Measurement Capabilities of the BKC Metrology Organization

Bendix Kansas City Division

L. M. Barnes

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PURPOSE

The purpose of this manual is to communicate to concerned persons the measurement and calibration capabilities of the Metrology Organization of the Allied Corporation, Bendix Kansas City Division (BKC). Included is a listing of the measurement types and ranges available, and the accuracies normally attainable. Also described are currently used standards and measurement devices.

The BKC Metrology organization performs the following general functions:

- Operation of a D.O.E. contractor standards laboratory and administration of a calibration program that meets the requirements of the ALO Standardization Program and satisfies the needs of the BKC facility;
- Maintenance of standards to support BKC calibration program requirements and calibration of transfer standards used by Metrology and the BKC calibrating organizations;
- Assignment of calibration responsibility for measuring instruments or devices to the appropriate calibration organization or to Metrology in cases not covered by establised policy or other special circumstances;
- Survey and audit of calibration programs of BKC calibrating organizations, selected suppliers, and certain commercial standards laboratories;
- Resolution of measurement differences between calibrating organizations;
- Performing special measurements requiring accuracy not attainable elsewhere in the Kansas City Division; and
- Review of procurement actions for standards and measuring instruments requiring calibration and providing consulting services.
- Review and control of exemption of instruments from normal periodic calibration and certification when appropriate.

ORGANIZATION

This manual is divided into four major sections, each describing a broad general area of measurement:

- Mechanical,
- Environmental, Gas, Liquid,
- Electrical (D.C., A.C., R.F./Microwave), and
- Optical and Radiation.

Each section includes capability tables which list specific types of measurement or calibration available and the normally achievable accuracy for each. The ranges and accuracies stated are those attainable in Metrology using normal measurement and calibration techniques. The term "accuracy" is used here as the relative agreement between the measured value and the true value of a quantity. Also included in each section are calibration flow charts with accompanying tables. These indicate the types of devices used and their traceability to national standards or independently reproducible standards.

Units of measurement in range and accuracy statements in this manual are those currently most commonly required by instrument users.

The abbreviations "PSL" and "NBS" used throughout this manual refer to the U.S. Department of Energy Primary Standards Laboratory and the U.S. National Bureau of Standards.

METROLOGY ORGANIZATION

The BKC Metrology organization consists of three departments, Calibration Control, Engineering, and Calibration. A photograph of the Calibration Control and Engineering office area follows. Photographs of the calibration laboratories appear throughout this manual.

Calibration Control administers the Metrology calibration recall system, performs surveys and audits, prepares calibration procedures, and provides computer programming support for Metrology.

Metrology Engineering provides engineering support for Metrology and other calibration organizations, and data review and certification of standards and instruments calibrated by Metrology.

The calibration group includes technologists who perform instrument calibration and data collection.

Metrology Engineering and Calibration Control

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 listed in the accompanying table can be improved by applying machine geometry corrections.

Many length measuring systems are calibrated using the laser interferometer.

GAGE BLOCK MEASUREMENT

Block measurement less than 2 in. is performed using a laser interferometer. Those longer than 2 in. are compared to blocks certified by the PSL using a gage block comparator.

ROUNDNESS MEASUREMENT

Roundness measurements are made using an instrument that indicates out-of-roundness on a circular paper graph with a resolution of 1 μin. The instrument 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. 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.

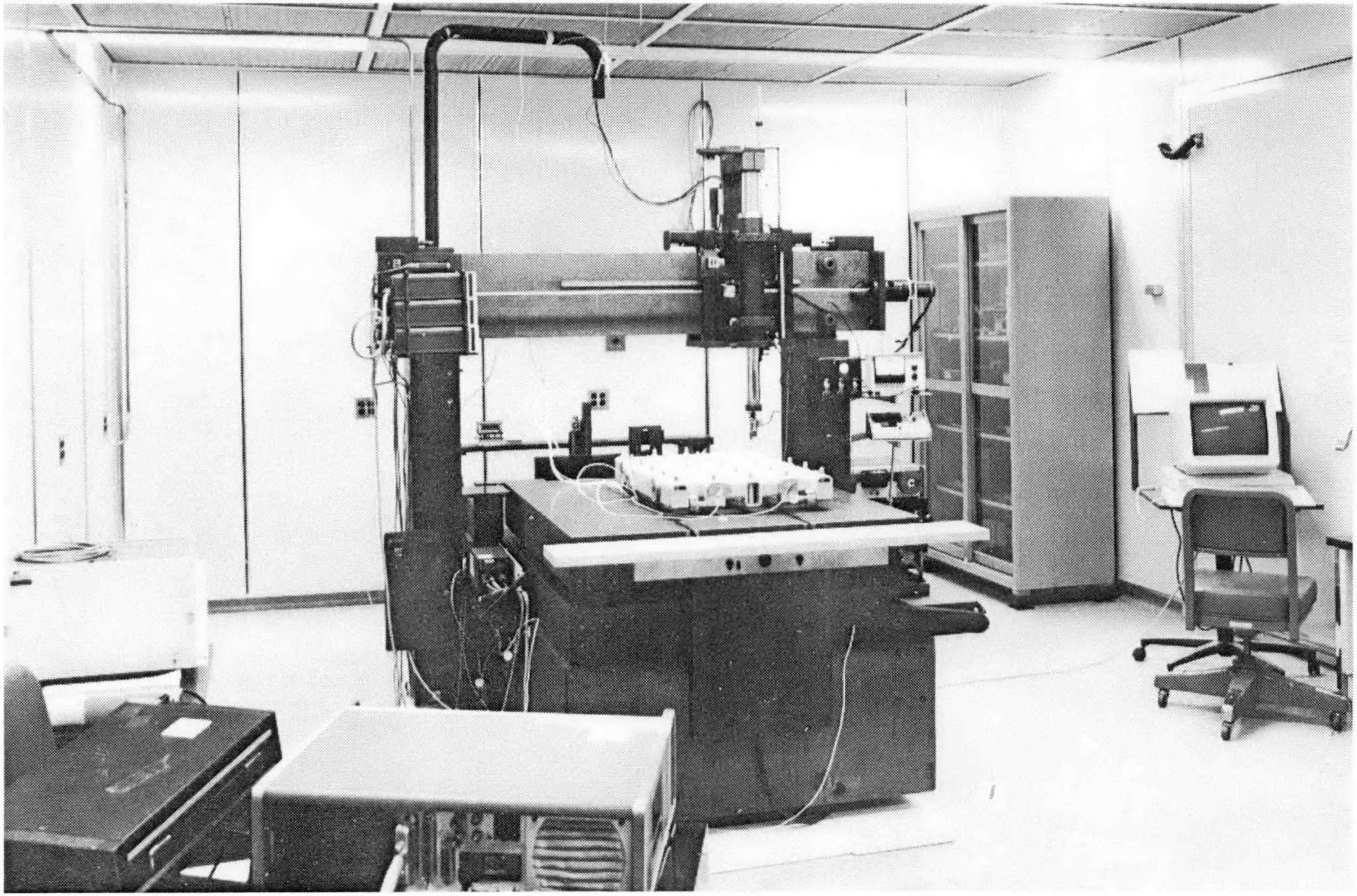
Large angles are measured using an autocollimator, a rotary table, and an optical polygon.

VIBRATION

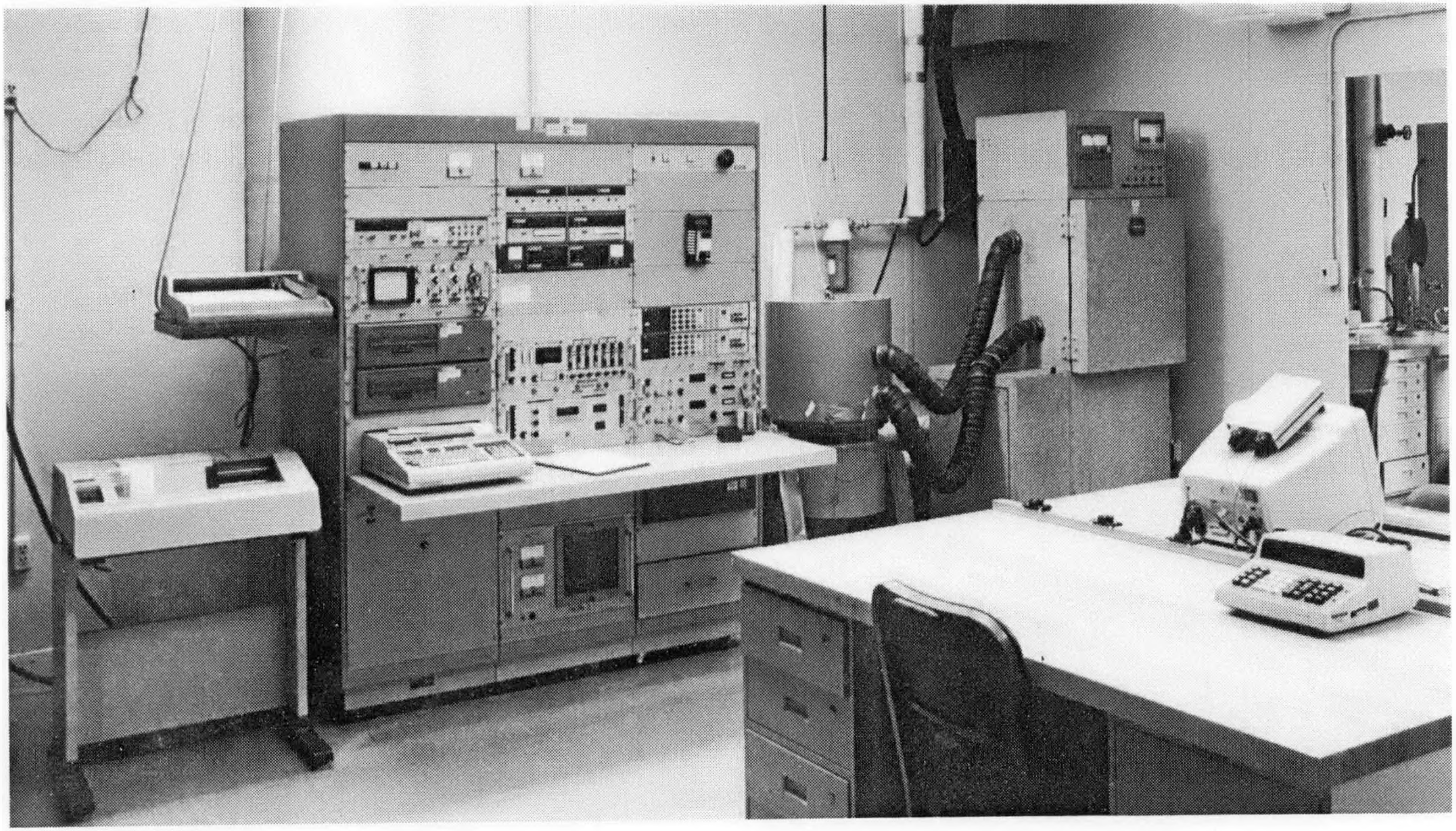
Accelerometers used for vibration testing are calibrated on a computer controlled shaker. Comparison is made to NBS and PSL certified accelerometers. The acceleration capability is up to 50 g. The frequency range is 10 Hz to 10 kHz at ambient temperatures. Calibration at temperatures ranging between -65°F and 250°F can be performed up to a frequency of 3 kHz.

MECHANICAL SHOCK

Accelerometers used for mechanical shock testing to 5000g's are calibrated in a back-to-back configuration on an air activated shock pulse generator. For shock levels above 5000g's, an elastic cord assisted impact device generates the shock pulse. A computer determines the velocity change and provides calibration data. Comparisons are made to PSL certified accelerometers.



Coordinate Measurement Machine With Ball Plate Standard

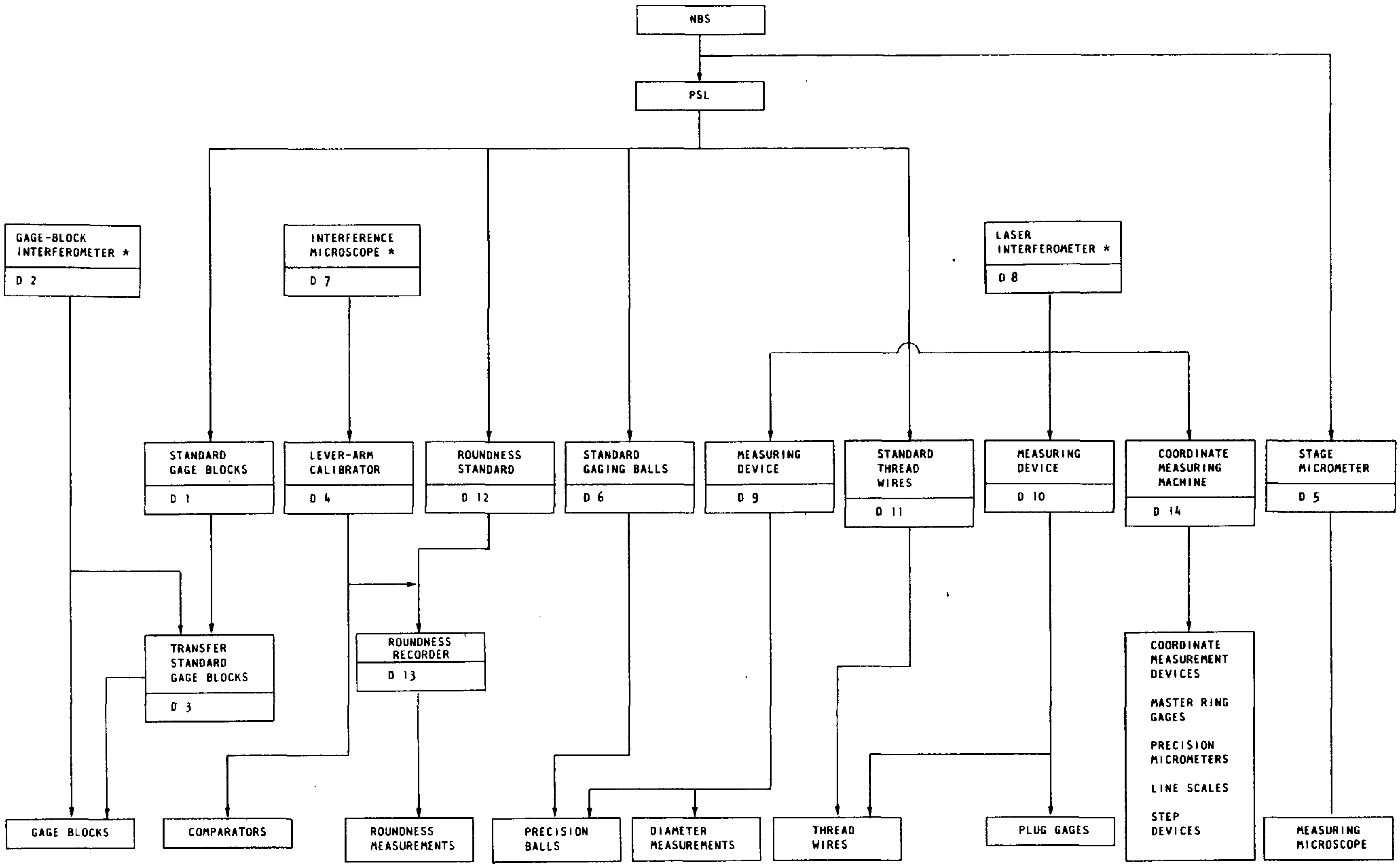


Automatic Accelerometer Calibrator

Table 1A. Dimensional Measurement Capability

Type	Range (in.)	Accuracy (±) Measuring
Length-Gage Blocks	0.01 to 2	4 μin.
	3	7 μin.
	4	8 μin.
	5 to 7	9 μin.
	8 to 10	10 μin.
	12	11 μin.
	16	12 μin.
	20	13 μin.
Length-Coordinate Measurement*	x axis	2 ppm + 15 μin.
	y axis	2 ppm + 10 μin.
	z axis	2 ppm + 5 μin.
	x-y plane	5 ppm + 15 μin.
	y-z plane	3 ppm + 10 μin.
	x-z plane	3 ppm + 10 μin.
	x-y-z space	6 ppm + 20 μin.
Diameter	0.02 to 15 in.	1 ppm + 10 μin.
Roundness	To 21 in. diameter	3 μin.
Thread Wire	All standard pitches	8 μin.

*Accuracy without correction and based on probe travel. Maximum range of length-coordinate measurement is x = 48 in, y = 36 in. and z = 12 in.



*Independently reproducible standard.

Figure 1A. Dimensional Measurement Capability

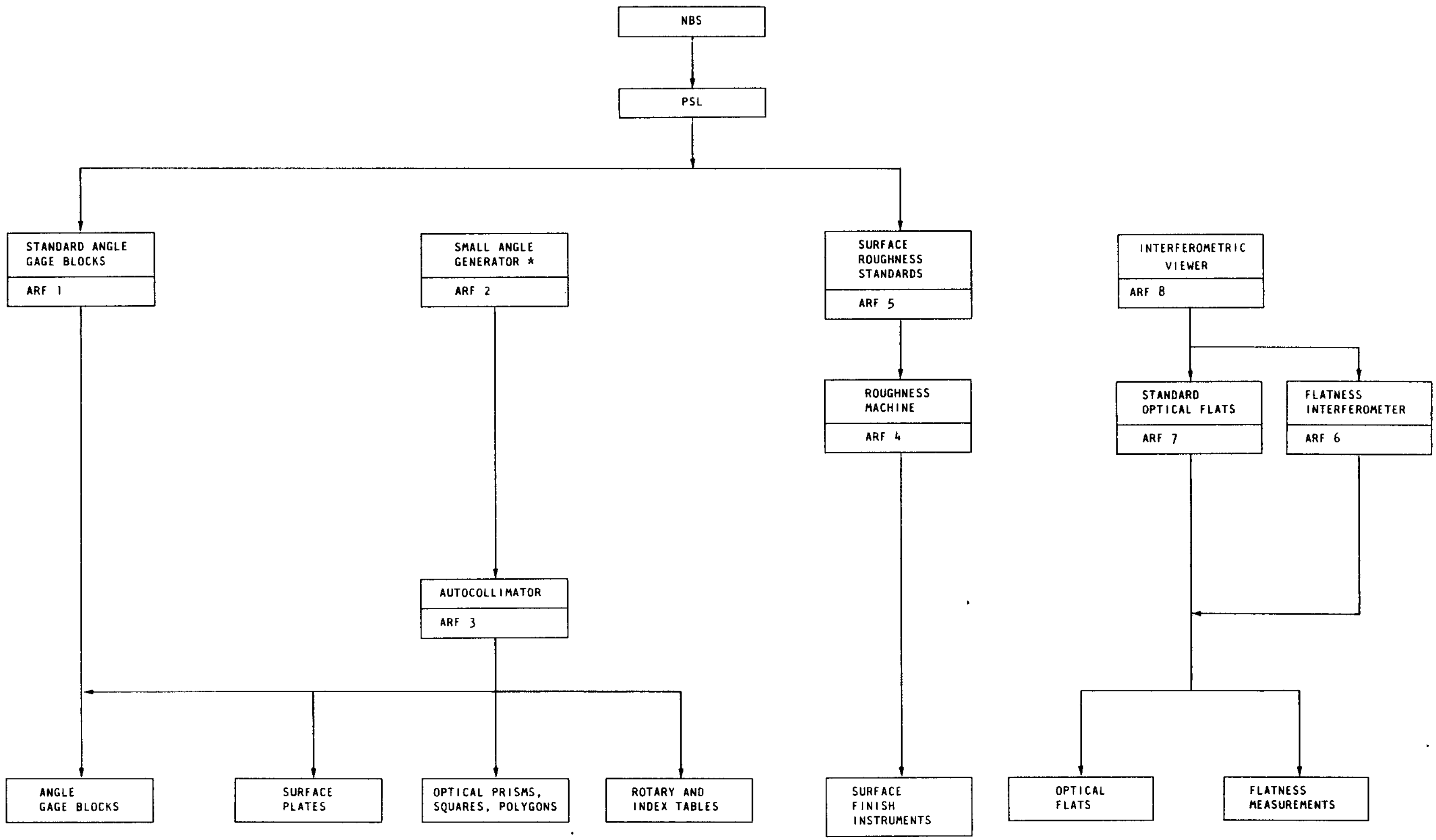
Table 2A. Dimensional Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
D 1	Standard Gage Blocks	Do All	0.01 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 to 7 in.	7 μin.
		Pratt & Whitney	8 to 10 in.	8 μin.
		Pratt & Whitney	12 in.	9 μin.
		Pratt & Whitney	16 in.	10 μin.
		Pratt & Whitney	20 in.	11 μin.
D 2	Gage Block Interferometer	Link	0 to 2 in.	3 μin.
D 3	Transfer Standard Gage Blocks	Do All	0.01 to 2 in.	4 μin.
		Do All	3 in.	7 μin.
		Do All	4 in.	8 μin.
		Pratt & Whitney	5 to 7 in.	9 μin.
		Pratt & Whitney	8 to 10 in.	10 μin.
		Pratt & Whitney	12 in.	11 μin.
		Pratt & Whitney	16 in.	12 μin.
		Pratt & Whitney	20 in.	13 μin.
D 4	Lever Arm Calibrator	Bendix	0 to 0.0002 in.	0.2 μin. + 0.5% of travel
		Mitutoyo	0 to 0.05 in.	4 μin. + 0.25% of travel
D 5	Stage Micrometer	American Optical	0 to 25 mm	0.15 μm
			0 to 1 in.	4 μin.

Table 2A Continued. Dimensional Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
D 6	Standard Gaging Balls	AA Industries	1/16 to 1 in. (1/32-in. increments)	7 μin.
D 7	Interference Microscope	Zeiss	0 to 0.01 in.	1 μin.
D 8	Laser Interferometer	Hewlett Packard	NA	1 ppm + 3 μin.
D 9	Measuring Device	Pratt & Whitney	1 in.	20 μin.
D 10	Measuring Device	Bendix	0 to 2 in.	10 μin.
D 11	Standard Thread Wires	Van Keuren	1 thru 80 TPI 60 deg. 1 thru 29 TPI 29 deg.	8 μin.
D 12	Roundness Standard	Taylor Hobson	NA	3 μin.
D 13	Roundness Measuring Instrument	Bendix A & M	20 μin. to 0.01 in.	3 μin.
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 + 15 μin. 2 ppm + 10 μin. 2 ppm + 5 μin. 5 ppm + 15 μin. 3 ppm + 10 μin. 3 ppm + 10 μin. 6 ppm + 20 μin.

*Accuracy is given without correction and is based on probe travel. Maximum range x = 48 in., y = 36 in., z = 12 in.



*Calibrated using laser interferometer.

Figure 2A. Dimensional Code Description

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

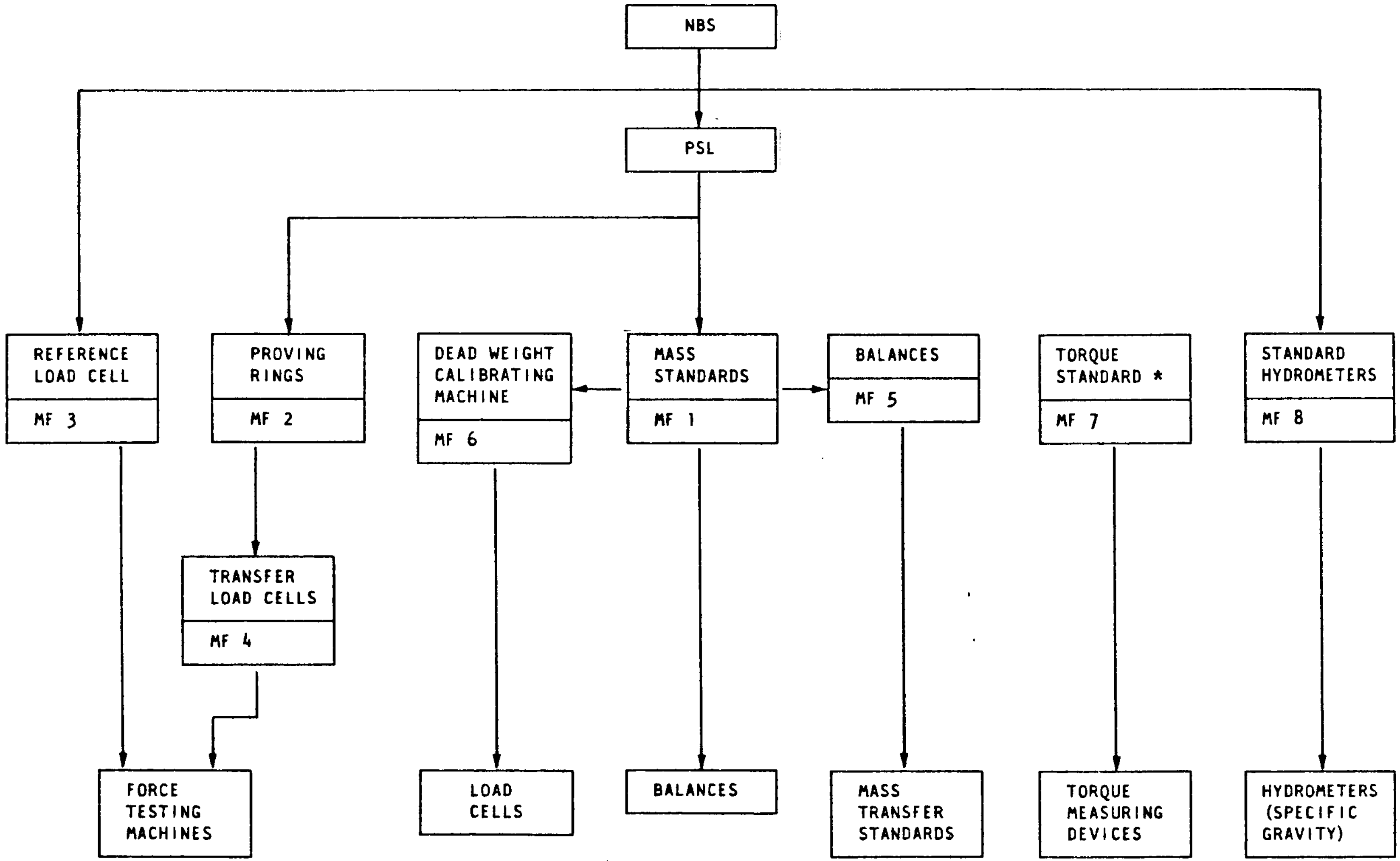
Type	Range	Measuring Accuracy (±)
Angle	0 to 360°	1 s of arc
Surface Roughness	10 μin. to 0.006 in. (AA)	±4 μin. AA
Surface Optical Flatness	To 12 in. diameter	2 μin.
Surface Plate Flatness	12 by 12 in. 4 by 6 ft 5 by 10 ft	30 μin. 50 μin. 100 μin.

Table 4A. Angle, Roughness, Flatness Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
ARF 1	Standard Angle Gage Blocks	Webber	1 s to 45° of arc (16 blocks)	0.7 arc-seconds
ARF 2	Small Angle Generator	Matrix	10 min of arc	0.2 arc-seconds
ARF 3	Autocollimator	Davidson	10 min of arc	0.3 arc-seconds + 0.25% of measured angle
		Hilger Watts	10 min of arc	0.5 arc-seconds + 0.25% of measured angle
ARF 4	Roughness Machine (Measuring)	Federal	0 to 0.008 in. AA (10 ranges)	4 μin. AA
ARF 5	Surface Roughness Standards	Taylor Hobson	9.6 μin. AA 30 μin. AA	2 μin. AA 2 μin. AA
		Brush Instruments	125 μin. AA	3.5 μin. AA
ARF 6	Flatness Interferometer	Davidson	2-3/4 in. diameter	2 μin.
ARF 7	Standard Optical Flats (set of 3)	Do All	12 in. diameter	flat within 3 μin.
ARF 8	Polychromatic Interference Fringe Viewer			1 μin.

Table 5A. Mass, Force, Torque, Specific Gravity Measurement Capability

Type	Range	Measuring Accuracy (±)
Mass	1 to 200 mg	0.012 mg (max.)
	0.2 to 100 g	0.050 mg (max.)
	100 to 2000 g	1 ppm
	2000 to 20 000 g	2 ppm
	20 000 to 60 000 g	2 g
Force	5 to 600 lbf	0.005 % nominal
	to 3000 lbf	1.5 lbf
	to 10 000 lbf	5.0 lbf
	to 30 000 lbf	20.0 lbf
	to 100 000 lbf	50.0 lbf
	to 300 000 lbf	80.0 lbf
Torque	1 to 5 ft·lb	0.125 %
	5 to 50 ft·lb	0.15 %
	50 to 750 ft·lb	0.15 %
Specific Gravity	1.050 to 1.500	0.005



*Calibrated using Metrology dimensional and mass standards.

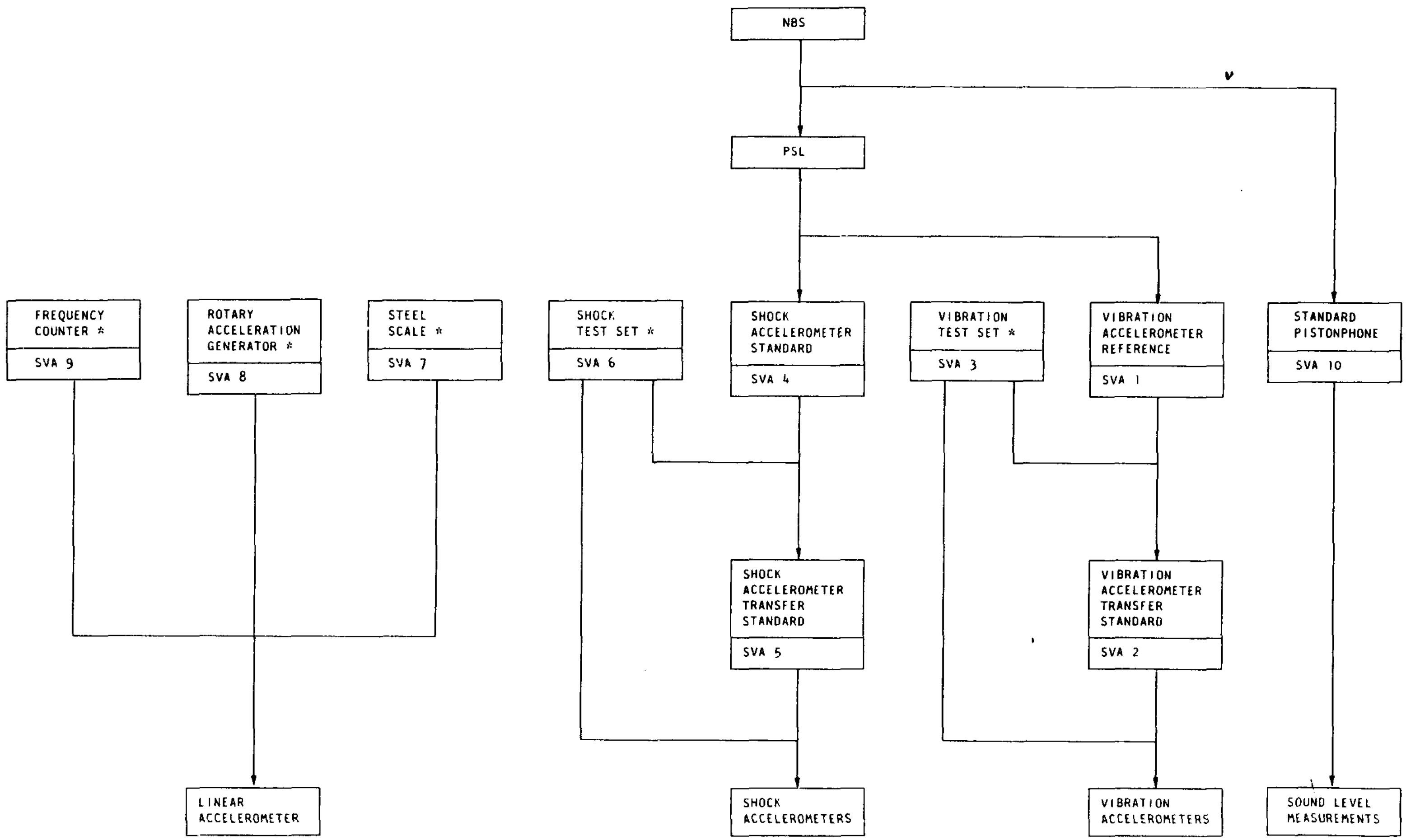
Figure 3A. Mechanical Calibration Flow Chart (Mass, Force, Torque, Specific Gravity)

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

Code	Description	Manufacturer	Range	Accuracy (±)
MF 1	Mass Standards	Ainsworth Troemner Troemner	1 mg to 100 g 200 g to 5000 g 1 lb to 50 lb	0.040 mg (max.) 1.1 mg (max.) 1 ppm
MF 2	Proving Rings	Morehouse	3000 to 300 000 lb	0.07 % of range
MF 3	Reference Load Cells	BLH Electronics	600 000 lb	170 lb
MF 4	Transfer Load Cells	BLH Electronics	60 to 600 000 lb 1000 to 240 000 lb	0.025 % F.S. +0.1 % load 0.033 % F.S. +0.2 % load (max.)
MF 5	Balances	Mettler Sartorious Mettler Mettler Stanton Mettler	0 to 20 g 0 to 100 g 0 to 1000 g 0 to 5000 g 5 to 25 kg 0 to 60 kg	0.12 mg (max.) 0.50 mg (max.) 3.6 mg (max.) 27 mg (max.) 50 mg (max.) 3 g
MF 6	Dead Weight Calibrating Machine Dead Weight Calibrating Machine	Morehouse (modified) Bendix	5 to 240 lb 50 to 2400 lb	0.005 % 0.005 %
MF 7	Torque Standard	Bendix	0 to 750 ft·lbs	0.15 %
MF 8	Standard Hydrometers	H-B Instruments	1.050 to 1.500	0.005

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

Type	Range	Measuring Accuracy (±)
Vibration	0.5 to 50 g (75°F) at 10 Hz to 10 kHz	2.5 %
	0.5 to 40 g (-100 to +350°F) at 100 Hz to 3 kHz	3.0 %
Shock	50 to 10 000 g (75°F)	4 %
Sound Level	124 dB at 250 Hz	0.5 dB
Linear Acceleration	0 to 90 g	1 %



*Indicates items certified using Bendix Metrology standards.

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

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

Code	Description	Manufacturer	Range	Accuracy (±)
SVA 1	Vibration Accelerometer Reference	Endevco	2 to 50 g 10 Hz to 10 kHz	2 %
SVA 2	Vibration Accelerometer Transfer Standard	Unholtz Dickie	2 to 50 g 10 Hz to 10 kHz	 3 %
SVA 3	Vibration Test Set	Bendix	10 Hz to 10 kHz	Used only with other cali- brated measur- ing instruments
SVA 4	Shock Accelerometer Standard	Kistler	to 10 000 g	5 %
SVA 5	Shock Accelerometer Transfer Standard	Endevco	100 to 5000 g	6 %
SVA 6	Shock Test Set	Bendix	50 to 5000 g (back to back) 3000 to 15 000 g (absolute)	Used only with other calibrated measuring instruments
SVA 7	Steel Scale	Lufkin	10 ft	0.002 in.
SVA 8	Rotary Acceleration Generator	Genesco	1 to 100 g	Used only with other calibrated measuring instruments
SVA 9	Frequency Counter	Hewlett Packard	to 10 kHz	10 ppm or 1 count
SVA 10	Standard Pistonphone	B and K	50 Hz to 5 kHz	0.5 dB

ENVIRONMENTAL, GAS, LIQUID

TEMPERATURE

All temperature measurements in the Metrology Laboratory are based on the International Practical Temperature Scale of 1968 (IPTS-68). There are two primary standards at Bendix for temperature calibration: one is the platinum resistance thermometer (PRT), the other is 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 ±0.02 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 by different types of devices. There are two stirred baths. One bath contains trichlorethelene and covers the range from -100 to +200°F, and the other bath contains silicon oil and covers the range from 73 to 500°F. These baths are used to calibrate thermocouples, PRT's, thermistors, liquid-in-glass thermometers, and some solid state sensors. There are vertical and horizontal electric tube furnaces. The vertical one covers the range from 73 to 2000°F, and the horizontal one covers the range from 73 to 2700°F. Both furnaces are used to calibrate thermocouples in air, such as types T, J, K, and S. There is an environmental chamber with interior dimensions of 25 inches wide, 20 inches deep, and 20 inches high covering the range from -100 to 570°F. An observation window in the door permits the calibration of various chart recording type instruments. Several fixed point temperature cells make possible very accurate single point temperature measurements. The most frequently used are the triple point of water cell, and the zinc cell. The temperatures of these cells are 0.01 and 419.580°C respectively. They are used in the calibration of PRT's and thermocouples.

HUMIDITY

Humidity calibration is performed using a dew point type system capable of generating and monitoring moist air from -100 to +200°F dew point to a certified accuracy of ±0.5°F at 75°F dew point to ±3.0°F at -90°F frost point. The chamber, where sensors are placed for calibration, is about 5 x 5 x 7 inches, and is mounted inside an environmental chamber for temperature control of the generated moist air.

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 2 to 15 cubic feet per hour.

Instruments with sensors made of lithiumchloride, aluminum oxide, phosphorus pentoxide, and some new solid-state materials can be calibrated. Instruments of the wet-dry bulb type cannot be calibrated because of the need for a very high air flow. Chart recording instruments, where the sensor cannot be removed from the instrument frame, cannot be calibrated because of the small test chamber size and the window in the chamber.

PRESSURE

Pressure gages are calibrated using dead weight piston gages. The effective area of the 0 to 500 psi reference is determined by the NBS. 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 BKC with NBS traceable standards. True mass for each reference is determined using standards certified by PSL.

GAS FLOW

Gas flow meters are calibrated by direct comparisons to PSL certified flowmeters or volumetric displacement meters. The Volumetric measurement combined with time, pressure, and temperature measurements, yields a flow calibration. All measurement parameters are certified and NBS traceable.

VACUUM

Vacuum gages lower than 5 mmHg are calibrated using a McLeod Gage. The reference is certified using standards certified by PSL.

Gages above 5 mmHg to atmospheric pressure, are calibrated using a mercury manometer. The manometer is certified using a PSL certified dead weight piston gage.

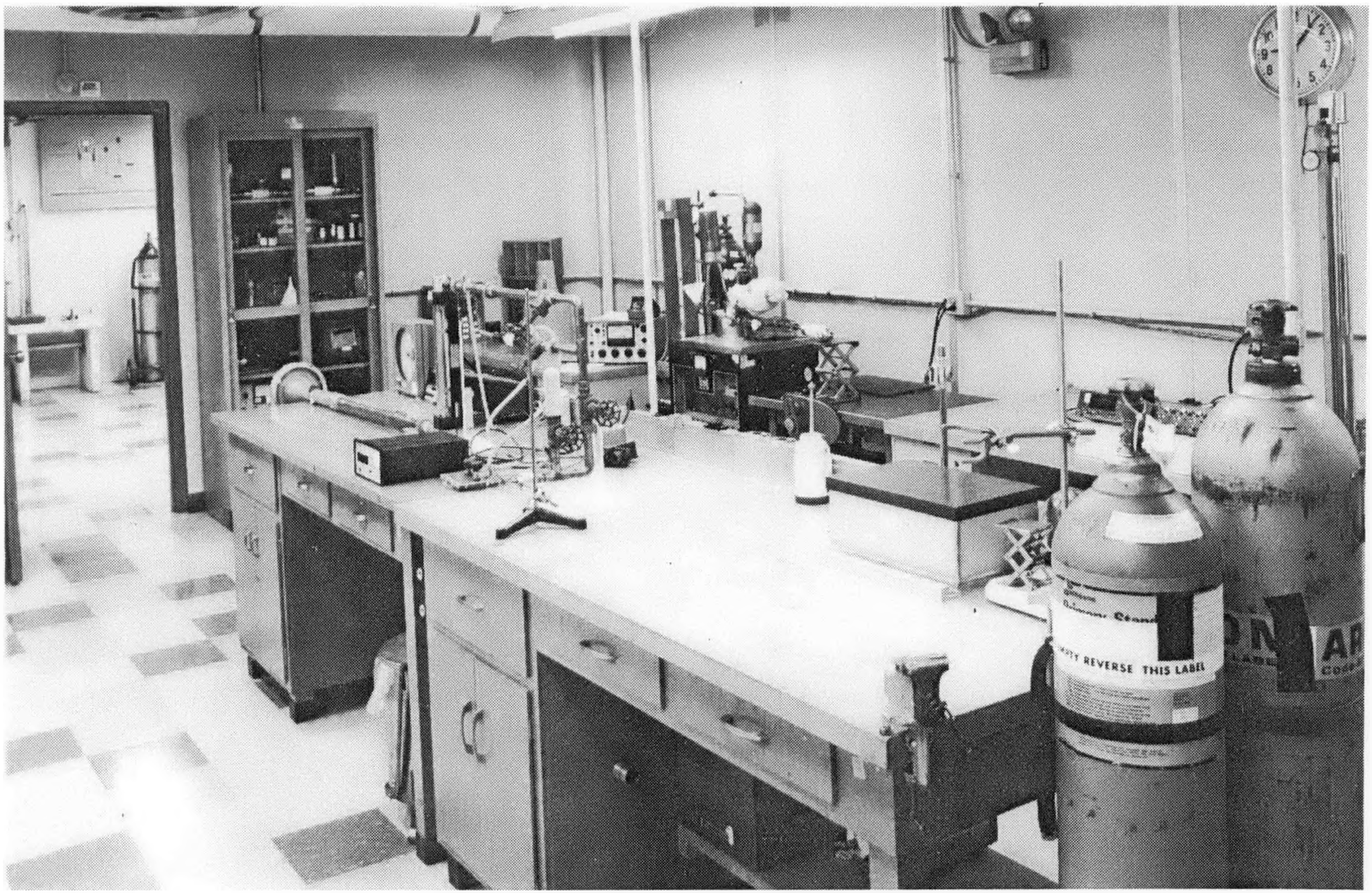
GAS LEAKS

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 NBS traceable.

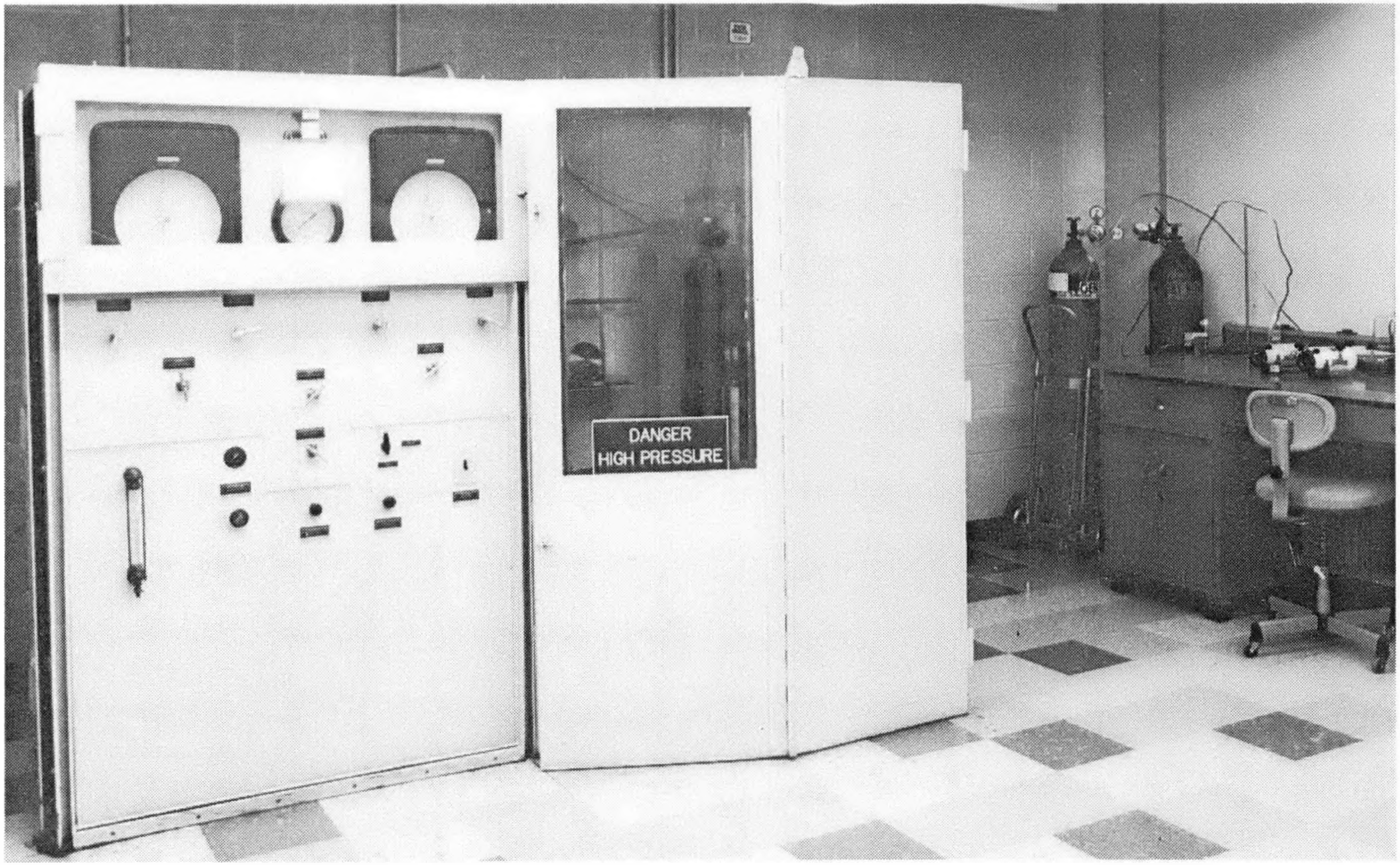
VISCOSITY

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

Temperature and Humidity Calibration Laboratory



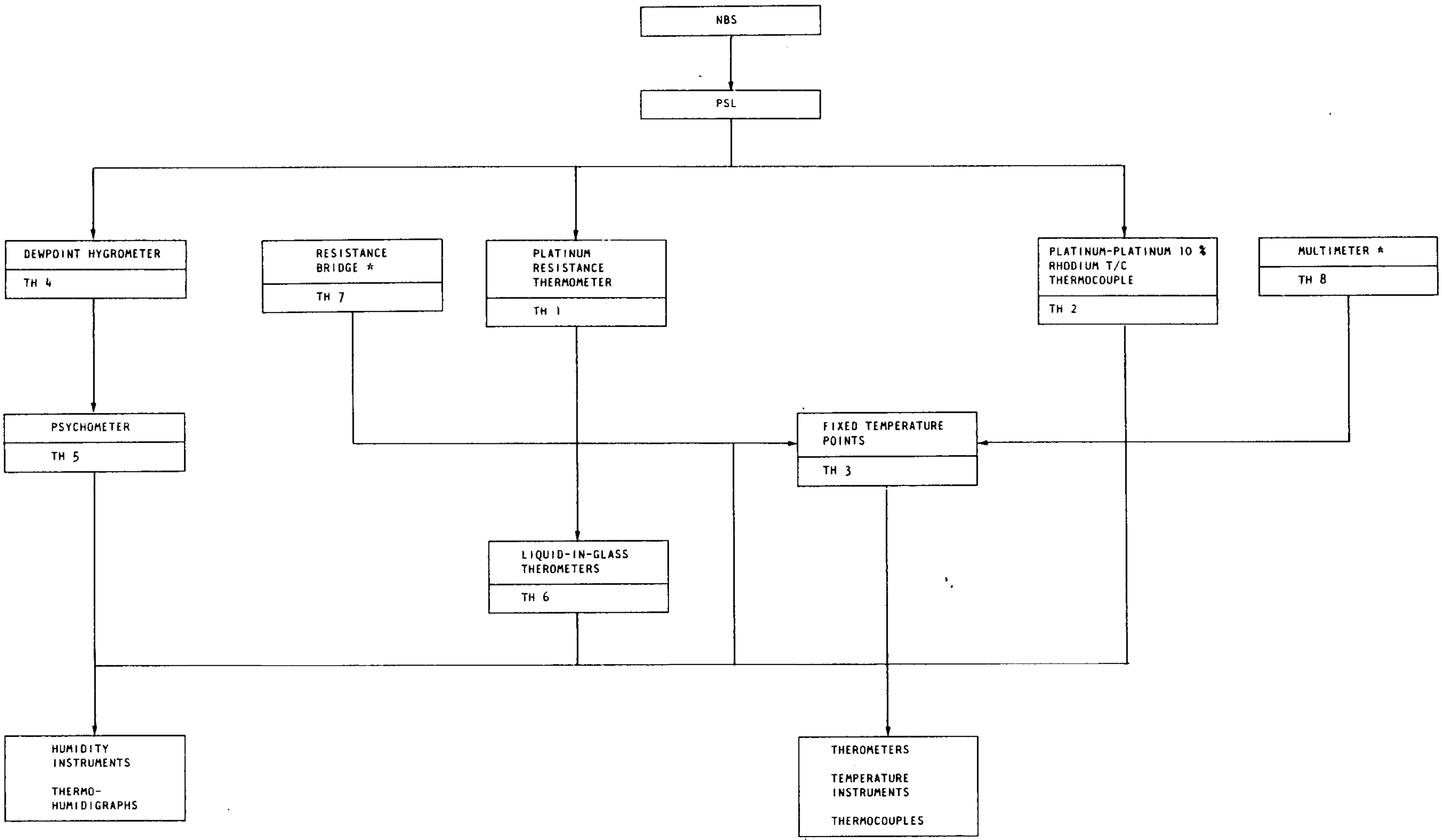
Viscosity, Flow, Vacuum, and Leak Laboratory



Harwood Pressure Standard

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

Type	Range	Measuring Accuracy (±)
Temperature	-183 to +500°C 0 to 1100°C	0.02°C to 0.05°C 1.0°C or 0.4 % whichever is greater
Temperature Fixed Points	0.01°C 122°C 419°C	0.001°C 0.01°C 0.01°C
Humidity	-90.0 to +75°F dew point	0.5°F dew point at 75°F increasing to 3.0°F frost point at -90°F



*Calibrated using Metrology DC voltage, current, and resistance standards.

Figure 1B. Environmental Calibration Flow Chart

Table 2B. Environmental Code Description

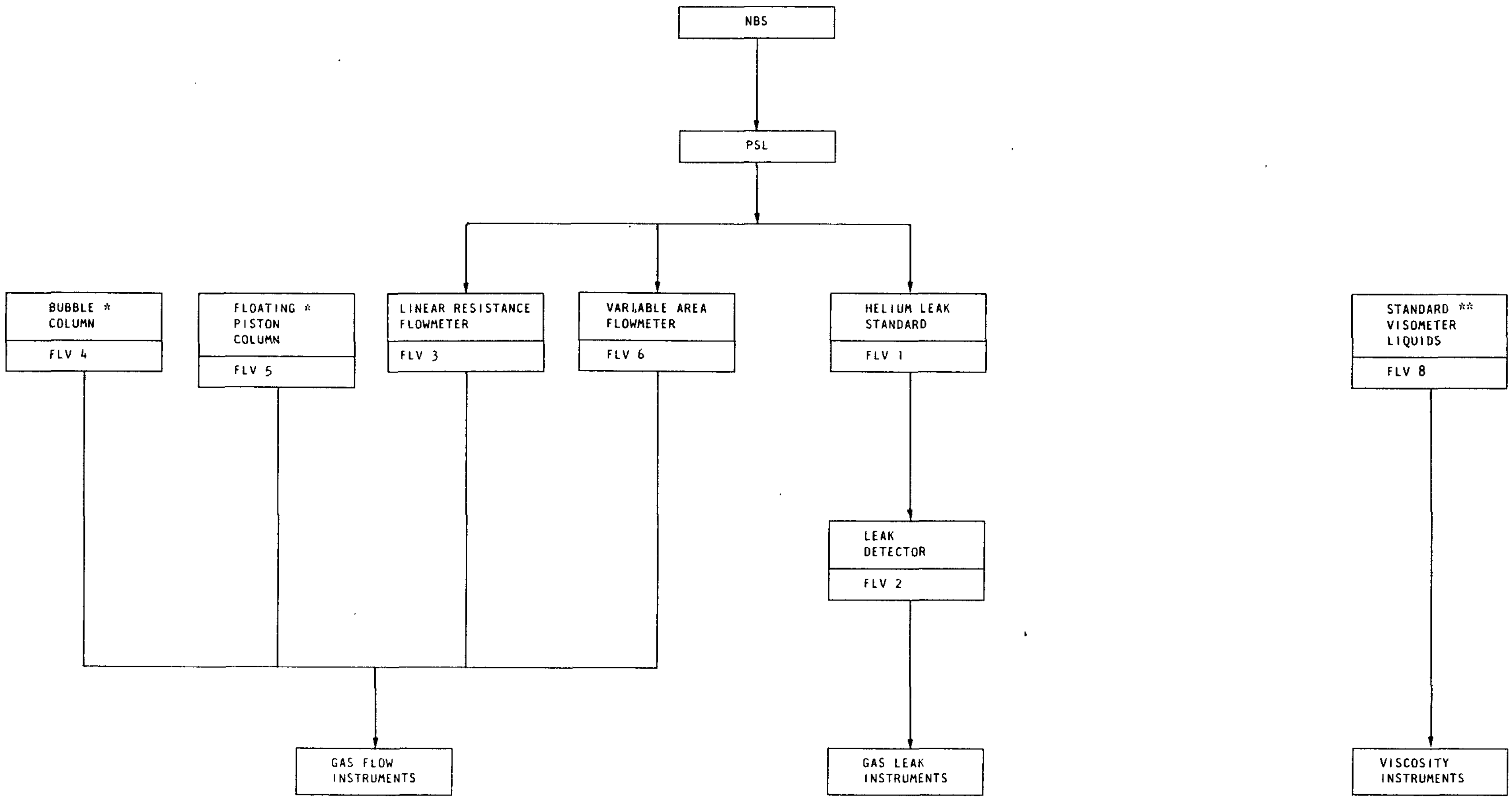
Code	Description	Manufacturer	Range	Accuracy (±)
TH 1	Platinum Resistance Thermometer	Leeds & Northrup	-186 to 0°C 0 to 100°C 100 to 500°C	0.05°C 0.02°C 0.05°C
TH 2	Platinum-Platinum 10 % Rhodium Thermocouple	Leeds & Northrup	0 to 1100°C	0.5°C or 0.2 % of reading (whichever is greater)
TH 3	Fixed Temperature Points			
	Triple Point of Water Cell	Trans-sonics	0.01°C	0.0002°C
	Phenol Cell	NBS	40.85°C	0.05°C
	Naphthalene Cell	NBS	80.24°C	0.05°C
	Phthalic Anhydride Cell	NBS	131.16°C	0.05°C
	Benzoic Acid Cell	NBS	122.370°C	0.003°C
	Zinc Cell	Trans-sonics	419.58°C	0.003°C
TH 4	Dewpoint Hygrometer	E.G.& G.	-100 to +200°F	0.5 to 3°F
TH 5	Psychrometer	Bendix-Friez	-15 to +45°C	0.25°C
TH 6	Liquid-in-Glass Thermometers (9)	Cenco	-38 to +405°C	0.1 to 0.5°C

Table 2B Continued. Environmental Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
TH 7	Resistance Bridge	Leeds & Northrup	0 to 111 ohms	Resistance 0.005 % or 0.005 ohm with correction Ratio 0.002 % with correction
TH 8	Digital Multimeter	Data Precision	0 to 1000 Vdc	0.01 % of reading or 4 digits

Table 3B. Gas, Liquid Measuring Capability

Type	Range	Measuring Accuracy (±)
Pressure	Absolute	
	10^{-5} to 5 mm Hg	30 to 2 %
	5 to 790 mm Hg	0.2 mm Hg
	0.5 to 600 psia	0.02 %
	Gage	
	0.5 to 600 psig	0.02 %
	30 to 15 000 psig	0.03 %
	15 000 to 100 000 psig	0.05 %
Gas Flow	0.01 to 0.2 standard cm^3/s	10 %
	0.2 to 40 standard cm^3/s	2 %
	16 to 1380 standard ft^3/h	2 %
Gas Leak Rate	2 x 10^{-4} to 5 x 10^{-9} standard cm^3/s	10 %
	10^{-10} standard cm^3/s	25 %
Viscosity	0.2 to 1900 poises	0.2 to 0.7 %

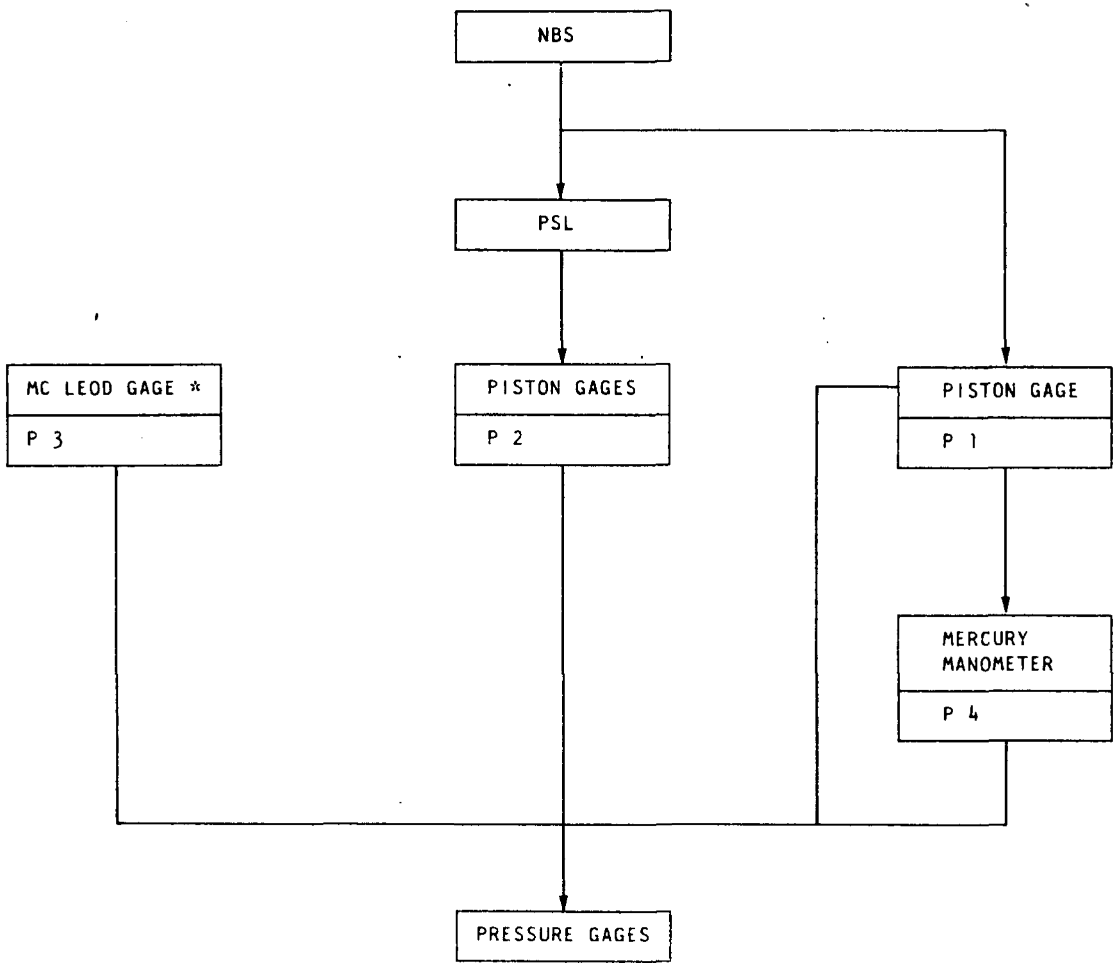


*Calibrated using Metrology mass and dimensional standards.
**Source: Cannon Instruments Co. (approved by PSL).

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

Table 4B. Gas Leak and Flow Rates Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
FLV 1	Helium Leak Standard	Veeco	10^{-4} to 10^{-8} cm^3/s 10^{-8} to 10^{-10} cm^3/s	10 % 10 % to 25 %
FLV 2	Leak Detector	Veeco	10^{-3} to 10^{-10} cm^3/s	5 %
FLV 3	Linear Resistance Flowmeter	National Instrument Laboratories	0.6 to 180 ft^3/hr	2 %
FLV 4	Bubble Column	Bubble-O-Meter	0.01 to 0.2 cm^3/s 0.2 to 4 cm^3/s	10 % 2 %
FLV 5	Floating Piston Column	George K. Porter	Volume 400 cm^3,	1 cm^3
FLV 6	Variable Area Flowmeter	Fisher & Porter	8 to 23 ft^3/min	2.5 %
FLV 8	Standard Visometer Liquids	Cannon Instruments	0.2 to 1900 poises	0.2 to 0.7 %



*Calibrated using Metrology mass and dimensional standards.

Figure 3B. Pressure Calibration Flow Chart

Table 5B. Pressure Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
P 1	Piston Gage	CEC	0.2 to 600 psig	0.015 %
P 2	Piston Gages	Ruska	30 to 15 000 psig	0.03 %
		Harwood	20 000 to 200 000 psig	0.05 %
P 3	McLeod Gage	CEC	10^{-5} to 5 mmHg	30 to 2 %
P 4	Mercury Manometer	Hass	0 to 790 mmHg	0.2 mmHg

ELECTRICAL

DC ELECTRICAL MEASUREMENT

DC Voltage

The basic reference for DC voltage measurements consists of three groups of saturated standard cells. Two groups are maintained in a temperature-controlled oil bath and one group is maintained in a temperature-controlled air bath. All three groups are re-certified by intercomparison tests with a cell group 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 NBS 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 250 amperes.

DC Resistance

The reference for resistance measurements is two groups of standard resistors, ranging from 0.001 ohm to 10 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 values are assigned using either a Wheatstone bridge or a teraohmmeter.

AC ELECTRICAL MEASUREMENT

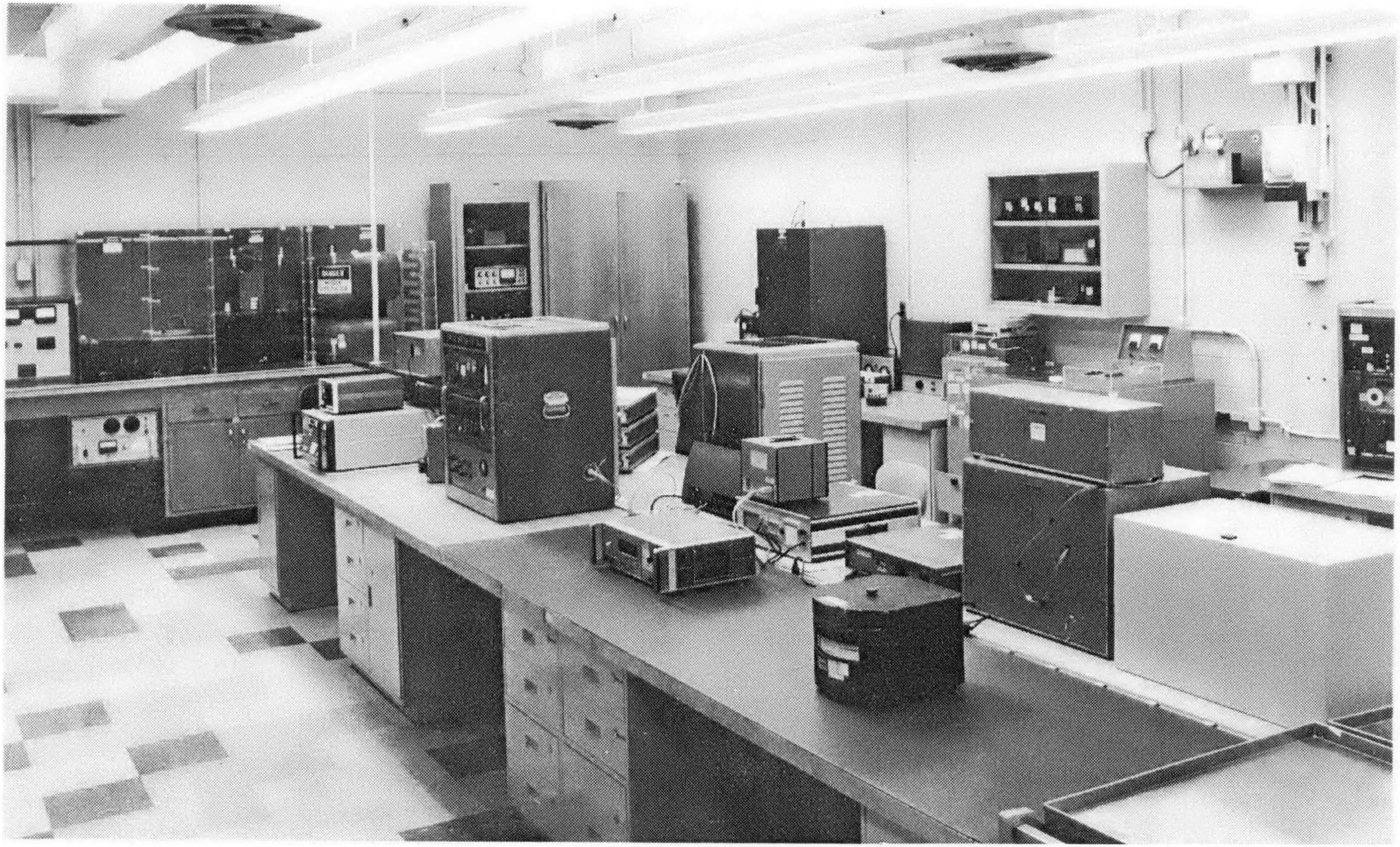
AC Voltage

AC voltage sources are calibrated using a DC voltage standard and standard thermocouple devices certified for AC-DC difference by the Primary Standards Laboratory.

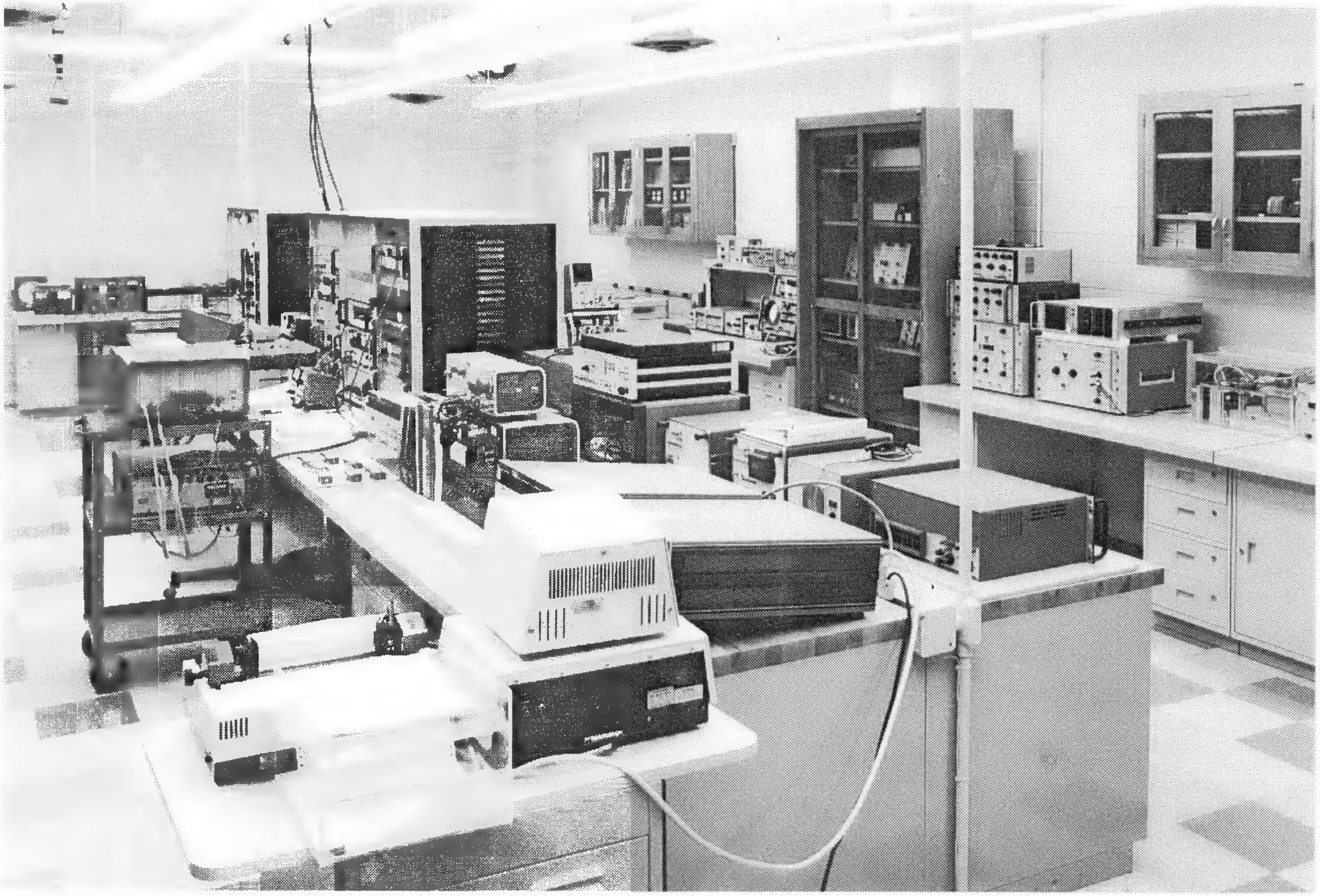
Test thermocouple devices can be calibrated for AC-DC differences by direct comparison of their response to the response of the standard thermocouple devices.

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



DC Calibration Laboratory



AC Calibration Laboratory

resistors. The shunts are terminated with a standard thermocouple device 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.

AC Ratio

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

The test transformer can be certified to ±(10 ppm + (F^2)ppm) from 50 Hz to 10 kHz where F=frequency in kHz.

CAPACITANCE AND INDUCTANCE

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

The measurement uncertainties vary with value and frequency. Capacitance uncertainties range above ±0.01%; inductance uncertainties range above ±0.05%.

FREQUENCY AND TIME

The frequency of a quartz crystal oscillator is compared once a month with the frequency transmitted by NBS on radio station WWVB. The oscillator 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 for accuracy once a month with time information transmitted by NBS on radio station WWV.

RF/MICROWAVE ELECTRICAL MEASUREMENT

Attenuation

The measurement of attenuation is one of the most familiar areas of microwave calibration. Attenuators provide a very accurate and highly portable means of determining a reference for receivers as well as providing a means of matching impedance systems. The standard for attenuation is a wave guide below cut-off piston calibrated by NBS. Attenuation may be calculated very accurately and correlated directly with piston displacement. A mechanical vernier furnishes the displacement information and is scaled in dB.

SWR and Reflection Coefficient

Standing wave ratio (SWR) is another very familiar microwave measurement area. In the past, this measurement has been accomplished using reflectometer techniques, reflecting a signal off of a device and measuring the amount of return compared to the impinging signal.

Reflection Coefficient is the ratio of the reflected to the incident voltage.

$$\Gamma = \frac{V-}{V+} \;\&\; \Gamma = |\Gamma| \measuredangle \theta,$$

where θ is the angle by which the reflected voltage leads the incident voltage.

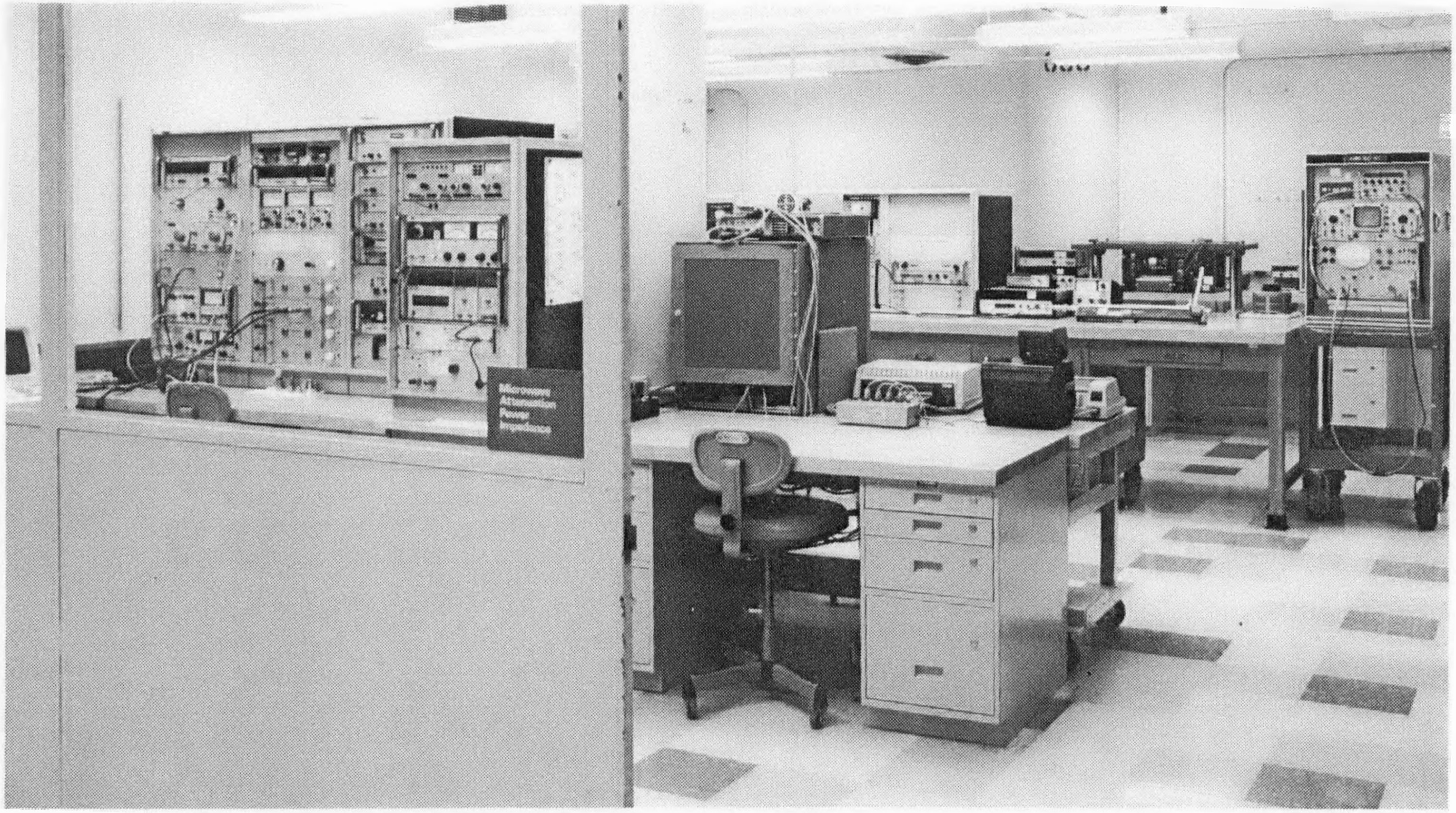
$$SWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

NEW DEVELOPMENTS

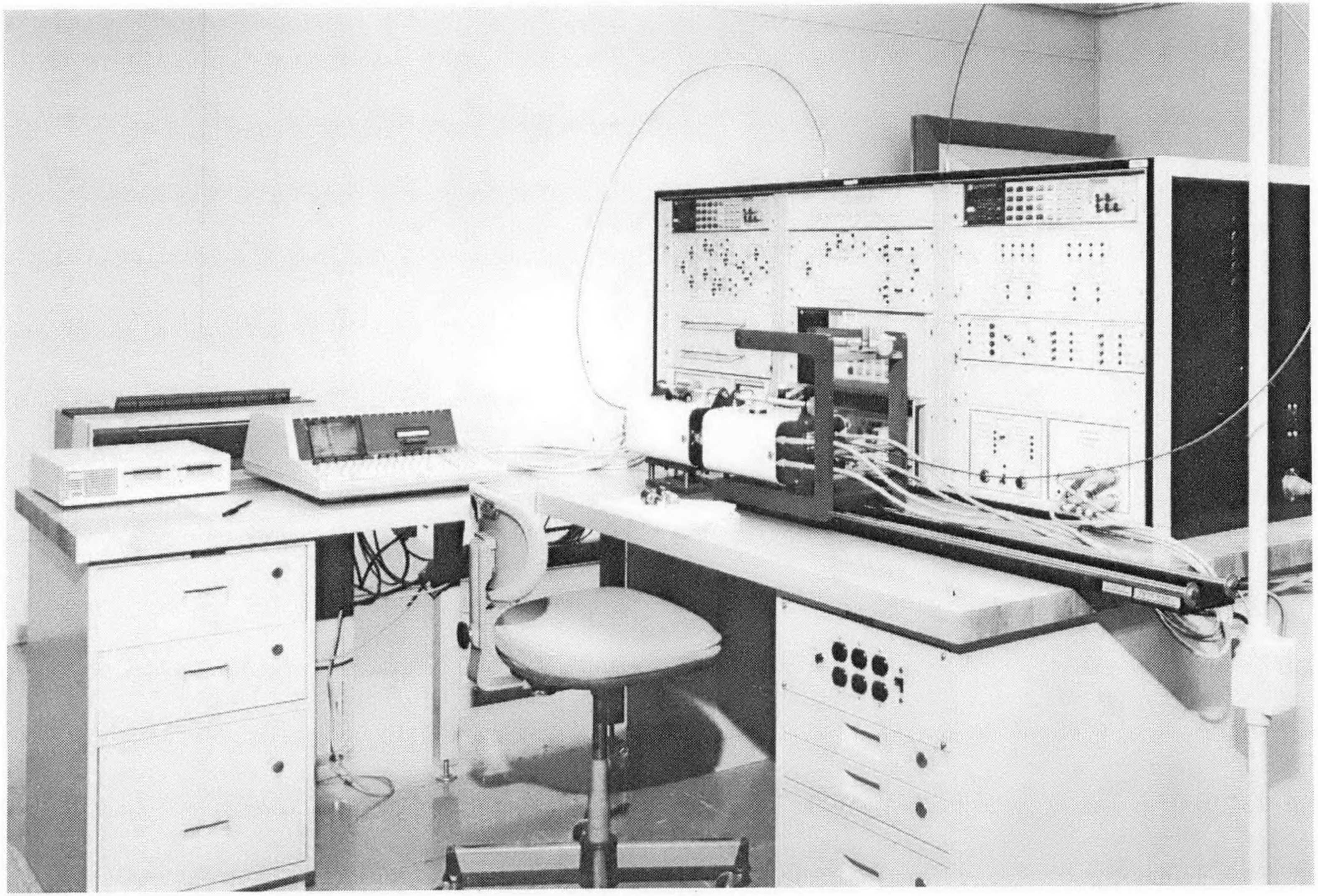
General, new measurement systems are forthcoming in the microwave area. Among these are a Waltron Scalar Network Analyzer, which will be utilized for impedance measurements of medium to low values. An automatic attenuation measurement system will replace the present manual single frequency unit and significantly reduce the throughput time of high value attenuation measurements over the available frequency range. This system also will have phase measurement capability of medium accuracy. An automatic network analyzer also is being developed to enhance most measurement areas.

RF POWER

Thermistor mounts are used for microwave power measurements in the BKC Metrology Laboratory. The effective efficiency and/or calibration factor with an unknown mount are determined by comparison with a mount of known characteristics certified by the Primary Standards Laboratory. Power meters are calibrated using thermistor mounts for frequency response accuracy and a bootstrap technique for power linearity.



Microwave Calibration Laboratory

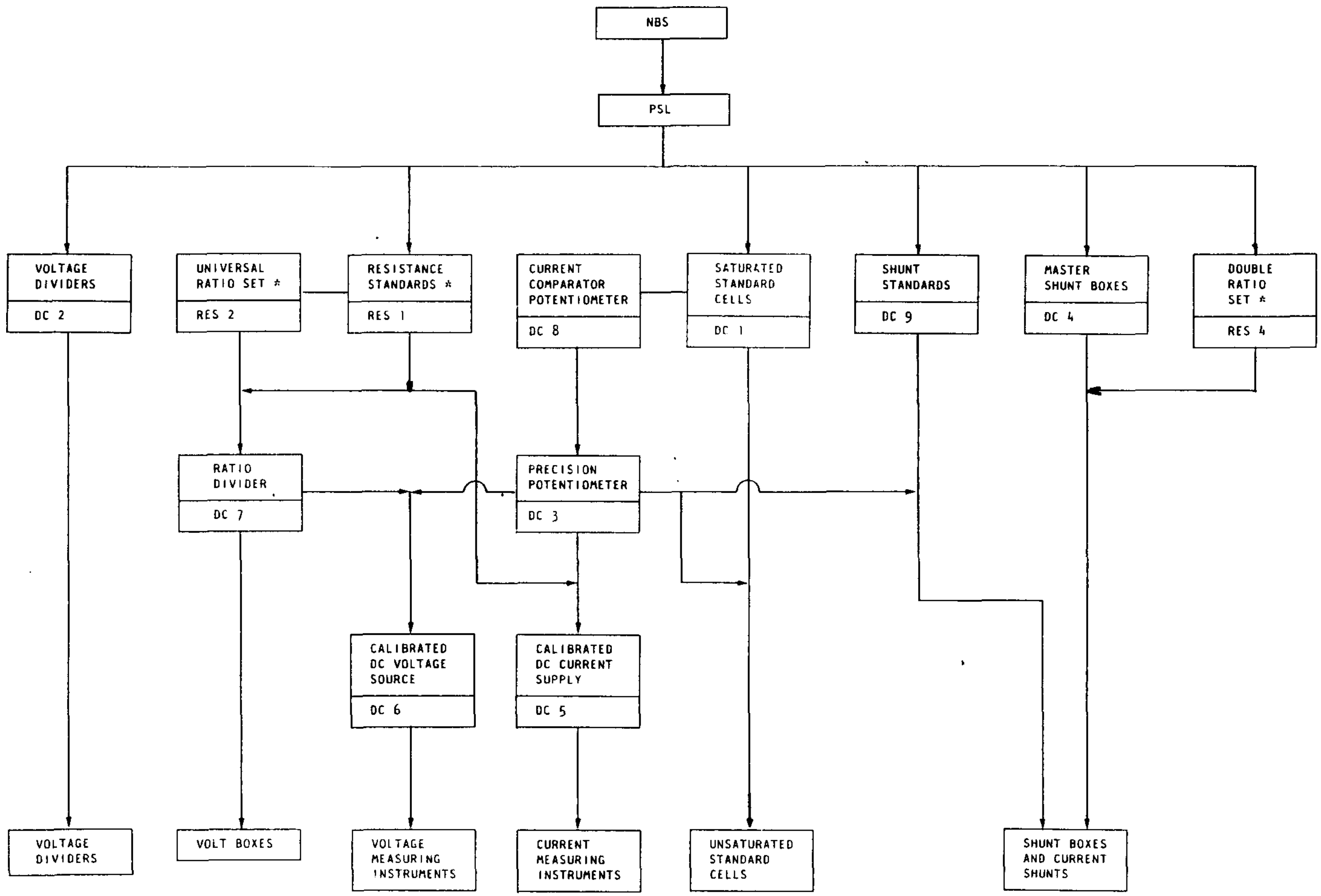


Dual Six-Port RF Automatic Network Analyzer

Table 1C. Electrical Direct Current Measurement Capability

Type	Range	Measuring 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 60 kV	0.075 %
	60 to 100 kV*	0.075 %
DC Current	10^{-4} μA	0.4 %
	10^{-3} μA	0.45 %
	10^{-2} to 1 μA	0.2 %
	1 μA to 0.3 A	0.005 %
	0.3 to 30 A	0.007 %
	30 to 100 A	0.03 %
	100 to 250 A	0.06 %
DC Resistance	10^{-4} to 10^{-1} ohms	0.007 %
	10^{-1} to 10^{6} ohms	0.005 %
	10^{6} to 10^{8} ohms	0.01 %
	10^{8} to 10^{9} ohms	0.25 %
	10^{10} to 10^{13} ohms	0.5 %
DC Magnetic Flux and Reference Magnets	Transverse Fields:	
	30 to 100 gauss	3 gauss
	100 to 200 gauss	6 gauss
	200 to 500 gauss	15 gauss
	500 to 1000 gauss	30 gauss
	1000 to 2000 gauss	60 gauss
	2000 to 5000 gauss	150 gauss
	5000 to 10000 gauss	300 gauss
	Axial Fields:	
	30 to 100 gauss	3 gauss
	100 to 500 gauss	15 gauss

* Current source only



*Refer to DC Resistance Calibration flow chart.

Figure 1C. DC Current and Voltage Calibration Flow Chart

Table 2C. DC Current and Voltage Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
DC 1	Saturated Standard Cells	Eppley/Muirhead	1.018 V nominal	5 µV
DC 2	Voltage Dividers	Bendix Julie Fluke	10 to 100 kV 10 to 100 kV 1 to 10 kV	0.1 % 0.05 % 0.04 %
DC 3	Precision Potentiometer	Leeds & Northrup	0 to 1.6 V	5 ppm to 15 ppm +0.1 µV
DC 4	Master Shunt Boxes	Leeds & Northrup	0.015 to 15 A	0.005 %
DC 5	Calibrated DC Current Supply	Bendix	1.5 µA to 15 A (8 ranges)	0.02 % + 1 nA
DC 6	Calibrated DC Voltage Source	Fluke	1 to 1000 V (3 ranges)	0.005 % or 20 µV 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 µV 2 ppm + 0.02 µV 4 ppm + 0.01 µV
DC 9	Shunt Standards	Leeds and Northrup	0 to 100 A 0 to 250 A	0.02 % 0.05 %

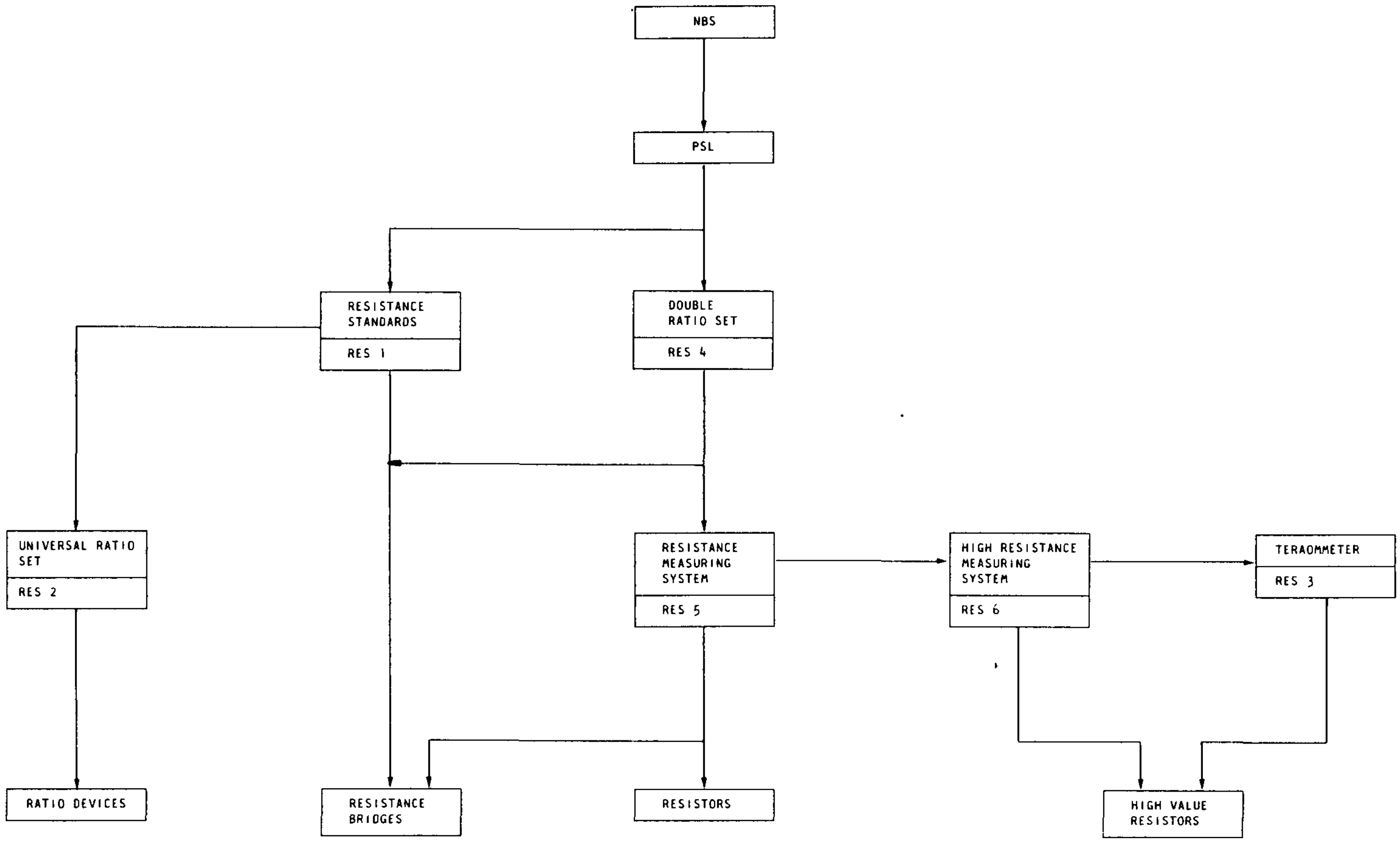


Figure 2C. DC Resistance and Ratio Calibration Flow Chart

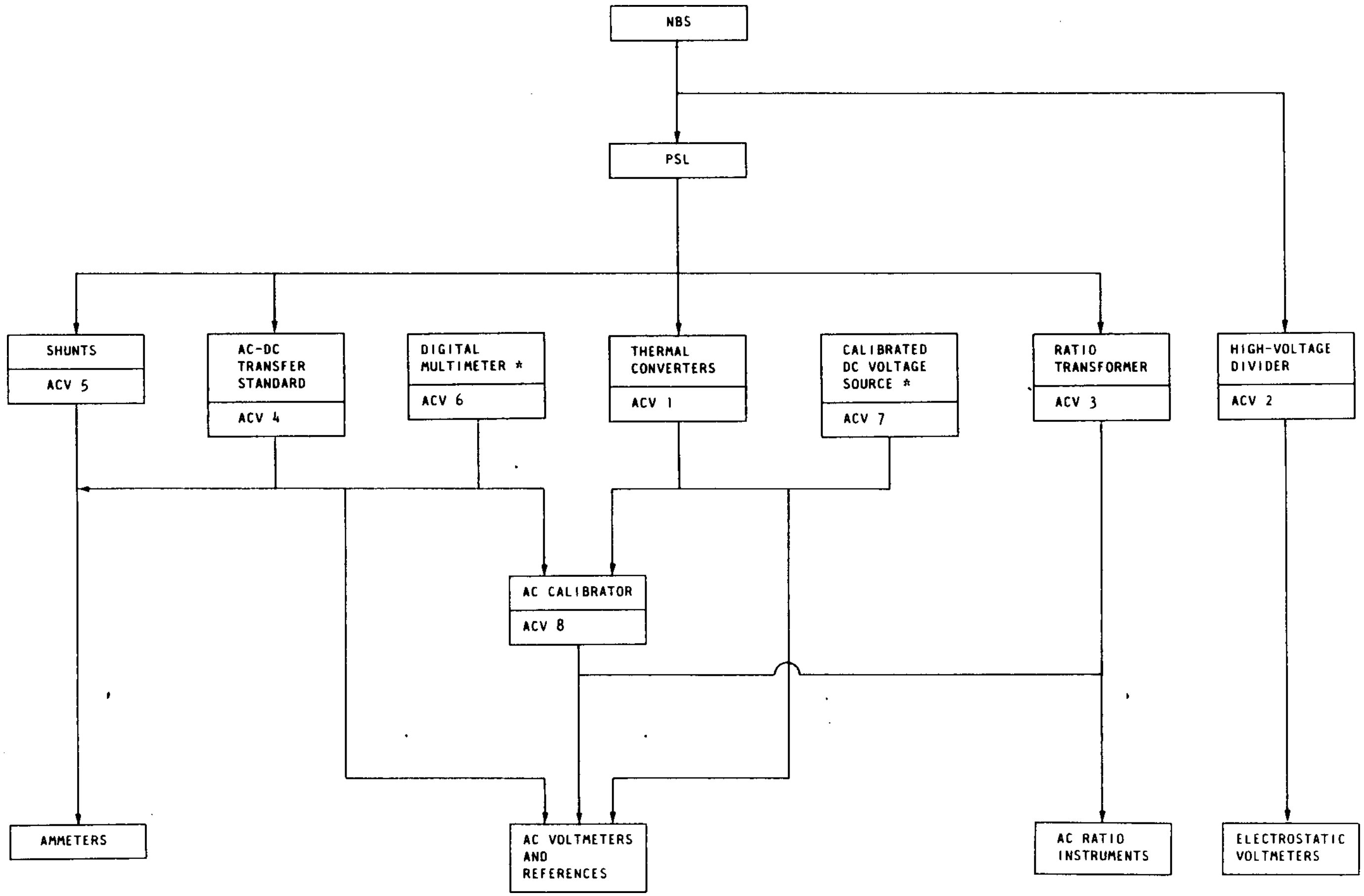
Table 3C. DC Resistance and Ratio Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
RES 1	Resistance Standard	Leeds & Northrup Julie	0.001 ohm to 10 megohm	0.003 to 0.01 %
RES 2	Universal Ratio Set	Leeds & Northrup	Ratio only, 0.5 ppm resolution	5 steps of last dial
RES 3	Teraommeter	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 %
RES 5	Resistance Measuring System	ESI	0.001 ohm to 100 megohm	0.01 % + M x 0.005 ohm (M = range multiplier)
RES 6	High-Resistance Measuring System	Mid-Eastern	10^8 to 10^{13} ohms	0.2 % to 0.5 %

Table 4C. Electrical Alternating Current Measurement Capability

Type	Range	Frequency	Measuring Accuracy (±)**
AC Voltage*	0.5 to 1000 V	10 Hz to 50 kHz	0.01 to 0.03 %
	0.5 to 1000 V	50 to 100 kHz	0.05 %
	0.5 to 50 V	100 kHz to 10 MHz	0.05 to 0.1 %
	0.5 to 10 V	10 to 100 MHz	0.2 to 1 %
	1 to 30 kV	60 Hz	0.3 %
	30 to 100 kV**	60 Hz	0.3 %
AC Current	5 ma to 10 A	10 Hz to 50 kHz	0.05 %
Capacitance	100 pF to 1 μF	50 to 120 Hz	0.05 %
	0.001 pF to 1 μF	1 kHz	0.01 + 0.000 05 pF
	1 to 10 μF	1 kHz	0.02 %
	10 to 100 μF	1 kHz	0.25 %
	10 pF to 0.01 μF	10 kHz	0.02 %
	0.01 to 10 μF	10 kHz	(0.02 + 0.02 x capacitance in μF)
	0.1 to 1000 pF	1 mHz	0.1 to 0.2 %
Inductance***	0.05 to 2 μH	10 kHz to 1 MHz	0.2 to 8 %
	1 to 100 μH	10 kHz to 1 MHz	0.2 to 1.5 %
	100 μH to 10 H	1 kHz	0.03 to 0.3 %
	100 to 50 mH	10 kHz	0.08 to 0.15 %
Frequency	1 Hz to 12.4 GHz		1 part in 10^9
Time of Day			1.0 second

*Accuracy depending on range and frequency
**Measurement capability only
***Accuracy depending on inductance and frequency



*Calibrated using Metrology DC standards.

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

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

Code	Description	Manufacturer	Range	Accuracy (±)
ACV 1	Thermal Converters	Holt	100 V 10 Hz to 100 kHz	0.02 to 0.1 %
		Fluke	1.0 to 50 V	0.05 to 1 %
ACV 2	High Voltage Dividers	Julie	1 to 100 kV	0.25 %
ACV 3	Inductive Ratio Divider	ESI	Ratio only 1 ppm resolution 50 Hz to 10 kHz	1 to 100 ppm
ACV 4	AC-DC Transfer Standard	Ballatine	0.5 to 1000 V 10 Hz to 50 kHz	0.01 to 0.03 %
			0.5 to 1000 V 50 kHz to 100 kHz	0.05 %
			0.5 to 16 V 100 kHz to MHz	0.05 %
ACV 5	Shunts	Holt	5mA to 10 A 10 Hz to 5kHz	0.05 %
ACV 6	Digital Multimeter	Fluke	100 mV Range	0.005 % or 5 digits
			1 to 1000 V Ranges	0.005 % or 8 digits
ACV 7	Calibrated DC Voltage Source	Fluke	10 to 1000 V three ranges	0.005 % or 20 μV whichever is greater

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

Code	Description	Manufacturer	Range	Accuracy (±)
ACV 8	AC Calibrator	Hewlett Packard	1 mV to 100 V Range	
			10 to 20 Hz	0.2 % setting + 0.005 % + 50 μV
			20 to 50 Hz	0.05 % setting + 0.005 % F.S. + 50 μV
			50 Hz to 20 kHz	0.02 % setting + 0.002 % F.S. + 10 μV
			20 to 110 kHz	0.05 % setting + 0.005 % F.S. + 50 μV
			1000 V Range	
			10 to 30 Hz	0.2 % setting + 0.005 % F.S.
			20 to 50 Hz	0.08 % setting
			50 Hz to 20 kHz	0.04 % setting
			20 kHz to 50 kHz	0.08 % setting
			50 kHz to 110 kHz	0.15 % setting

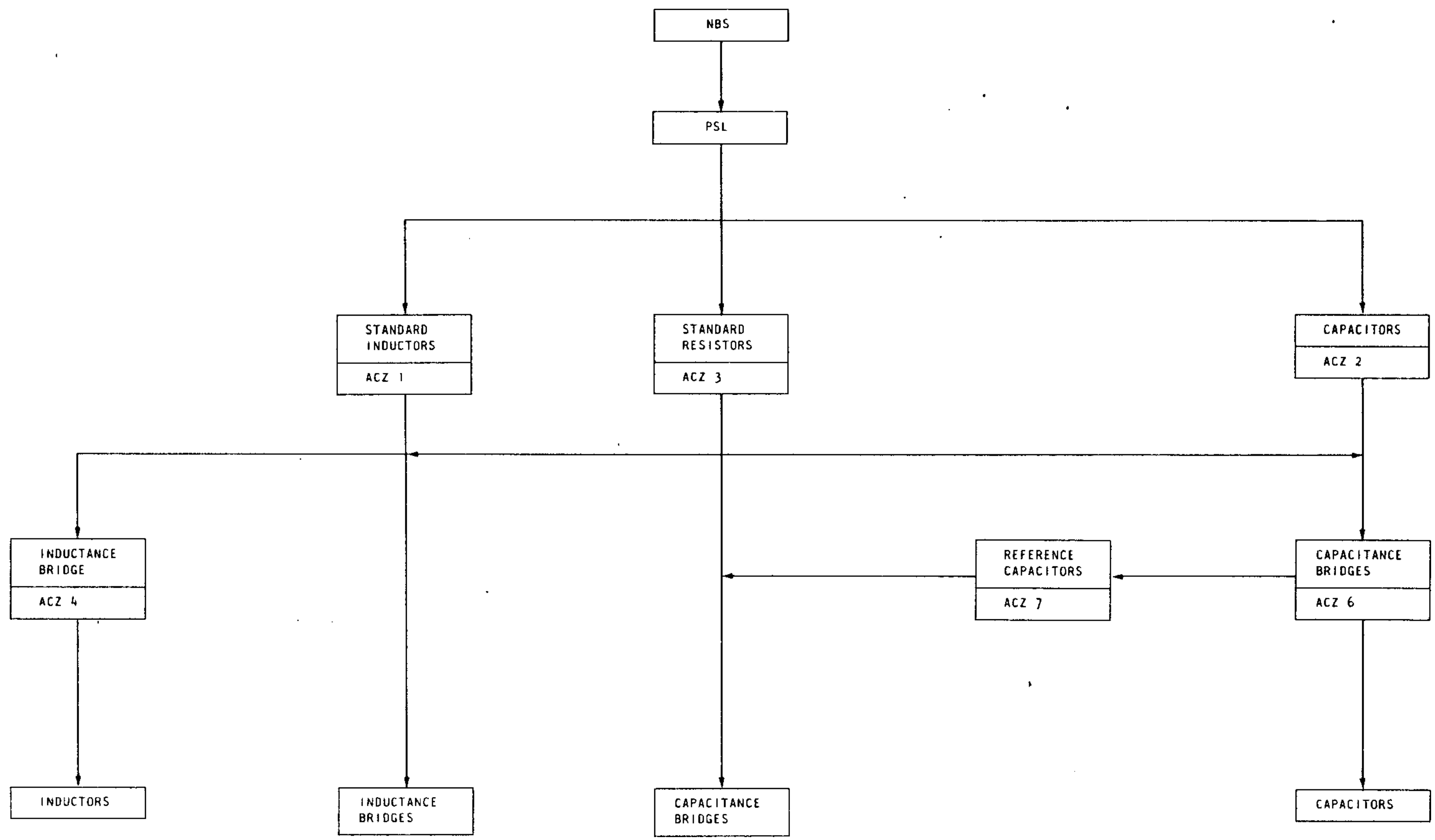


Figure 4C. Inductance and Capacitance Calibration Flow Chart

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

Code	Description	Manufacturer	Range	Accuracy (±)
ACZ 1	Standard Inductors	General Radio	100 μH to 10 H	0.03 to 0.3 %
		Bendix	50 nH to 100 μH	0.2 to 8 %
ACZ 2	Standard Capacitors	General Radio	1000 pF, fixed	0.004 %
ACZ 3	Standard Resistors	Leeds & Northrup	1 to 20K ohms	0.05 %
ACZ 4	Inductance Bridge	Hewlett Packard	100 μH to 5H (direct measurement)	0.15 to 0.3 %
			0.05 μH to 10H (comparison to standard inductors)	0.05 to 8%
ACZ 6	Capacitance Bridges	General Radio	0.001 pF to 1 μF	0.01 % + 0.00005 pF
			1 μF to 10 μF (at 1 kHz)	0.02 %
		Hewlett Packard	0.1 to 1000 pF at 1 MHz	0.1 to 0.2 %
ACZ 7	Reference Capacitors	General Radio	0.01 to 1000 pF	0.01 to 0.5 %
		General Radio	0.001 to 1 μF	0.02 %
		Bendix	1 to 10 μF in 1 μF increments	0.1 %
			10 to 100 μF in 10 μF increments	0.25 %

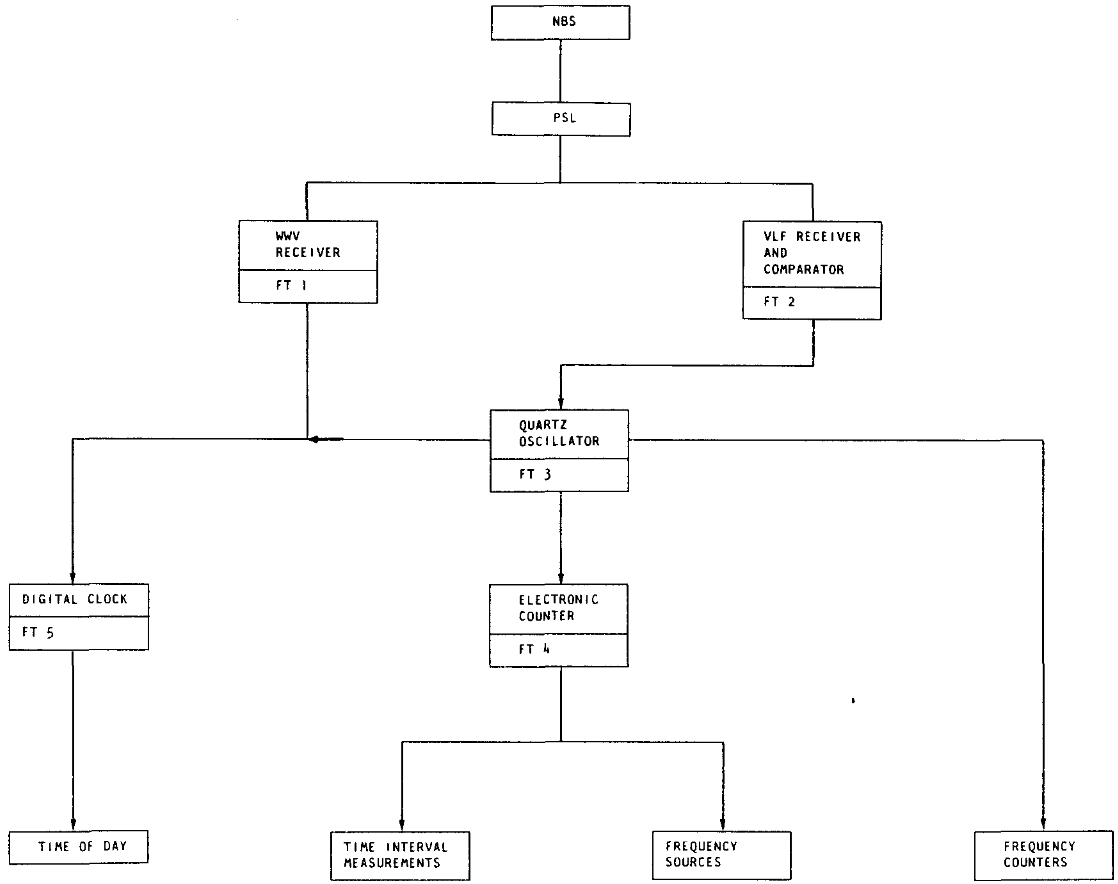


Figure 5C. Frequency and Time Calibration Flow Chart

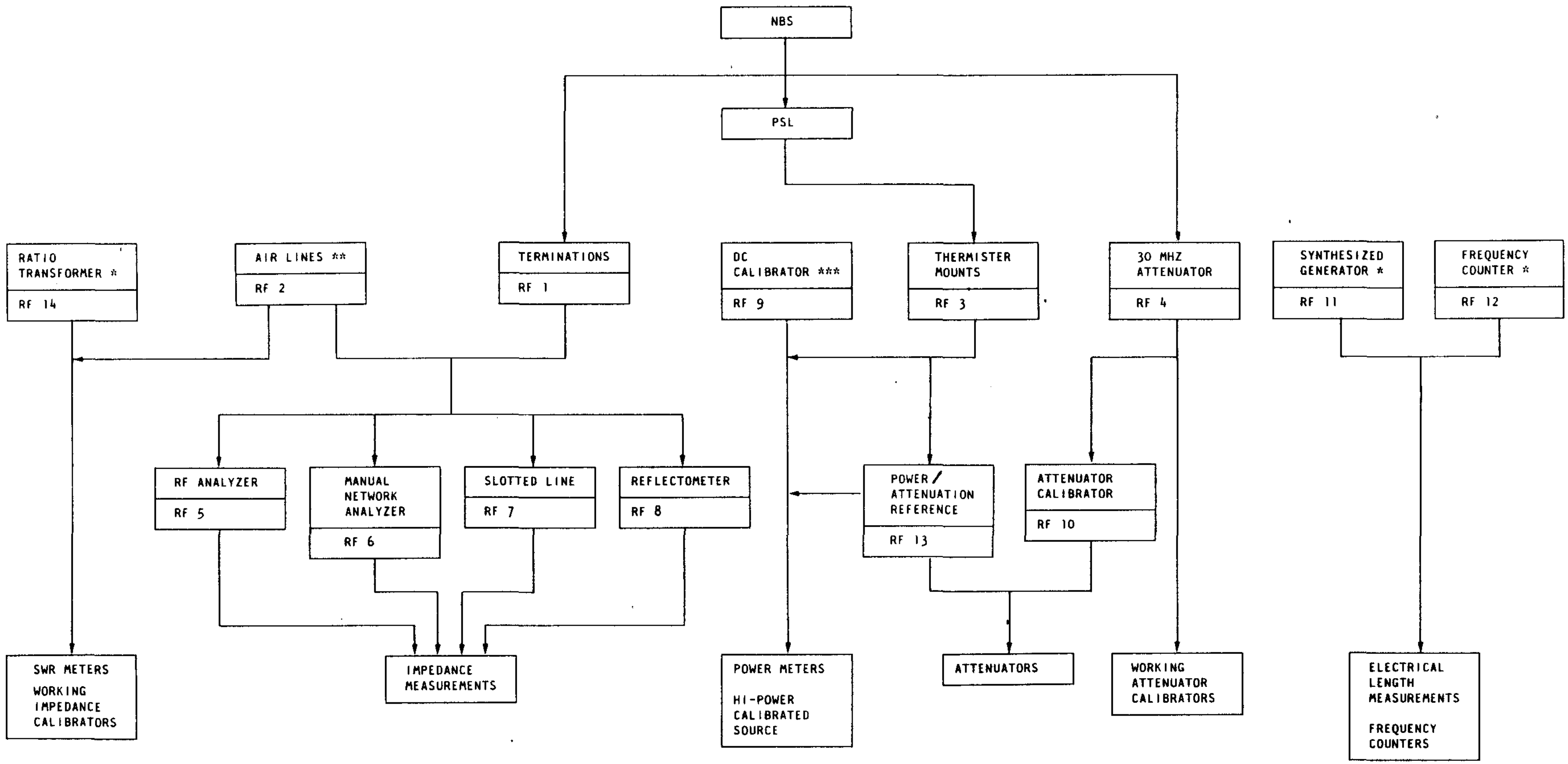
Table 7C. Frequency and Time Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
FT 1	WWV Receiver	Specific Products	2.5, 5, 10, 15, and 20 MHz	Comparison device
FT 2	VLF Receiver and Comparator	Fluke	20, 24, 60 kHz	Comparison device
FT 3	Quartz Oscillator	Hewlett-Packard	1 MHz	1 part in 10^9
FT 4	Electronic Counter	Hewlett-Packard	0 to 12.4 GHz	1 part in 10^6
FT 5	Digital Clock	Bendix	24 hours	1 second

Table 8C. Electrical Radio Frequency/Microwave Measurement Capability

Type	Range	Frequency	Measuring Accuracy (±)
RF Attenuation	0 to 80 dB	30 MHz	0.5 dB + 0.001 x measured attenuation*
	0 to 60 dB	10 MHz to 5.765 GHz	0.05 dB + 0.003 x measured attenuation*
RF Power	1 mW	10 MHz to 7.6 GHz	1.0 to 2.0 %
	10 uW to 10 mW	10 MHz to 7.6 GHz	2.3 to 3.0 %
	1 nW to 10 uW	10 MHz to 7.6 GHz	3.8 to 6.0 %
	10 to 100 mW	10 mHz to 7.6 GHz	6.4 to 7.3 %
	30 mW to 12 W	1509.5 MHz and 2.2 to 2.3 GHz	4.0 %
SWR	1:1 to 1.1:1	0.5 to 7.5 GHz	0.02 + 0.006 x frequency (GHz)
Reflection	0.0 to 1.0	1 to 1000 MHz	0.007 to 0.012 (GR-900 connector type)
Coefficient	0.0 to 0.8	0.5 to 7 GHz	0.0011 to 0.07

*Component SWR <1.2:1



*Calibrated using Metrology AC standards.
**Calibrated using Metrology dimensional standards.
***Calibrated using Metrology DC standards.

Figure 6C. Radio Frequency/Microwave Calibration Flow Chart

Table 9C. Radio Frequency and Microwave Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
RF 1	Termination	General Radio 14 mm type	Reflection coefficient 0 to 0.333, 5 to 1000 MHz	Magnitude 0.0007 to 0.005 Angle 0.03° to 180°
RF 2	Air Line	General Radio 14 mm type	50 ohm 0.25 to 8.5 GHz	0.0009 + 0.0001 x F in GHz*
		Maury 7 mm type	50 ohm 0.25 to 18 GHz	0.0018 + 0.0001 x F in GHz*
RF 3	Thermistor Mount	Hewlett Packard	1 mW, 10 MHz to 7.6 GHz	0.6 to 1.3 % mount efficiency
RF 4	30 MHz Attenuator	Weinschel Engineering	10 to 100 dB, 30 MHz	0.018 to 0.107
RF 5	RF Analyzer	Hewlett Packard	Reflection coefficient 0 to 1.0 1 to 1000 MHz	0.007 + 0.000 005 x F in MHz
RF 6	Manual Network Analyzer	Bendix	Complex reflection coeficient 0 to 1.0, 10 MHz to 7.6 GHz	Magnitude 0.0011 to 0.1 Angle 0.62 to 7 degrees

*Accuracy of Reflection Coefficient Magnitude

Table 9C Continued. Radio Frequency and Microwave Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
RF 7	Slotted Line	General Radio	SWR range: 1.0 to 1.3, 0.5 to 7.0 GHz	VSWR <(1.005 + 0.002 x F in GHz)
RF 8	Reflectometer	General Radio	SWR range: 1.0 to 1.10, 0.5 to 7.5 GHz	0.002 to 0.004 plus RF2 air line efficiency
RF 9	DC Calibrator	Hewlett Packard	Simulates RF power 1 nW to 100 mW	0.25 to 0.5 %
RF 10	Attenuator Calibrator	Weinschel Engineering	0 to 60 dB, 10 MHz to 5.765 GHz	0.05 dB + 0.003 x measured attenuation, component SWR <1.2
RF 11	Synthesized Signal Generator	Systron Donner	1 MHz to 18 GHz	1 ppm
RF 12	Frequency Counter	Hewlett Packard	1 MHz to 12.4 GHz	1 ppm + 1 count
RF 13	Power/Attenuation Reference	Bendix	2 to 20 dB 0.5 to 5.765 GHz	0.025 to 0.082 dB referenced to a 50 + j0 ohm system
RF 14	Ratio Transformer	ESI	50 Hz to 10 kHz	$10 + (F \text{ in kHz})^2$ ppm of input

OPTICAL AND RADIATION

OPTICAL RADIOMETRIC MEASUREMENT CAPABILITY

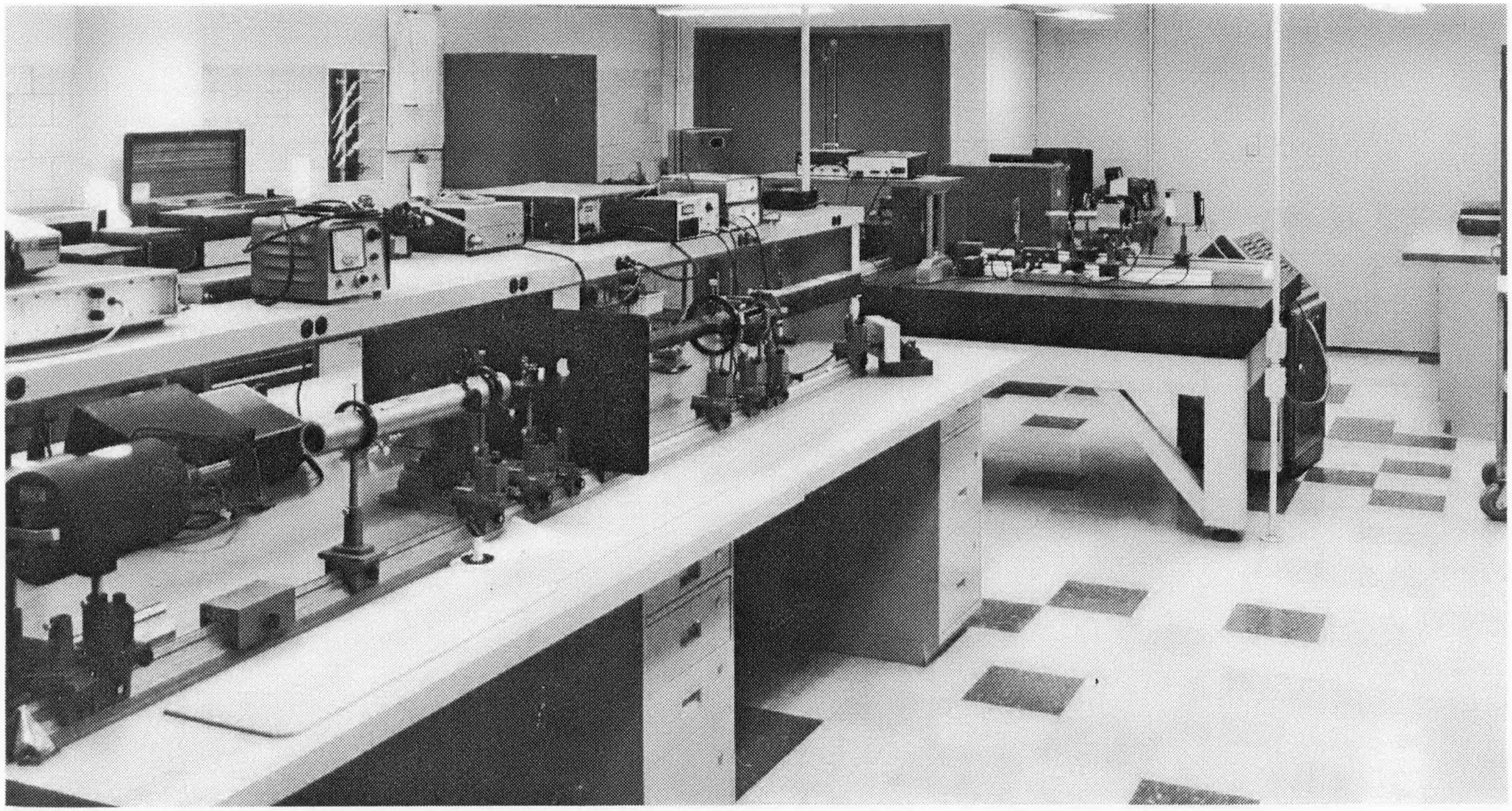
Radiometry is the measurement of radiation in the optical spectrum which includes ultraviolet, visible and infrared light. The main radiometric reference standards at BKC are heat-flow calorimeters and wavelength standards which include HeNe lasers and Hg lamps. The heat flow calorimeters are calibrated by the Primary Standards Laboratory. The wavelength standards do not require calibration because of their physical characteristics. Measurements performed include non-coherent 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 μm. Most of the radiometric calibration activity at Bendix Kansas City is measuring the power output and characteristics of the forementioned 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 BKC are Luminous Intensity Standard Lamps, a Luminous Directional Transmittance Standard, and Gloss Standards. The Standard Lamps are calibrated in units of candellas and are normally used with an optical bench to calibrate light meters in units of foot candles. These lamps also are used with the transmittance standard to calibrate brightness meters in units of foot lamberts. Gloss Standards are used to calibrate meters for measuring specular gloss of paint films.

RADIATION MEASUREMENT CAPABILITY

Radiation measurements are made using standards of alpha-particle emission rate from plutonium 239, lead-probe neutron detectors, and condenser R-meters for measurement of gamma/X-rays from 0 to 250 R. Alpha sources and lead probes are calibrated by the PSL. Condenser R-meters are calibrated by the NBS. Accuracy of these standards ranges from ±3% to ±10%.



Optical and Radiation Calibration Laboratory

Table 1D. 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	10 % 4 % 0.5 %
Laser Transmission	λ=633 nm, 1.064 nm, 10.6 μm, 0.1 to 100 %	1 %
Optical Spectral Response	350 to 400 nm 400 to 500 nm 500 to 1000 nm	15 % 5 % 2 %

Table 1D Continued. Optical Radiometric Measurement Capability

Type	Range	Measuring Accuracy (±)
Laser Average Power	λ=516 to 663 nm	
	1 to 100 μW	5 %
	100 μW to 1 W	4 %
	1 W to 10 W	5 %
	λ=1.064 μm	
	0.1 mW to 10 W	5 %
	10 to 100 W	7.5 %
	λ=10.6 μm	
	1 mW to 10 W	5 %
	10 to 1000 W	7.5 %
Laser Peak Power	λ=514 to 633 nm	
	Pulse length 20 ns to 1 ms	
	1 to 10 W	10 %
	λ=890 to 905 nm	
	Pulse length 20 ns to 1 ms	
	1 to 75 W	15 %
	λ=1.064 μm	
	Pulse length 20 ns to 1 ms	
	0.1 to 10 W	15 %
	10 W to 5 kW	20 %
LED Power	λ=570 to 910 nm	
	10 μW to 10 mW (CW)	6 %

Table 1D Continued. Optical Radiometric Measurement Capability

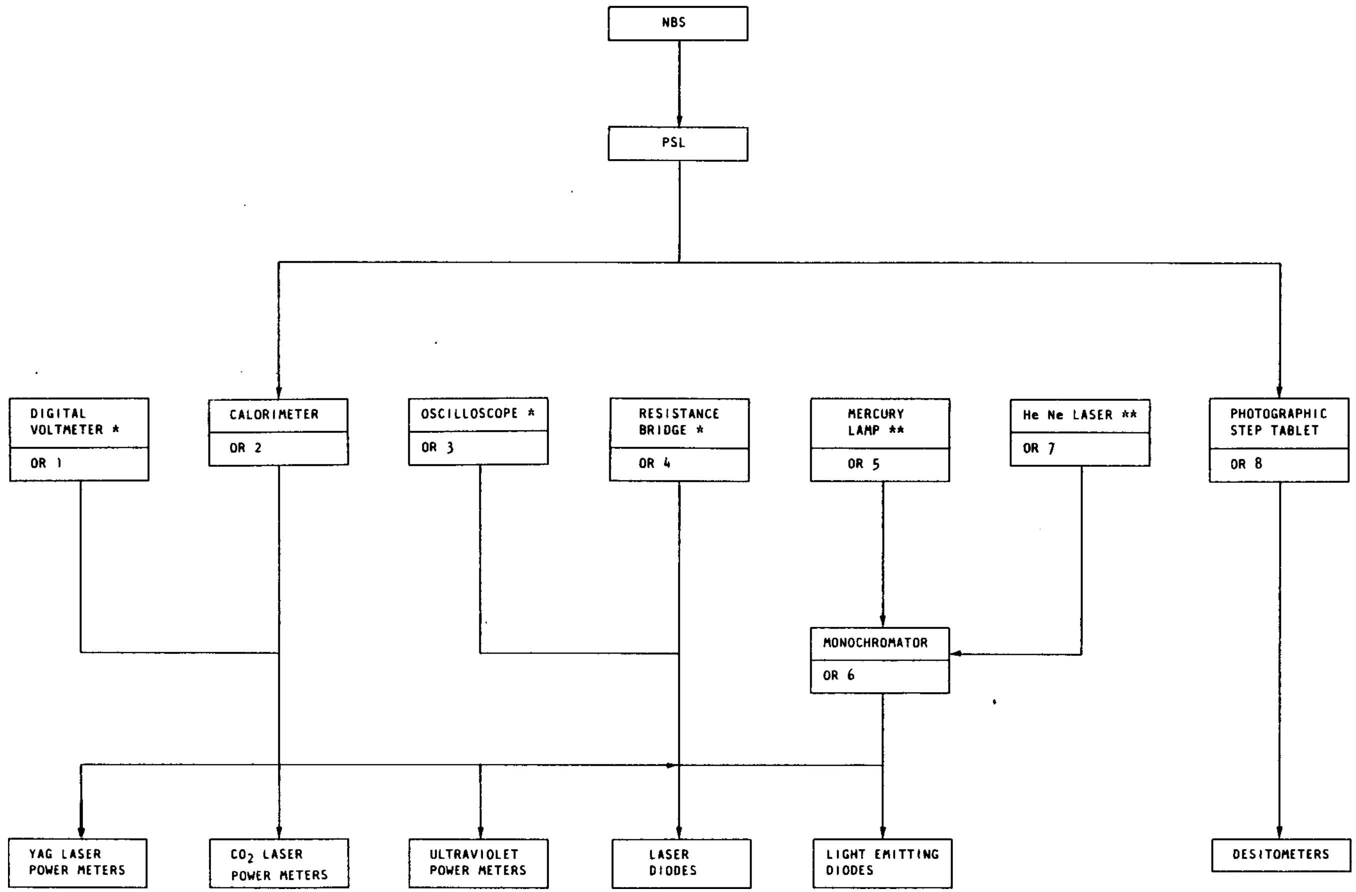
Type	Range	Measuring Accuracy (±)
Ultraviolet Power	λ=365 nm 0.1 to 10 mW/cm^2	15 %
X-Ray Film Density	0 to 4 visual monochromatic optical density	0.03 density scale units + 1 % of reading

Table 2D. Optical Radiometric Measurements Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
OR 1	Digital Voltmeter	Various	1 mV to 1000 V	0.01 % to 5 digits
OR 2	Calorimeter	Scientech	10 μW to 10 W	2 %
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	Better than 1 nm
OR 6	Monochromator	Jarrell Ash	365 to 1092.2 nm	1 nm
OR 7	HeNe Laser	Varous	6328 angstroms	Better than 1 angstrom
OR 8	Photographic Step Tablet	NBS	0 to 4 density	0.01 or 1 % whichever is greater

Table 3D. Optical Photometric Measurement Capability

Type	Range	Measuring Accuracy (±)
Illuminance	10^{-3} to 750 ft. candles	7.5 %
Specular Gloss	1 to 90 units ASTM 60 degrees	3 units
Luminuous Intensity	10 to 1000 candles	5 %



*Calibrated using Metrology standards.

**Independently Reproducible Standard

Figure 1D. Optical Calibration Flow Chart (Radiometric)

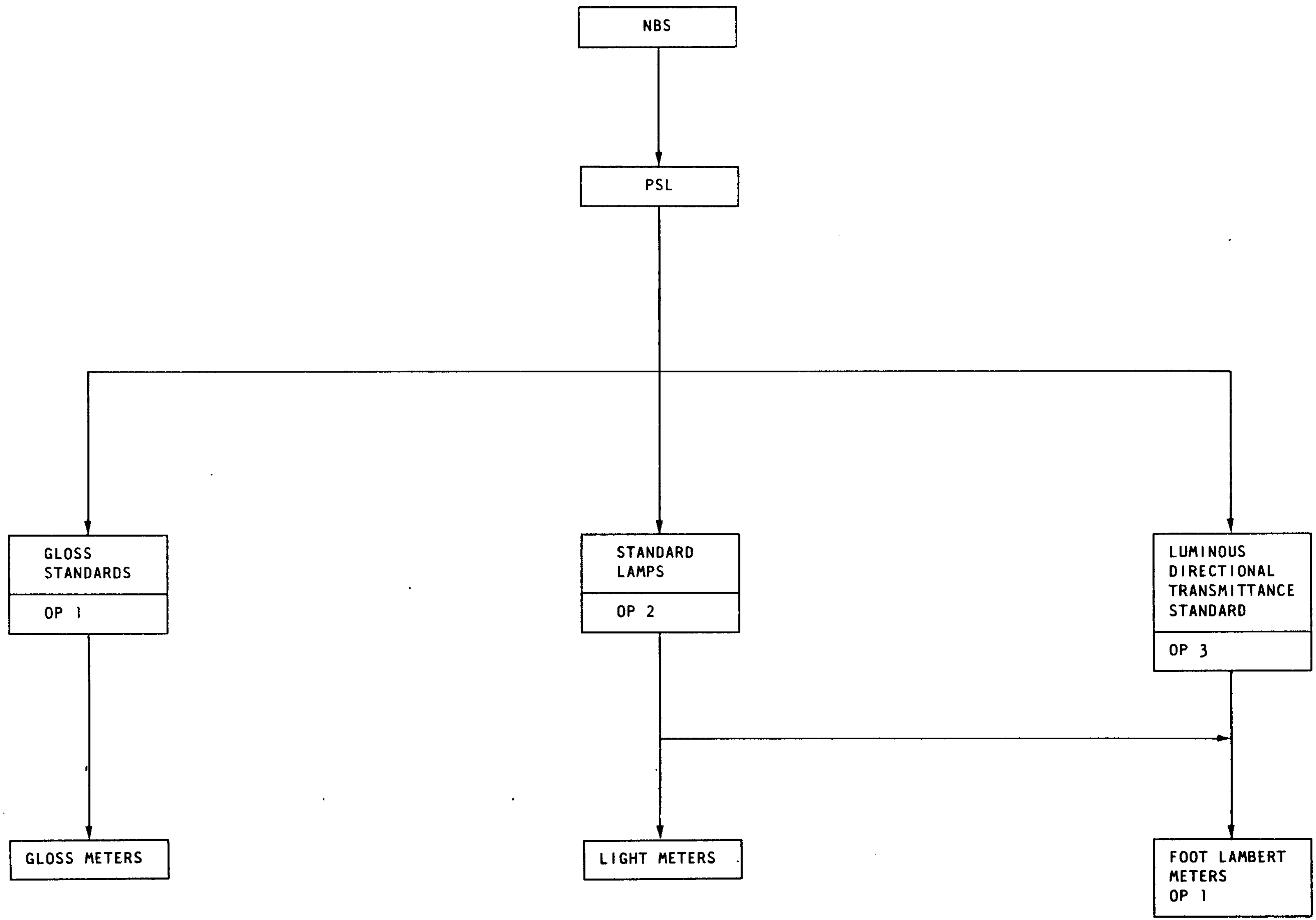


Figure 2D. Optical Calibration Flow Chart (Photometric)

Table 4D. Optical Photometric Measurements Code Description

Code	Description	Manufacturer	Range	Accuracy (±)
OP 1	Gloss Standards	Hunterlab	6 to 93.5 gloss units	3 gloss units
OP 2	Standard Lamps	NBS	90.5 to 706 candellas	4.1 %
OP 3	Luminous Directional Transmittance Standard	NBS	0.500 foot lambert per foot candle	10 %

Table 5D. Radiation Measurement Capability

Type	Range	Measuring Accuracy (±)
Alpha radiation	1590 to 1 530 000 particles/minute	3 %
Neutron radiation	14 mev neutron pulse 1×10^7 to 5×10^8 total neutrons	10 %
Gamma/X-Ray radiation	0 to 250 R	4 % of reading plus 1/2 division with NBS corrections