SAULT COLLEGE OF APPLIED ARTS & TECHNOLOGY

SAULT STE. MARIE, ONTARIO

COURSE OUTLINE

Course Title: ELECTRICAL METROLOGY

Code No.: ELN 312

Program: ELECTRICAL TECHNOLOGY AND ELECTRONIC TECHNOLOGY

Semester: 6

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APPROVED: L.P. Crozietto (Chairperson)   83/06/02 (Date)

CALENDAR DESCRIPTION

ELECTRICAL METROLOGY	ELN 312
Course Name	Course Number

PHILOSOPHY/GOALS:

To develop students' skills and knowledge in precision electrical measurement and calibration to a level necessary for performance of the following tasks:

1. Evaluation of an organization's test equipment needs.

2. Interpretation of test equipment specifications.

3. Planning a calibration facility.

4. Development of calibration procedures.

METHOD OF ASSESSMENT (GRADING METHOD):

Written tests.

Seminars, including written papers.

Satisfactory completion of laboratory projects and subjective evaluation of lab performance and behaviour.

A	75% or higher
B	66% - 74%
C	55% - 65%
R	less than 55%

TEXTBOOK(S):

Calibration - Philosophy & Practice. Fluke

Equipment Manufacturer's Manuals.

Application Notes - (Fluke)

Application Notes - (Hewlett-Packard)

ELECTRICAL METROLOGY

Course Outline

1. Standardized Calibration

   The need
   International and national hierarchies
   Classification of Standards
   Traceability and Certification
   Design Requirements of a Standards Laboratory

2. DC Measuring Instruments

   Amplifilier Drive - Techniques
   Differential
   Digital Read-out
   Guarding Techniques
   Selection of a DC Instrument

3. AC Measuring Instruments

   Classification by response - AVE, RMS, PEAK
   AC-DC Transfer Techniques
   The True RMS Voltmeter
   Distortion effects
   Selection of an AC Instrument
   The R.F. Millivoltmeter

4. Electrical Standards

   Voltage Standards, Standard Cells, Zener Transfer Standards, Josephson Junction Device
   Resistance Standards
   Capacitance Standards - The Calculable Capacitor
   Inductance Standards
   Magnetic Standards

5. Potentiometric Measurement

   Principles & application of Potentiometers
   Sources of Error
   Volt-Ratio Box
   Galvanometers
   Stability of Voltage Source
   Self-Balancing Potentiometer

6. DC Voltage and Ration Calibration Systems

Kelvin-Varley Voltage Divider
High Imedance null Detector
Lead Current and Thermal Effects
Universal Ratio Set
Self-Calibrating Systems

7. Time and Frequency Measurement

Standard Time and Frequency Broadcasts
Frequency Calibration
VLF Comparator
Cesium Beam Frequency Standard
Frequency Synthesizer

8. Microprocessing in Electrical Metrology

Self Testing
Auto-Calibration
Production Line Performance Testing
Automatic System Analysis and Reconfiguration

9. DC Current Comparator Equipment

DC/CC Resistance Bridge
DC/CC Potentiometers
AC/CC Capacitance Bridge
AC/CC Transformer Test Set

SPECIFIC OBJECTIVES

Block 1 - Standardized Calibration

1. Recall that the Metric Convention of 1875 signed by 17 countries, established the General Convention of Weights and Measures (GCWM) and the International Bureau of Weights and Measures (BIPM).

2. Recall that the GCWM is the governing body of the BIPM and meets every six years to consider any needed improvements to the standards.

3. Recall that the International Committee of Weights and Measures (ICWM) was established to implement the recommendations of the GCWM and to direct the activities of the BIPM. The ICWM meets every two years.

4. Recall that the International System of Units (SI) was established in 1960 by the GCWM.

5. Recall that the National Research Council (NRC) is responsible for the maintenance of Canadian national standards.

6. Recall that the National Bureau of Standards (NBS) is responsible for the maintenance of Primary Standards in the United States and was established to provide scientific services to Government, business, industry and science.

7. Recall that the NRC and NBS provide the following services:\
   - maintains national measurement standards
   - develops methods for accurate measurement
   - provides calibration services for governmental & industrial standards laboratories
   - conducts research in the above area and in the properties of matter and materials

8. Recall that the United Kingdom's national standards are maintained by the National Physical Laboratory under the authority of the Department of Trade and Commerce.

9. Recall that measurement standards are classified as follows:

   a) Absolute Standards

      Devices constructed to specifications based on the legal international definitions of the fundamental SI units - periodically checked by ABSOLUTE measurement as agreed by the GCWM.

   b) International Standards

      Absolute standards maintained by the BIPM as a reference for national standards. This comparison leads to a world average figure for national standards.

   c) National (Primary) Standards

      i. Absolute standard maintained by a National Laboratory as the National Standard.

      ii. Secondary standards from Government and industrial laboratories are referred to the National Standard.

      iii. Provides for certification of measured value in terms of primary standard.

d) <u>Secondary Standard</u>

i. Constructed from absolute standards.

ii. Maintained by Standards laboratories in industry and governmental departments.

iii. Calibrated against primary standards.

e) <u>Interlaboratory Standards</u>

Ruggedized equipments transported between National and Standards laboratories - used as check of accuracy between primary and secondary standards.

f) <u>Working Standards</u>

i. Principle tools of Standards laboratories used in calibration of field equipments.

ii. Used in industrial quality control departments to check field measurement equipment.

g) <u>AC-DC Transfer Standard</u>

Precise AD-DC transfer instruments used for measuring AC currents or voltages by comparison with equal, known DC quantities.

10. Recall that the quantitative value of a standard must be traced in an unbroken chain to the national standard. All links must be certified by a standards laboratory or NRC and with reasonable additional tolerance for each additional ink.

ELECTRICAL METROLOGY

Calibration Laboratories

Certification and Traceability

SPECIFIC OBJECTIVES:

1. Recall the following general specifications of a good standards/ calibration laboratory.

    a) Lighting to provide 100 ft. candles at bench level.
    b) Temperature $72^{\circ}F + 5^{\circ}F$ ($23^{\circ}C$ or $25^{\circ}C$ in North America, 20 = 1 C in UK).
    c) Lamina-air-flow benches.
    d) Elimination/exclusion of corrosive vapours and dust. Dust filters should ensure 90% dust separation (grain size 3 50 5 m). Slight pressurization.
    e) Relative humidity 50% + 2%.
    f) Isolation from RF interference.
    g) Isolation from shock and vibration.
    h) Restricted admission.
    i) Air change 24 times per hour (typical).
    j) Filtered and stable AC power supply.
    k) Excellent "earth" system.
    l) Nard, smooth (melamine) surfaces on walls and ceilings to reduce build up of contamination.
    m) Air lock entrance with decontamination features.
    n) Control metal parts likely to cause measurement errors.
    o) Lab clothing.

2. Recall that mobile calibration centres have an added requirement that its equipment, through design or special mounting, must be resistant to shock.

3. Recall that only Primary Laboratories and NRC (NBS in USA) can CERTIFY equipment and standards since only these have reference standards and measuring devices of the required order of accuracy. (See Item 4).

4. Recall that in order for a device to be certified AT LEAST THREE INDEPENDENT DETERMINATIONS OF THE ABSOLUTE VALUE OF A FIXED STANDARD (Guage block, resistor, capacitor, etc.) must be used. The calibratic record should include the results of all three determinations along with the arithmetic average of the three and their deviation or range (largest recorded value minus smallest value.)

5. Recall that the Secondary Standards labs relate their measurements to Primary Labs (or to NRC/NBS if accuracy requirements demand) and must document this TRACEABILITY.

SPECIFIC OBJECTIVES .....continued

6. Recall that an Industrial Standards lab relates its measurements to an of the foregoing three lab classes or may itself be a Secondary Standards Lab.

THE MODERN METRIC SYSTEM (Included as a review only)

1. Recall that the six base of fundamental units of measurement defined i the International System of Units (SI) are: Meter, Second, Kilogram, Kelvin, Ampere, Candela.

2. Recall that the first four are ABSOLUTE units and that all other units of measurement are derived from them.

   The change over the Absolute System made no difference in the maintenance of national standards, but numerical values were reassigned in accordance with Table 1

Quantity	Unit	Conversion Factor
Resistance	Ohm	1.000495
Electromotive force	Volt	1.000330
Current	Ampere	0.999835
Charge	Coulomb	0.999835
Inductance	Henry	1.000495
Capacitance	Farad	0.999505
Energy	Joule	1.000165
Power	Watt	1.000165

Units in the Absolute System of Measurements are related by means of conversion factors to "The International Units" which were abandoned for the MKS (SI) system.

3. Recall that the International Units of the CGS system, and the British System of Units although still in use are now obsolescent and are gradually being abandoned for the MKS (SI) system.

4. Recall that the Ampere is the absolute unit for the foundation of the legal system (MKS) of electromagnetic units.

5. Recall that:

   a) the science of electromagnetism relates electric and magnetic quantities by means of a set of exact mathematical equations.

   b) the practical units for measuring the quantities (see Table 1) are related by exact definitions based on the equations in "a" above.

   c) the practical electromagnetic units can all be traced back to absolute dimensions (See Table 1 and attached chart).

<u>TABLE 2 - The Rationalized MKS (Practical) System of Electromagnetic Units and Dimensions</u>.

Quantity	Unit	Dimension
Current	Ampere	1
Emf and Potential	Volt	$ML^{2}I^{-1}T^{-3}$
Resistance	Ohm	$ML^{2}I^{-2}T^{-3}$
Charge	Coulomb	IT
Inductance	Henry	$ML^{2}I^{-2}T^{-2}$
Capacitance	Farad	$M^{-1}L^{-2}I^{2}T^{-4}$
Inductive Reactance	Ohm	$ML^{2}I^{-2}T^{-3}$
Capacitance Reactance	Ohm	$ML^{2}I^{-2}T^{-3}$
Energy	Joule	$ML^{2}T^{-2}$
Power	Watt	$ML^{2}T^{-3}$
Mmf	Ampere turn	IT
Mangetic Flux	Weber	$ML^{2}I^{-1}T^{-2}$
Pole Strength	Unit Pole	$ML^{2}I^{-1}T^{-2}$
Frequency	Cycle/Sec	T^{-1}

TABLE 2 - continued

Absolute quantity: all others are derived.
Based on current in one turn of a conductor.

6. Recall that although any group of fundamental (electromagnetic) units may be used to derive the other units, voltage and resistance were chosen. accurate standard models can be obtained from standard cadmiu cells and manganin wire resistors.

7. Recall the definition of absolute measurement - "One that can be referred to absolute dimensions". (See Objective 2 above.)

SPECIFIC OBJECTIVES:

BLOCK 3 - DC MEASURING INSTRUMENTS

1. With the aid of diagrams recalled from memory, describe the following techniques employed in high quality DC measuring instruments.

   a) amplifier driven - DC and "Chopper"
   b) Differential - including both manual and servo balance
   c) Automatic Digital Readout
   d) Automatic polarity and overrange protection
   e) Automatic range selection

2. Given a set of task statements, prepare performance rating information (specification sheet) for a DC instrument. The following information must be included:

   a) accuracy
   b) range
   c) stability
   d) response time
   e) input characteristics
   f) normal mode interference rejection
   g) common mode interference rejection
   h) output characteristics
   i) extreme operating conditions

3. With the aid of diagrams recalled from memory, explain how the response to extraneous noise can be reduced by guarding and shielding.

4. Given a performance rating, together with price and availability information, select a suitable measuring equipment and prepare data in support of the choice.

5. Perform precision calibration of a DC measuring instrument.

BLOCK 4 - AC MEASURING INSTRUMENTS

1. With the aid of diagrams recalled from memory, compare the characteristics of the four classes of AC measuring instruments:

   a) average responding
   b) RMS responding
   c) Peak responding
   d) true RMS

2. Draw a functional block diagram of a True RMS voltmeter and explain it operation.

3. Given a set of task statements for an AC measuring instrument, prepare a specification document, select a suitable instrument and prepare dat in support of the choice.

4. Perform precision calibration of an AC measuring instrument.

BLOCK 5 - ELECTRICAL MEASUREMENTS STANDARDS

A. Standard Resistor

1. Draw a sketch to show the construction of a primary standard resistor. (See fig. 4-6 attached).

2. Recall that the resistance wire (or strip) is usually made of manganin alloy whose temperature co-efficient is almost zero.

3. Given the expression: $R_t = R_{25^oC} + A\ (t-25) + B\ (t-25)^2$ and the numerical value of co-efficients A and B, determine the true resistance for the ambient temperature.

4. Recall that for a change of $+10^oC$, the resistor value changes between 30 and 60 ppm.

5. Recall that these resistors should be used in DC measurements only since the value of R is affect by:

   inductance of the winding
   distributed capacitance
   dielectric properties of the insulation
   skin effect
   capacitance with surrounding objects.

6. Recall that specially designed standard resistors are available for use up to 3000 Hz and that resistors now being developed will have the same resistance value at the comparison frequency as at DC.

7. Recall that transfer-standard resistors are specially supported to withstand shock and vibration and are immersed in a moisture free oil.

8. Recall that the calibration report should show:

   measured value in absolute ohms
   Specified traceability to National Standard
   Numerical value of co-efficients A and B
   Special conditions of testing

9. Recall that standard resistors are used in the construction and calibration testing of:

Precision resistors	Precision decade dividers
Precision potentiometers	Precision ratio boxes

10. Explain that the four terminal resistor is preferable to two terminals because circuit current does not flow through the voltmeter contact-resistance and therefore does not affect the voltage across the standard resistance.

11. Recall that the National standard of resistance consists of a group of 10 resistors immersed in a temperature controlled oil bath.

B. <u>Voltage Standards</u>

1. Draw a sketch to show the construction of a saturated Weston (standard cell. (See fig. 3-3 attached).

2. Recall that the output of the saturated cell decreases by 40 volt for each 1°C increase in temperature.

3. Recall that the annual drift of the saturated Weston cell is in the order of 1 Volt.

4. Recall that secondary standards are usually unsaturated Weston cells. The electrolyte is saturated at 4°C.

5. Recall that the output of the unsaturated cell varies 0.01% from 10°C to 40°C.

6. Recall that the internal resistance of the Weston working standard lies between 500 and 800 ohms and that the current drawn SHOULD NOT EXCEED 100 A. Current drain on a laboratory standard should be limited to only a few micro amps.

7. Recall that because of the variation of individual cells all standards laboratories rely on the characteristics of the mean value of a group of standard cells. At NRC the basic group consists of 18 cells maintained in a fixed position, constant temperature circulating oil bath at an ambient temperature of 28°C in a controlled temperature lab at 21°C. There is now a secondary group of 12 cells whose history allows their replacement of a faulty cell in the basic group.

8. Recall that cells employed as interlaboratory standards are preferably "hand carried" and are contained in temperature controlled housings with automatic changeover to standby (battery) power.

9. Recall that an over-all temperature change may produce hysteresis error - rapid change in EMF with gradual return to nearly the original value. Compete recovery may take several hundred hours.

10. Perform intercomparison of standard cells and assess the quality of the individual cells in a group as an aid to assessing the reliability of the assumed constant mean value of the group.

Zener Diode

11. Recall that transfer and working standards sometimes employ Zener Diodes in a temperature controlled enclosure.

12. With the aid of sketches, explain in qualitative terms, the operation of a voltage standard employing a josephson Junction Device.

C Standard Capacitor

1. Recall that the unit of capacitance is derived from the ohm and the second, and that capacitors constructed as standards are calibrated on this principle with a Maxwell commutator bridge. (See fig. 4.8 attached).

2. Draw a simplified circuit diagram and explain in qualitative terms, th operation of the Maxwell commutator bridge.

3. Recall that standards of capacitance are constructed of interleaved square plates with air dielectric, and the distance between plates ver accurately known.

4. Recall that secondary and working standard capacitors with air or mica dielectric ar available.

5. With the aid of diagrams recalled from memory describe the calculable capacitor, list its applications and its advantages over earlier standards.

D Standard Inductance

1. Recall that construction of the primary inductance standard was based on the ohm and the farad.

2. Recall that the commercial standard inductors are available in sets ranging from 100 micro-Henries to 10 Henries, accurate to 0.25% at 100 Hz.

3. Recall that when using commercial standard conductors, the specified considers for distributed capacitance must be observed.

E Magnetic Standards

1. Recall that the unit of magnetic flux, the weber, is derived from the henry and the ampere.

2. Recall that in determining standard flux known current changes are applied to a standard mutual conductor and a ballistic galvanometer is used to measure flux changes in terms of angular deflection. Deflections are then used to calculate flux in webers.

3. Draw a sketch to show the construction of the Hibbert magnetic flux standard and explain its operation in qualitative terms. (See Fig. 4. attached).

4. Recall that the Hibbert device is secondary standard and must be calibrated against the absolute mutual inductance.

5. a) Recall that portable secondary standard solenoids are available. The flux at the centre of the coil is determined by the expression:

   = NIA webers

   Where N = number of turns per meter
   I = current in amperes
   = permeability of free share (4 x 10^{-7})
   A = Cross sectional area in square meters.

   b) If the ratio length to radius is 40, the flux near the ends will differ from that at the center by only 0.13%.

VOLT TRANSFER STANDARD

Versatile laboratory working standards have been developed with accuracies in the order of standard cell accuracy. Figure 3-5 shows a photograph of multipurpose laboratory voltage standard, called a transfer standard, base on the operation of a Zener diode as the voltage reference element. The instrument basically consists of a Zener-controlled voltage source placed in a temperature-controlled environment to improve its long-term stability and a precision output voltage divider. The temperature-controlled oven i held to within +0.03°C over an ambient temperature range of 0°C to 50°C, providing and output stability in the order of 10 ppm/month. The four available outputs are (a) a 0-1000 V source with a 1-V resolution, called (   ); b) a 1.000-V reference for voltbox potentiometric measurements; c) a 1.018 + (   ) reference for saturated cell comparisons; d) a 1.0190 + (   ) reference for unsaturated cell comparisons. The DC transfer standard can be used as a transfer instrument and can be moved to the piec of equipment to be calibrated, since it can easily be disconnected from th power line at one location and set up at a different location where it wil recover to within +1 ppm in approximately 30 minutes warm-up time.

FIG. 3-5 A DC transfer standard that can be used as a 1.000-V referenc source, a standard cell comparison instrument, and a 0-1,000 DC Source. (Courtesy Hewlett Packard Co.)

BLOCK 6 - MEASURING BRIDGES - AC & DC

1. With the aid of diagrams recalled from memory, discuss the characteristics of the measurement bridges listed below:

   a) wheatstone
   b) Kelvin
   c) Maxwell
   d) Hay
   e) Schering

2. Given circuit values and/or conditions, resolve problems related to th above bridges in the balanced or unbalanced condition.

3. Given circuit diagrams, explain the operation and discuss the characteristics of the following bridges:

   a) Julie
   b) Dauphinee
   c) Wien
   d) Universal

BLOCK 7 - POTENTIOMETRIC MEASUREMENT

1. With the aid of drawings recalled from memory, describe the potentiometer technique of DC calibration.

2. a) List and explain, illustrating where necessary, the precautions to be observed in precision potentiometric measurement.

   b) Discuss the characteristics of the equipments listed below and explain how each affects the quality of measurement.

      volt-ratio box
      galvanometer
      voltage source

3. Given the circuit details, resolve problems related to potentiometric measurement.

4. Demonstrate the ability to calibrate a digital or analog multimeter using the poteniometer method.

5. With the aid of a diagram recalled from memory, explain the operation of a self-balanced potentiometer.

BLOCK 8 - DC VOLTAGE AND RATIO CALIBRATION SYSTEMS

1. Recall that electrical calibration and measurement frequently involves the determination of a ratio and that in such instances it is more convenient to perform a single ratio measurement rather than take a series of readings and calculate the ratio.

2. Recall and describe typical ratio mesurements in order to illustrate the advantages of this technique.

3. With the aid of diagrams recalled from memory, describe the construction, operation, calibration and use of direct-reading and universal ratio sets.

4. With the aid of diagrams recalled from memory, describe the operation of a Kelvin-Varley Voltage Divider; discuss and explain its advantages over other ratio sets.

5. Describe and explain with illustrations a technique for calibrating a K-V voltage divider.

6. Using the K-V voltage divider and the fluke reference divider, demonstrate the ability to:

   a) calibrate a voltage divider
   b) calibrate a voltage source
   c) determine the value of an unknown resistor

INS FREQUENCY CALIBRATION

SPECIFIC OBJECTIVES

1. Recall that:

   a) Time keeping has two distinct aspects - INTERVAL and EPOCH (When the event occurred)

   b) Time-of-day (epoch) is measured in terms of the UNIVERSAL TIME (UT) scale based on the earth's rotation

   c) Universal Time corrected for both observed polar motion and seasona variations in designated UT.

   d) To avoid non-uniformity of UT, astronomers adopted (1956) EPHEMERIS TIME based on the motion of the earth during the year 1900.

e) Although Ephemeris Time is now being superseded by Atomic Time (Cesium Beam), no change in the size of the unit is involved. This is because the second of atomic time was deliberately chosen to agree as closely as experimentally as possible with the Ephemeris second.

2. Recall that comparison of local standards with the U.S. Frequency Standard is made possible by the following frequency and time standard broadcast stations.

WWVL	20 Hz
WWVB	60 Hz
WWV	2.5; 5; 10; 20; 25 MNZ
WWVH	2.5; 5; 10 MHZ

3. Recall that even at great distances the frequency comparison accuracy that can be achieved over 24 hours with very low frequencies (VLF) exceeds that which could be realized by use of high frequency transmissions over months.

4. Recall that when a VLF comparison system is used, the degree of precision will depend on the duration of the test as listed below provided the instrument being calibrated is capable of such accuracy.

a) 1 in 10^8 - almost instantaneous direction comparison
b) 1 in 10^9 - sufficient duration to reveal any ionospheric disturbances
c) 1 in 10^{10} - 8 hours
d) 2 in 10^{11} - 24 hours
e) parts in 10^{12} - 30 days

5. Draw a simplified block diagram of a typical VLF Comparator system and describe its operation.

6. Recall that station WWVB broadcasts a 60 KHz carrier which is referenced to the atomic second rather than the second of Universal time.

7. Using the VLF Comparator, determine the frequency offset, long term and short term drift of the HP 5245 L frequency clock and the fluke frequency synthesizer.

8. With the aid of a block diagram recalled from memory, describe the theory of operation of a Cesium Beam Frequency Standard and discuss its advantages over other frequency standards.

BLOCK 10 - MICROPROCESSORS IN ELECTRICAL METROLOGY

1. With the aid of suitable diagrams recalled from memory, describe achievement of the following functions of measurement/testing systems under microprocessor control:

   a) self testing
   b) automatic calibration
   c) auto-ranging
   d) performance testing on the production line
   e) automatic system analysis together with reconfiguration in the even of failure.

BLOCK 11 - DC CURRENT COMPARATOR BRIDGE

1. Recall that the use of ratio transformers with their excellent ratio stability, high magnetizing impedance and low leakage has led to new methods in the comparison of AC currents.

2. Recall that the current comparator is a current ratio indicator based on the detection of a zero flux condition in a magnetic core.

3. Explain in descriptive terms how a magnetic modulator enables the comparison of DC currents using a ratio transformer.

4. With the aid of a block diagram recalled from memory, describe the operation of a DC current comparator (DC/CC) employing automatic ampere - turn balance.

5. Recall that a DC/CC bridge may be designed for use as a potentiometer or it may be designed to give direct readings in ohms.

6. Give a circuit diagram of a DC/CC resistance bridge, explain the circuit operation in both the calibrate and measure modes.

7. Recall that bridge balance is indicated by two simultaneous balances: a voltage balance and an ampere - turn balance.

8. With the aid of a simple diagram recalled from memory, describe the operation of a DC/CC potentiometer in both the standardizing and measuring modes.

obtained by the use of a resistive divider which diverts one-tenth of the primary current into a switched ten-turn winding. Each step of the fourth dial therefore switches in one-tenth of the primary current through on turn, thus producing one-tenth of the M.M.F. produced by each step of dial 3. To ensure an overall accuracy on one part in 10^7, the current divider resistors require a minimum accuracy of one part on 10^4 or + 0.01%. In actual manufacture the ratio is adjusted to less than 0.001% and drift rates of less than 0.001% per year can be expected.

10. Recall that the usable sensitivity of the magnetic modular is limited by its zero stability which is affected by temperature and my amplitud of output of the driving oscillator. In order to improve stability, the cores are driven to the same degree of saturation, independent of temperature. This is accomplished by a feedback signal generated by core saturation and used to control the switching point of the square wave oscillator.

STUDENT TEXTS:

1. Electrical Metrology Notes - Sault College

2. Calibration - Philosophy in Practice - Fluke

REFERENCES

a. Electronic Instrumentation and Measurement Techniques - Cooper (Prentice-Hall)

b. Electronic Precision Measurement Techniques and Experiments - Philco (Prentice-Hall)

c. Handbook of Electronic Instruments and Measurement Techniques - Thomas & Clark (Prentice-Hall)

d. Electrical Measuring Instruments and Measurements - Karsa

e. Precision DC Measurements and Standards - Lupold

f. Precision Measurements and Calibration - NBS Spec 300 Vol. 3

g. Hewlett-Packard Application Notes

h. Fluke Application Bulletins