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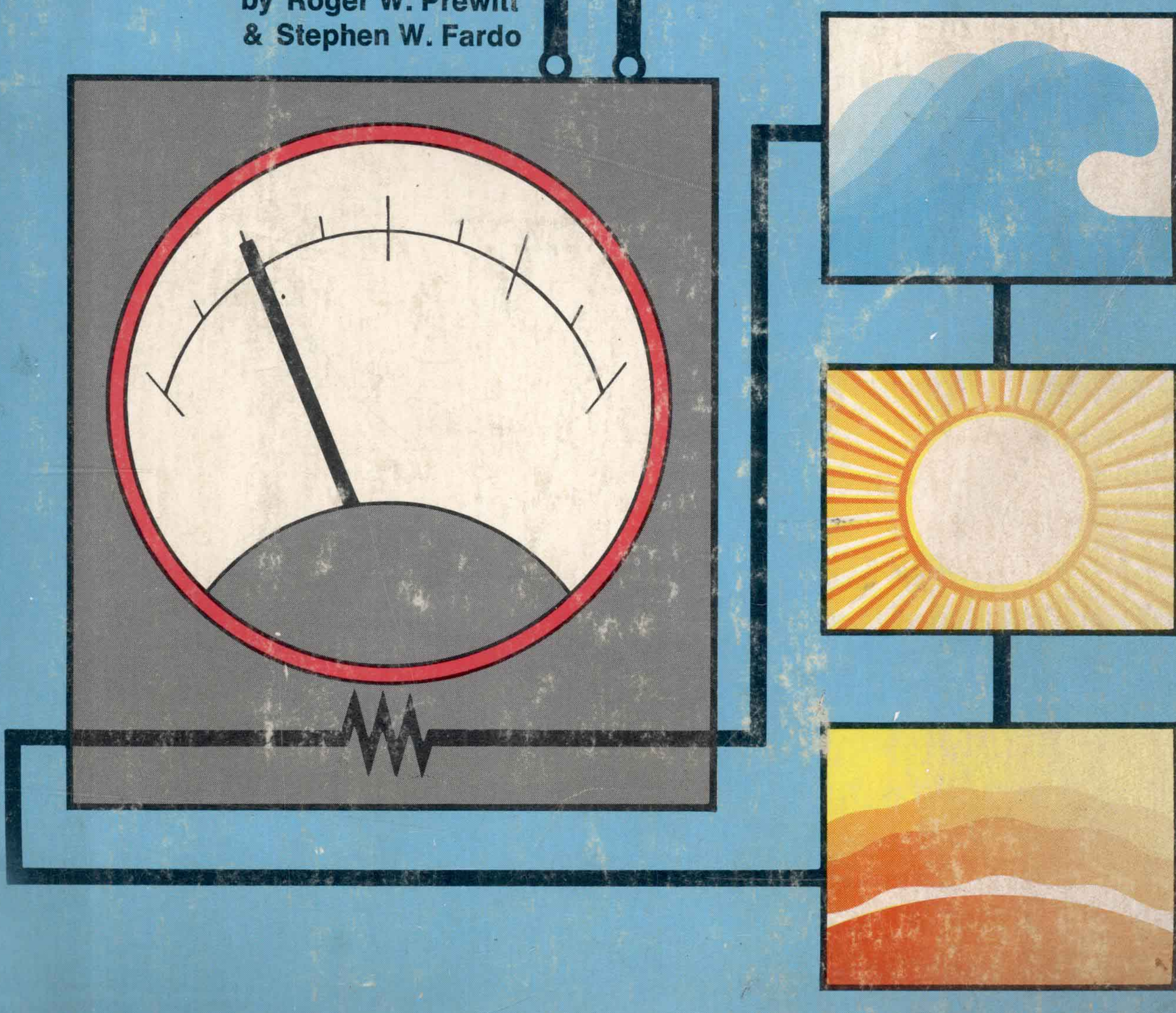
# Instrumentation: Transducers, Experimentation, & Applications

by Roger W. Prewitt
& Stephen W. Fardo



# Instrumentation

## Transducers, Experimentation, & Applications

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Roger W. Prewitt, Associate Professor
and
Stephen W. Fardo, Associate Professor

Department of Industrial Education and Technology
College of Applied Arts and Technology
Eastern Kentucky University

Howard W. Sams & Co., Inc.
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# Preface

This laboratory oriented activities manual can be used by vocational/technical or college-level instrumentation programs. The unique aspect of this manual is that it does not deal with the use of specific instruments. However, completion of the activities in this manual will provide the student with an in-depth understanding of instrumentation and measurement. The student will learn *how* measurement systems operate, not just how to operate a particular instrument. The cost of the lab equipment required to complete these activities is very low. No massive equipment is needed.

The approach taken in this manual is to acquaint the student initially with instrumentation and measurement systems. The basics of measurement, such as units of measurement, scientific notation, and metric measurement, are presented in the first unit of activities. Basic meter design and measurement circuits are then investigated. These include current, voltage, and resistance measurements, bridge circuits, oscilloscope measurements, and numerical readout devices.

Unit 2 deals with thermoelectric transducers used for instrumentation systems, such as thermocouples, thermistors, and rtd's.

Unit 3 investigates photoelectric transducers, such as photoconductive, photoemissive, and photovoltaic devices, that are used in instrumentation systems.

Unit 4 is designed to explore miscellaneous types of transducers, including potentiometric, capacitive, inductive, and resistive transducers.

Unit 5 provides some practical applications of instrumentation circuits for measuring physical quantities. These include the measurement of humidity, pressure, gas flow, liquid flow, and pH.

This manual presents a basic approach to instrumentation. Any institution which has electricity/electronics programs could build an instrumentation course around it. The basic equipment and materials, such as power supplies, meters, resistors, capacitors, and potentiometers, would most likely be available in any laboratory. The remaining materials necessary to complete these activities are primarily small components, such as photoelectric and thermoelectric devices, which are used as instrumentation transducers. The cost would be exceptionally low for adding a one-semester course in instrumentation. Specialized instrumentation techniques, such as calibration, are beyond the scope of this manual.

The authors would like to thank their wives, Mary Ann and Helen, for their cooperation and patience during the preparation of this manuscript.

ROGER W. PREWITT
STEPHEN W. FARDO

# Laboratory Equipment and Components

The following list of equipment and components is necessary for the successful completion of the activities included in this laboratory manual.

**Resistors** (1 W unless specified)

100 Ω
150 Ω
220 Ω, 2 W
270 Ω
365 Ω
390 Ω
470 Ω (8)
560 Ω
650 Ω
680 Ω
1 kΩ
1.2 kΩ, 20 W
2 kΩ
2.7 kΩ
4.7 kΩ
5.6 kΩ
6.8 kΩ
10 kΩ, 2 W
12 kΩ
15 kΩ
20 kΩ
25 kΩ
33 kΩ
120 kΩ
100 kΩ (2)
200 kΩ (2)
1 MΩ
5.6 MΩ

**Potentiometers** (1 W unless specified)

200 Ω
1 kΩ
1.5 kΩ
2.5 kΩ
5 kΩ
10 kΩ
25 kΩ
50 kΩ
500 kΩ

**Transformers, Inductors, and Coils**

Center-tapped oscillator coil
30-mH choke coil
Air-core coils, 100 turns, A.S. No. 16 wire (2)
Air-core coil, 200 turns, A.S. No. 24 wire
Audio output transformer, 2.5-H primary

**Capacitors** (50 Vdcw unless specified)

50 μF
20 μF
1.5 μF
1 μF
0.1 μF, 200 Vdcw
0.01 μF
0.02 μF
24 pF
47 pF
20–150 pF (variable)

**Semiconductors**

Diodes: IN4004 (4)
Transistors: 2N2405 (2)
2N1086
2N3053 (2)
GE-FET-1
Photocells: GE-X6 (3)
GE-X19
Photovoltaic solar cell
LED
LED readout: MAN-1
IC: 555 timers (2)
LM3900 op amp
RCA DR2000 Numitron

**Equipment**

Dual-channel oscilloscope
Digital vom
Ac-dc power supply

Vtvm
0–1000-mV meter
Zero-centered 50-mA meter
Zero-centered 100-mA, 500-Ω meter
Chart recorder
Decade resistance box
Signal generator

### Specialized Components and Devices

Bimetal thermometer (0°F–250°F or −17.7°C–121.1°C)
Type J thermocouples (2)
GE-X15 thermistor
KA314 thermistor
JA41J1 thermistor
JA35J1 thermistor (2)
Rtd (100 Ω @ 0°C, platinum element)
Phototube: 917
Vacuum tube: 6C4
Optical coupler (Clairey CLM7H16A073)
Variable resistor with slider (250 Ω, 5 W)
Strain gages: foil, 120 Ω, GF = 2.1 (2)
Sling psychrometer (20°F to 120°F or −6.67°C to 48.8°C)
Tapered-tube flowmeter
Electrochemical cell: Plessey 560
Nixie tube with socket
Guardian 1335-2C-120D relay
U-tube manometer
Am receiver

### Miscellaneous Components, Tools and Devices

Lamps with socket: 7 W, 60 W
Spst switch
660-W heat cone
Soldering gun
Styrofoam cups (2)
Cardboard box: 4 × 4 × 6 inches (10 × 10 × 15 cm)
Cardboard cylinder: 1½ inches (D) × 6 inches or 3.8 cm (D) × 15 cm
Metal foil: 1 × 1 inch or 2.5 × 2.5 cm (2)
Steel core: ¾ (D) × 6 inches or 1.89 × 15 cm
Jar top
Adhesive
Balloon
Funnel
Plastic tubing
Plastic container

# Contents

## UNIT 1

### Introduction to Instrumentation and Measurement Systems



## UNIT 2

### Thermal Input Transducers for Instrumentation Systems



## UNIT 3

### Photoelectric Transducers for Instrumentation Systems

## UNIT 4

### Miscellaneous Input Transducers for Instrumentation Systems



## UNIT 5

### Measurement of Physical Quantities

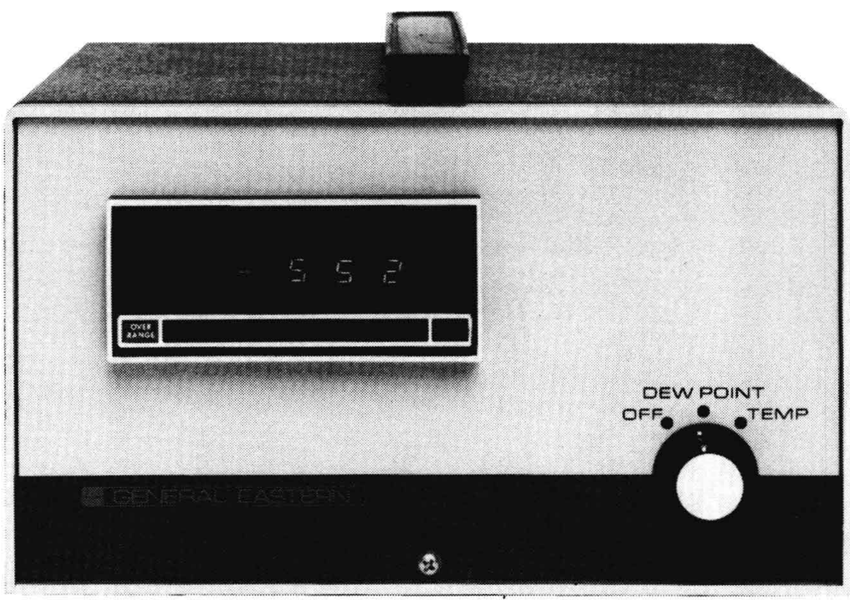
Unit 1

# Introduction to Instrumentation and Measurement Systems

This unit provides a basic introduction to instrumentation and measurement. Activities 1-1 through 1-3 deal with measurement units, scientific notation, and metric measurement. An individual involved in instrumentation of any type must understand basic units. These activities make good review material for those already familiar with measurement. Activities 1-4 through 1-7 are used to familiarize the student with the measuring instruments which he or she will use in the laboratory. In most cases the student will be able to omit these activities, since most basic electricity and electronics courses deal with the use of specific types of vom's, electronic meters, oscilloscopes, and chart recorders.

Meter design using moving-coil movements is studied in Activities 1-8 through 1-13. These activities help the student to understand the operation of pointer-deflection meters such as vom's, vtvm's, and tvm's. They are also important for the student as a practical application of electrical circuit design. Several basic mathematical calculations are necessary to extend the range of a meter movement for measuring current, voltage, and resistance.

One of the most essential measurement circuits is the bridge circuit. This circuit is used to make comparative measurements where an unknown value is compared with a known value. The basic Wheatstone bridge and several other types of bridge circuits are studied in Activities 1-14 through 1-18. Another type of comparative measurement can be made with a potentiometric circuit used to measure voltage values. Activity 1-19 deals with potentiometric circuits. Frequency can also be measured through comparative techniques. Activity 1-20 investigates frequency measurement using Lissajous patterns on the oscilloscope.




**Dew-point hygrometer indicator unit.**

Courtesy General Eastern Instruments Corp.

Various types of numerical readout instruments are now used. These instruments provide a direct visual display of the value of the measured quantity; the user does not have to be able to interpret a meter scale. Activities 1-21 through 1-23 study numerical readout devices, such as Nixie tubes and LEDs, which are used with various instruments.

# Introduction to Measurement

## Introduction

Most measurement is based on the International System of Units (SI). The basic units of this system are the meter, kilogram, second, and ampere (MKSA). These are the units of length, mass, time, and electrical current. Other systems, such as the meter-kilogram-second (MKS) and centimeter-gram-second (CGS), recognize only three base units. These two systems, however, are closely associated with the International System.

There are several derived units that are used extensively for electrical and other related measurements. The electrical units that we now use are part of the International System of Units (SI) based on the meter-kilogram-second-ampere (MKSA) system. The International System of Derived Units is shown in Table 1-1A.

The coordination necessary to develop a standard system of electrical units is very complex. The International Advisory Committee on Electricity makes recommendations to the International Committee on Weights and Measures. Final authority is held by the General Conference on Weights and Measures, which meets periodically. The laboratory associated with the International System is the International Bureau of Weights and Measures, located near Paris, France. Several laboratories in different countries cooperate in this process of standardizing units of measurement. One such laboratory is the National Bureau of Standards in the United States.

Sometimes it is necessary to make conversions of measurement units so that very large or very small numbers may be avoided. For this reason, decimal multiples and submultiples of the basic units have been developed by using standard prefixes. These standard prefixes are shown in Table 1-1B. As examples, we may express 1000 volts as 1 kilovolt, or 0.001 ampere as 1 milliampere. A chart is shown in Fig. 1-1A that can be used for converting from one unit to another. To use this conversion chart, follow these simple steps:

1. Find the position of the unit as expressed in its original form.
2. Find the position of the unit to which you are converting.

**Table 1-1A. International System of Derived Units**

| Measurement Quantity | SI Unit |
|---|---|
| Area | square meter |
| Volume | cubic meter |
| Frequency | hertz |
| Density | kilogram per cubic meter |
| Velocity | meter per second |
| Acceleration | meter per second per second |
| Force | newton |
| Pressure | pascal (newton per square meter) |
| Work (energy), quantity of heat | joule |
| Power (mechanical, electrical) | watt |
| Electrical charge | coulomb |
| Permeability | henry per meter |
| Permittivity | farad per meter |
| Voltage, potential difference, electromotive force | volt |
| Electric flux density, displacement | coulomb per square meter |
| Electric field strength | volt per meter |
| Resistance | ohm |
| Capacitance | farad |
| Inductance | henry |
| Magnetic flux | weber |
| Magnetic flux density (magnetic induction) | tesla |
| Magnetic field strength (magnetic intensity) | ampere per meter |
| Magnetomotive force | ampere |
| Magnetic permeability | henry per meter |
| Luminous flux | lumen |
| Luminance | candela per square meter |
| Illumination | lux |

3. Write the original number as a whole number and a derived unit or as a power of 10 and a basic unit.
4. Shift the decimal point the appropriate number of units in the direction of the term to which you are converting, and count the difference in decimal multiples from one unit to the other.

The use of this step-by-step procedure is illustrated in the following examples:

(a) Convert 100 picofarads to microfarads:
   1. 100 picofarads (pF).
   2. ______ microfarads ($\mu$F).
   3. 100 pF or $100 \times 10^{-12}$F.

**Table 1-1B. Standard Prefixes**

| Prefix | Symbol | Factor by Which the Unit is Multiplied |
|---|---|---|
| exa | E | $1{,}000{,}000{,}000{,}000{,}000{,}000 = 10^{18}$ |
| peta | P | $1{,}000{,}000{,}000{,}000{,}000 = 10^{15}$ |
| tera | T | $1{,}000{,}000{,}000{,}000 = 10^{12}$ |
| giga | G | $1{,}000{,}000{,}000 = 10^{9}$ |
| mega | M | $1{,}000{,}000 = 10^{6}$ |
| kilo | k | $1{,}000 = 10^{3}$ |
| hecto | h | $100 = 10^{2}$ |
| deka | da | $10 = 10^{1}$ |
| deci | d | $0.1 = 10^{-1}$ |
| centi | c | $0.01 = 10^{-2}$ |
| milli | m | $0.001 = 10^{-3}$ |
| micro | $\mu$ | $0.000001 = 10^{-6}$ |
| nano | n | $0.000000001 = 10^{-9}$ |
| pico | p | $0.000000000001 = 10^{-12}$ |
| femto | f | $0.000000000000001 = 10^{-15}$ |
| atto | a | $0.000000000000000001 = 10^{-18}$ |

4. 0.0001 $\mu$F (decimal shifted six units to the right).

(b) Convert 20,000 ohms to kilohms:
1. 20,000 ohms ($\Omega$).
2. ______ kilohms (k$\Omega$).
3. 20,000 $\Omega$ or $20{,}000 \times 10^0$ $\Omega$.
4. 20 k$\Omega$ (decimal shifted three units to the left).

(c) Convert 10 milliamperes to microamperes:
1. 10 milliamperes (mA).
2. ______ microamperes ($\mu$A).
3. 10 mA or $10 \times 10^{-3}$ A.
4. 10,000 $\mu$A (decimal shifted three units to the right).

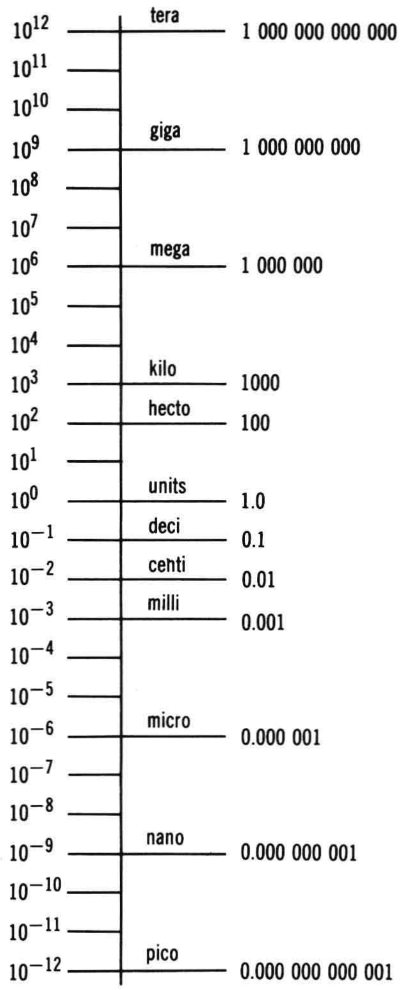



**Fig. 1-1A. Conversion chart for large and small numbers.**

### Objective

In the study of instrumentation it is often necessary to convert numbers from one unit to another in order to solve problems. In this activity you will study unit conversion. You will then be able to successfully complete an exercise involving unit conversion.

### Procedure

Convert each of the following quantities to the unit indicated. Use Table 1-1B and Fig. 1-1A to convert these units.

1. 0.0053 ampere to milliampere = ______ mA
2. 890 microamperes to amperes = ______ A
3. 3380 ohms to megohms = ______ M$\Omega$
4. 0.65 megohm to ohms = ______ $\Omega$
5. 1370 microvolts to millivolts = ______ mV
6. 16,000 watts to kilowatts = ______ kW
7. 13,520,000 ohms to megohms = ______ M$\Omega$
8. 25.24 volts to millivolts = ______ mV
9. 35,129 microamperes to amperes = ______ A
10. 83.21 milliamperes to microamperes = ______ $\mu$A
11. 2500 amperes to microamperes = ______ $\mu$A
12. 10,005 microamperes to milliamperes = ______ mA
13. 86,225 volts to kilovolts = ______ kV
14. 9122 ohms to kilohms = ______ k$\Omega$
15. 218,000,000 ohms to megohms = ______ M$\Omega$
16. 53.58 microvolts to volts = ______ V
17. 85,820 milliamperes to amperes = ______ A
18. 422 microamperes to amperes = ______ A
19. 58,250 watts to megawatts = ______ MW
20. 96.28 megohms to ohms = ______ $\Omega$

# Scientific Notation

## Introduction

The technique of using powers of 10 can greatly simplify mathematical calculations. A number containing many zeros to the right or to the left of a decimal point can be dealt with much more easily when put in the form of powers of 10. For example, $0.0000027 \times 0.000028$ can be handled more easily when put in the form $(2.7 \times 10^{-6}) \times (2.8 \times 10^{-5})$. Notice the number of places that the decimal point is moved in each situation.

**Table 1-2A. Powers of 10**

| Number | Power of 10 |
|---|---|
| 1,000,000 | $10^6$ |
| 100,000 | $10^5$ |
| 10,000 | $10^4$ |
| 1000 | $10^3$ |
| 100 | $10^2$ |
| 10 | $10^1$ |
| 1.0 | $10^0$ |
| 0.1 | $10^{-1}$ |
| 0.01 | $10^{-2}$ |
| 0.001 | $10^{-3}$ |
| 0.0001 | $10^{-4}$ |
| 0.00001 | $10^{-5}$ |
| 0.000001 | $10^{-6}$ |

Table 1-2A lists some of the powers of 10. For a number consisting of a 1 followed by zeros, the power to which the 10 is raised is positive and equals the number of zeros following the 1. In decimal fractions (numbers less than 1), the power is negative and equals the number of places the decimal point is moved to the left.

Any number which is written as a product of a power of 10 and a number between 1 and 10 is said to be expressed in *scientific notation*. For example:

$$91{,}000{,}000 = 9.1 \times 10{,}000{,}000 \text{ or } 9.1 \times 10^7$$

$$800{,}000{,}000 = 8 \times 100{,}000{,}000 \text{ or } 8 \times 10^8$$

$$0.0000000007 = 7 \times 0.0000000001 \text{ or } 7 \times 10^{-10}$$

Scientific notation greatly simplifies the multiplication and division of large numbers or small decimals. For example:

$$\begin{aligned} 1800 \times 0.000015 \times 300 \times 0.0048 &= 1.8 \times 10^3 \times 1.5 \times 10^{-5} \times 3 \times 10^2 \times 4.8 \times 10^{-3} \\ &= 1.8 \times 1.5 \times 3 \times 4.8 \times 10^{3-5+2-3} \\ &= 38.88 \times 10^{-3} \\ &= 0.03888 \end{aligned}$$

Divide 75,000 by 0.00005:

$$\begin{aligned} \frac{75{,}000}{0.00005} &= \frac{7.5 \times 10^4}{5 \times 10^{-4}} \\ &= \frac{7.5}{5} \times 10^{4-(-4)} \\ &= 1.5 \times 10^8 \\ &= 150{,}000{,}000 \end{aligned}$$

## Objective

Convert each of the following quantities to scientific notation. Place the correct responses in the blank spaces.

1. 0.0053 ampere = $5.3 \times 10^{-3}$ A
2. 890 microamperes = ______ μA
3. 3380 ohms = ______ Ω
4. 0.65 megohm = ______ MΩ
5. 1370 microvolts = ______ μV
6. 16,000 watts = ______ W
7. 13,520,000 ohms = ______ Ω
8. 25.20 volts = ______ V
9. 35,200 microamperes = ______ μA
10. 83.21 milliamperes = ______ mA

11. 2500 amperes = ______ A
12. 10.10 microamperes = ______ $\mu$A
13. 86,200 volts = ______ V
14. 9100 ohms = ______ $\Omega$
15. 218,000,000 ohms = ______ $\Omega$
16. 5350 microvolts = ______ $\mu$V
17. 85,300 milliamperes = ______ mA
18. 420 microamperes = ______ $\mu$A
19. 0.058 kilowatt = ______ kW
20. 0.962 megohm = ______ M$\Omega$

# Metric Measurements

## Introduction

Most nations today use the metric system of measurement. In the United States the National Bureau of Standards began a study in August, 1968, to determine the feasibility and costs of converting industries and everyday activity to the metric system. Today this conversion is taking place. Metric measurement is becoming more common.

The units of the metric system are decimal measures based on the kilogram and the meter. Although this system is very simple, several countries have been slow to adopt it. The United States has been one of the reluctant countries due to the complexity of a complete changeover of measurement systems.

## Objective

The importance of the metric system of measurement must be stressed in instrumentation. Conversion of units from the U.S. system to the metric system is easy to perform. In this activity you will become familiar with the metric system of measurement and complete a brief exercise dealing with metric conversions. Refer to the comparison of U.S. and metric units in Table 1-3A.

## Procedure

1. List the basic units of the metric system.

______________________________

______________________________

______________________________

2. Complete the following conversions:

(a) 1 meter = ______ centimeters

(b) 1 centimeter = ______ millimeters

(c) 5000 grams = ______ kilograms

(d) 2 liters = ______ milliliters

(e) 1 meter = ______ inches

(f) 1 centimeter = ______ inches

(g) 1 mile = ______ kilometers

(h) 1 gram = ______ ounces

(i) 30 ounces = ______ grams

(j) 1 kilogram = ______ pounds

(k) 3 liters = ______ quarts

**Table 1-3A. Comparison Chart for U.S. and Metric Units**

| U.S. | METRIC | | METRIC | U.S. | |
|---|---|---|---|---|---|
| 1 inch | = 25.4 | millimeters | 1 millimeter | = 0.03937 | inch |
| 1 foot | = 0.3048 | meter | 1 meter | = 3.2808 | feet |
| 1 yard | = 0.9144 | meter | 1 meter | = 1.0936 | yards |
| 1 mile | = 1.609 | kilometers | 1 kilometer | = 0.6214 | mile |
| 1 square inch | = 6.4516 | square centimeters | 1 square centimeter | = 0.155 | square inch |
| 1 square foot | = 0.0929 | square meter | 1 square meter | = 10.7639 | square feet |
| 1 square yard | = 0.836 | square meter | 1 square meter | = 1.196 | square yards |
| 1 acre | = 0.4047 | hectare | 1 hectare | = 2.471 | acres |
| 1 cubic inch | = 16.387 | cubic centimeters | 1 cubic centimeter | = 0.061 | cubic inch |
| 1 cubic foot | = 0.028 | cubic meter | 1 cubic meter | = 35.3147 | cubic feet |
| 1 cubic yard | = 0.764 | cubic meter | 1 cubic meter | = 1.308 | cubic yards |
| 1 quart (liq) | = 0.946 | liter | 1 liter | = 1.0567 | quarts (liq) |
| 1 gallon | = 0.00378 | cubic meter | 1 cubic meter | = 264.172 | gallons |
| 1 ounce (avdp) | = 28.349 | grams | 1 gram | = 0.035 | ounce (avdp) |
| 1 pound (avdp) | = 0.4536 | kilogram | 1 kilogram | = 2.2046 | pounds (avdp) |
| 1 horsepower | = 0.7457 | kilowatt | 1 kilowatt | = 1.341 | horsepower |

(l) 1 gallon = ______ liters

(m) 10 cups = ______ liters

(n) 50 miles = ______ kilometers

(o) 2 cubic centimeters ($cm^3$) = ______ cubic inches ($in^3$)

(p) 4 cubic feet ($ft^3$) = ______ cubic meters ($m^3$)