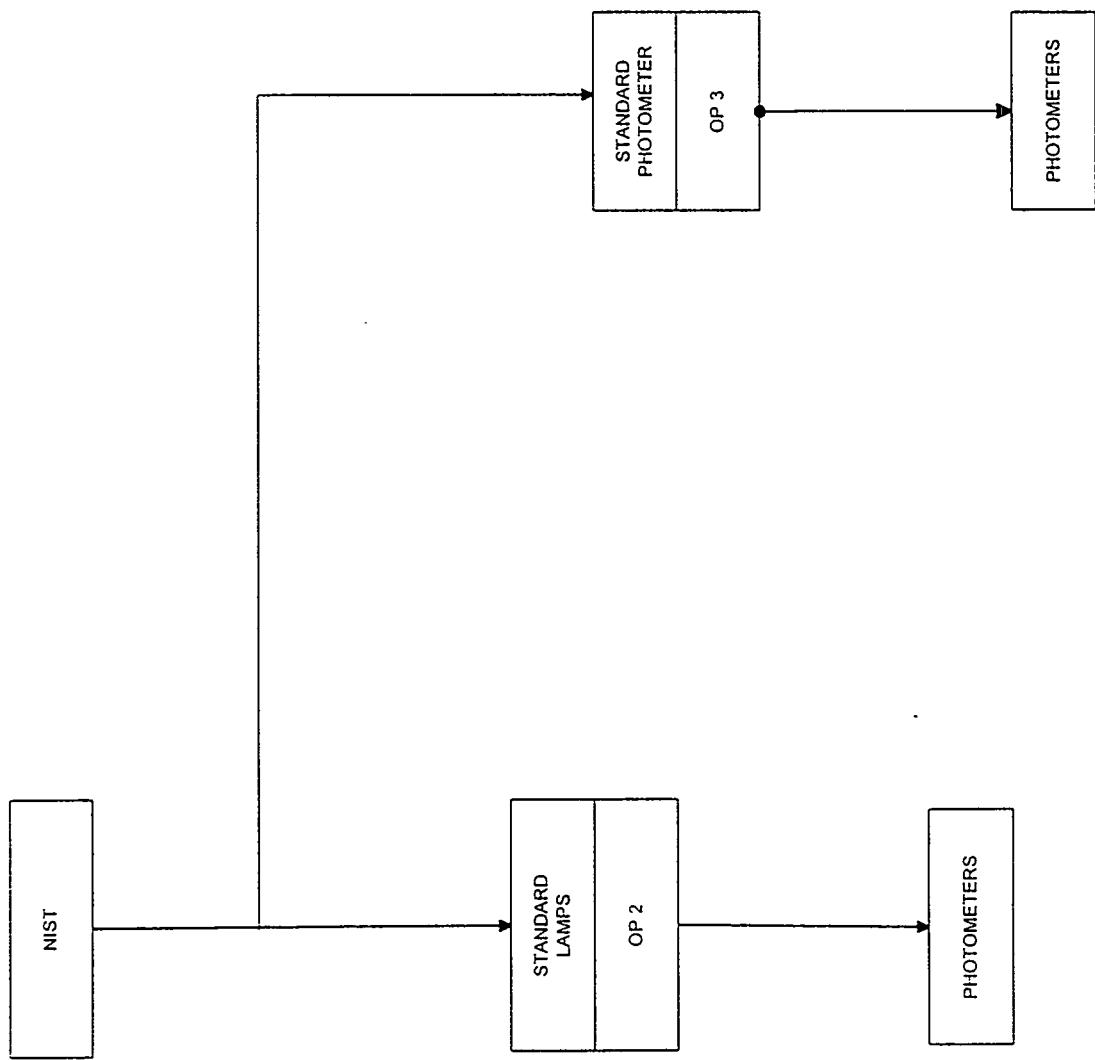


Figure 2D Optical Calibration Flow Chart (Photometric)

Table 3D. Optical Photometric Measurement Capability

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

Table 4D. Optical Photometric Measurements Code Description

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

Table 5D. Radiation Measurement Capability

Type	Range	Measuring Accuracy (\pm)
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%