1-0 INTRODUCTION

Modern technology leans heavily on the science of measurement. The control of industrial processes and automated systems would be very difficult without accurate sensor measurements. The widespread use of microelectronics and computers is having a profound effect on the design of sensor systems. Signal processing functions increasingly are being integrated within sensors, and digital-type sensors directly compatible with computer inputs are emerging. Nevertheless, measurement is an inexact science requiring the use of reference standards and an understanding of the energy translations involved more directly as the need for accuracy increases.

This chapter presents electrical sensor/transducer techniques and devices useful for both industrial and laboratory measurements. Basic principles are discussed preliminary to examination of a variety of devices applicable to sensor-based data acquisition systems. Emphasis is on contemporary sensors supporting motion, ultrasonics, imaging, and chemical measurements as well as the traditional engineering measurements of temperature, pressure, flow, force, and level. Excitation and linearization circuits also are developed with an interest in minimizing the sensor error contribution to a data acquisition or control system. In practice, the words sensor and transducer are used interchangeably, although the former more accurately describes the device and the latter the principle involved.
1-1 BASIC PRINCIPLES

A transducer is a device that transfers energy between two systems as in the conversion of thermal into electrical energy by the Seebeck-effect thermocouple. Transducer excitation more often is required as in the case of a bridge sensor element. Figure 1-1 describes a basic sensor circuit and its relationship to the measurement quantity. Transducers are classified by the electrical principle involved in their operation. The actual functioning of a particular transducer is of less concern here than the parameters associated with its output signal as a representation of the measurement. Six descriptive parameters applicable to sensors are found in the following. Sensor error typically is dominated by the nonlinearity of the sensor transfer characteristic, which may be minimized by linearization methods developed in a later section.

Accuracy: the closeness with which a measurement approaches the true value of a measurand, usually expressed as a percent of full-scale output

Error: the deviation of a measurement from the true value of a measurand, also usually expressed as a percent of full-scale output

Precision: an expression of a measurement over some span described by the number of significant figures available

Resolution: an expression of the smallest quantity to which a quantity can be determined

Span: an expression of the extent of a measurement between any two limits

Range: an expression of the total extent of possible measurement values

A general convention is to provide sensor measurements in terms of signal amplitudes as a percent of full scale, or %FS, where minimum-maximum values correspond to 0 to 100%FS. This range may correspond to analog signal levels between 0 and 10 V (unipolar) with full scale denoted as 10 VFS. Alternately, a signal range may correspond to ±50%FS with signal levels between ±5 V (bipolar) and full scale denoted as ±5 VFS.

Sensor signals typically vary in amplitude with time to represent the information content of a measurement. However, a minimum frequency re-
response or bandwidth must be provided by the data acquisition system to accommodate signal spectral occupancy requirements. The Fourier transform is a convenient method of describing the information bandwidth requirements of a signal. Of interest is the rate at which the Fourier spectral components diminish with increasing frequency. We can acquire insight into this matter by examining the waveforms of Figure 1-2 and their frequency spectrums. Pro-

**Figure 1-2.** Instrumentation Signal Waveform Classifications
TABLE 1-1 SIGNAL BANDWIDTH
REQUIREMENTS

<table>
<thead>
<tr>
<th>Signal</th>
<th>Bandwidth (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dc</td>
<td>(dV_j/\pi V_{FS}dt)</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>1/period</td>
</tr>
<tr>
<td>Harmonic</td>
<td>10/period</td>
</tr>
<tr>
<td>Single events</td>
<td>2/width (\tau)</td>
</tr>
</tbody>
</table>

Providing signal bandwidth for spectral components until their amplitude diminishes to 5 percent of the fundamental-frequency amplitude value generally is adequate, and will accommodate the typical \(-20\, \text{dB/decade}\) rolloff of complex harmonic signals. The more severe signal classification should be applied when signals are hybrid combinations of the waveforms shown to ensure adequate bandwidth. Table 1-1 summarizes the minimum bandwidth requirements for instrumentation signals, where dc signal rate of change is equated to its sinusoidal equivalent frequency in Hz.

1-2 TEMPERATURE SENSORS

Thermocouples are widely used temperature sensors because of their ruggedness and broad temperature range. Two dissimilar metals are used in the Seebeck-effect temperature-to-emf junction with transfer relationships described by Figure 1-3. Proper operation requires the use of a thermocouple reference

![Figure 1-3. Temperature-Millivolt Graph for Thermocouples (Courtesy Omega Engineering, Inc., an Omega Group Company)](image-url)
Sec. 1-2 Temperature Sensors

Thermocouple

Figure 1-4. Electrical Reference Junction

jouction in series with the measurement junction to polarize the direction of current flow and maximize the measurement emf. Omission of the reference junction introduces an uncertainty evident as a lack of measurement repeatability equal to the ambient temperature. Figure 1-4 describes an elementary electrical-bridge reference junction. This incorporates a temperature-sensitive resistor as one leg of a bridge circuit that is thermally integrated with the reference-junction thermocouple where the leads of the measurement-junction thermocouple are referenced to copper. However, the requirement for an isolated supply or battery excitation is an implementation disadvantage of this cold-junction reference method.

An electronic reference junction that does not require an isolated supply can be realized with an Analog Devices AD590 temperature sensor as shown in Figure 1-5. This reference junction usually is attached to an input terminal barrier strip in order to track the thermocouple-to-copper circuit connection thermally. The error signal is determined by the compensation resistor R values referenced to the Seebeck coefficients in mV/°C of Table 1-2, and provided as a compensation signal for ambient temperature variation. The single calibration trim at ambient temperature provides temperature tracking within a few tenths of a °C.

Resistance-thermometer devices (RTDs) provide greater resolution and repeatability than thermocouples, the latter typically being limited to approximately 1 °C. RTDs operate on the principle of resistance change as a function of temperature, and are represented by a number of devices. The platinum resistance thermometer is frequently utilized in industrial applications because it offers good accuracy with mechanical and electrical stability. Thermistors are fabricated from a sintered mixture of metal alloys forming a ceramic that exhibits a significant negative temperature coefficient. Metal film resistors have an extended and more linear range than thermistors, but thermistors exhibit
approximate ten times the sensitivity. RTDs require excitation, usually provided as a constant-current source, in order to convert their resistance change with temperature into a voltage change. Figure 1-6 presents the temperature-resistance characteristic of common RTD sensors.

Optical pyrometers are utilized for temperature measurement when sensor physical contact with a process is not feasible, but a view is available. Measurements are limited to energy emissions within the spectral response capability of the specific sensor used. A radiometric match of emissions between a calibrated reference source and the source of interest provides a current analog corresponding to temperature. Automatic pyrometers employ a servo loop to achieve this balance as shown in Figure 1-7. Operation to 5,000°C is available.

Temperature measurement using a forward-biased pn junction is capable of accuracy to 0.1°C over a span of about ±100°C. Fortunately, many temper-

---

**TABLE 1-2 THERMOCOUPLE COMPARISON DATA**

<table>
<thead>
<tr>
<th>Type</th>
<th>Elements, +/−</th>
<th>mV/°C</th>
<th>Range (°C)</th>
<th>Error (%FS)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Chromel/constantan</td>
<td>0.063</td>
<td>0 to 800</td>
<td>0.5</td>
<td>High output</td>
</tr>
<tr>
<td>J</td>
<td>Iron/constantan</td>
<td>0.054</td>
<td>−250 to 700</td>
<td>0.75</td>
<td>Reducing atmospheres</td>
</tr>
<tr>
<td>K</td>
<td>Chromel/alumel</td>
<td>0.040</td>
<td>−250 to 1,200</td>
<td>0.75</td>
<td>Oxidizing atmospheres</td>
</tr>
<tr>
<td>R&amp;S</td>
<td>Pt-Rh/platinum</td>
<td>0.010</td>
<td>0 to 1,400</td>
<td>0.25</td>
<td>Corrosive atmospheres</td>
</tr>
<tr>
<td>T</td>
<td>Copper/constantan</td>
<td>0.040</td>
<td>−250 to 350</td>
<td>1.0</td>
<td>Moist atmospheres</td>
</tr>
<tr>
<td>C</td>
<td>Tungsten/rhenium</td>
<td>0.012</td>
<td>0 to 2,000</td>
<td>0.5</td>
<td>High temperature</td>
</tr>
</tbody>
</table>
Figure 1-6. RTD Devices

Temperature measurements of interest fall within this range. The negative temperature coefficient of a diode-connected bipolar transistor can be made very linear by means of constant-current excitation as shown in Figure 1-8. The base-to-emitter forward voltage drop varies by $-2.5 \text{ mV per plus degree Centigrade}$.

Figure 1-7. Automatic Pyrometer
1-3 PRESSURE, FLOW, AND LEVEL MEASUREMENT

Fluid pressure is defined as the force per unit exerted by a gas or a liquid on the boundaries of a containment vessel. Pressure is a measure of the energy content of hydraulic and pneumatic (liquid and gas) fluids. Hydrostatic pressure refers to the internal pressure at any point within a liquid directly proportional to the liquid height above that point independent of vessel shape. The static pressure of a gas refers to its potential for doing work, which does not vary uniformly with height as a consequence of its compressibility. Equation (1-1) expresses the basic relationship between pressure, volume, and temperature as the general gas law. Pressure typically is expressed in terms of pounds per square inch (psi) or inches of water (in H_2O) or mercury (in Hg). Absolute pressure measurements are referenced to a vacuum, whereas gage pressure measurements are referenced to the atmosphere.

A pressure sensor detects pressure and provides a proportional analog signal by means of a pressure-force summing device. This usually is implemented with a mechanical diaphragm and linkage to an electrical element such as a potentiometer, strain gage, or piezoresistor. Quantities of interest associated with pressure-force summing sensors include their mass, spring constant, and natural frequency. Potentiometric elements are low in cost and have high output, but their sensitivity to vibration and mechanical nonlinearities combine to limit their utility. Unbonded strain gages offer improvement in accuracy and stability, with errors to 0.5 percent of full scale, but their low output signal requires a preamplifier. Present developments in pressure transducers involve integral techniques to compensate for the various error sources, including crystal diaphragms for freedom from measurement hysteresis. Figure 1-9 illustrates...
Figure 1-9. Integrated-Circuit Pressure Transducer (Courtesy National Semiconductor)

a National Semiconductor LX-3700 integrated circuit pressure transducer with an internal vacuum reference, chip heating to minimize temperature errors, and a piezoresistor bridge transducer circuit with on-chip signal conditioning.

\[
\frac{\text{Absolute pressure} \times \text{Gas volume}}{\text{Absolute temperature}} = \text{Constant} \quad (1-1)
\]

Fluid-flow measurement generally is implemented either by differential-pressure or mechanical-contact sensing. Flow rate \( F \) is the time rate of fluid motion with dimensions typically in feet per second. Volumetric flow \( Q \) is the fluid volume per unit time such as gallons per minute. Mass flow rate \( M \) for a gas is defined, for example, in terms of pounds per second. Differential-pressure flow sensing elements also are known as variable-head meters because the pressure difference between the two measurements \( \Delta P \) is equal to the head. This is equivalent to the height of the column of a differential manometer. Flow rate is therefore obtained with the 32 ft/sec\(^2\) gravitational constant \( g \) and differential pressure by equation (1-2). Liquid flow in open channels is obtained by head-producing devices such as flumes and weirs. Volumetric flow is obtained with the flow cross-sectional area and the height of the flow over a weir as shown by Figure 1-10 and equation (1-3). Figure 1-11 shows examples of differential-pressure elements to which pressure sensors are attached.

Mass flow-rate measurements also require static temperature and pressure sensing as illustrated in Figure 1-12. For accuracy temperature must be measured where the flow-rate \( \Delta P \), or velocity, is acquired. Single-point velocity measurements are common, but are generally inaccurate representations of a process stream. Line-averaging sensors such as an annubar are more accurate.
The mass flow rate calculation of equation (1-4) is preceded by a probe calibration factor whose constants are defined. Mechanical-contact flow sensors employ various methods to derive flow rate including angular momentum, thermoelectric cooling, electrical resistivity, and nuclear beta decay. The turbine flowmeter of Figure 1-13 is an angular momentum device that implements equation (1-5) to measure flow rate.

Flow rate \( F = \sqrt{2g\Delta P} \) feet/second \hspace{2cm} (1-2)

Volumetric flow \( Q = \sqrt{2gL^3H^5} \) cubic feet/second \hspace{2cm} (1-3)

Mass flow \( M = \sqrt{\frac{\Delta P_0}{\Delta P_x}} \cdot \sqrt{\frac{P\Delta P}{T}} \) pounds/second \hspace{2cm} (1-4)
where

\[ R = \text{universal gas constant} \]

\[ \Delta P_o = \text{true differential pressure } P_o - P_\infty \]

\[ \Delta P_x = \text{calibration differential pressure} \]

Flow rate \( F = \frac{\omega r}{\tan \alpha} \) \text{ feet/second} \]

where

\[ \omega = \text{rotor angular velocity} \]

\[ r = \text{rotor blade radius} \]

\[ \alpha = \text{rotor blade angle} \]

Liquid levels are frequently required process measurements in tanks, pipes, and other vessels. Sensing methods of various complexity are employed including float devices, differential pressure, ultrasonics, and bubblers. Float devices offer simplicity and various ways of translating motion into a level reading. A differential-pressure transducer can also measure the height of a liquid when its specific weight \( W \) is known, and a \( \Delta P \) cell is connected between the vessel surface and bottom. Height is provided by the ratio of \( \Delta P/W \). Ultrasonic level sensing can be implemented by an echo-ranging system, which is especially useful for tall tanks. Bubbling a small flow of air from a submerged dip tube
Figure 1-13. Turbine Flow-Rate Transducer

Figure 1-14. Bubbler Liquid Level System
results in a pneumatic back pressure that is equal to the liquid hydrostatic pressure. The air pressure measured by the pressure transducer in Figure 1-14 therefore represents the liquid level. Bubbler systems may be used with most liquids including viscous fluids, slurries, cement, and molten metal.

1-4 MOTION, VIBRATION, FORCE, AND TACTILE TRANSDUCERS

Accurate sensing of position, shaft angle, and linear displacement is possible with the linear variable-displacement transformer (LVDT). With this device, an ac excitation introduced through a variable-reluctance circuit is induced in an output circuit through a movable core that determines the amount of displacement. LVDT advantages include overload capability and temperature insensitivity. Sensitivity increases with excitation frequency, but a minimum ratio of 10:1 between excitation and signal frequencies is considered a practical limit. LVDT variants include the induction potentiometer, synchros, resolvers, and the microsyn. Figure 1-15 describes a basic LVDT circuit with both ac and dc outputs.

Ac-servos provide useful actuator mechanizations in motion-control systems as illustrated by Figure 1-16. To achieve a new output position, the input crank displaces the LVDT control transformer winding $S_4$, thereby repositioning synchro winding $S_8$ until a new null is achieved at $S_4$. This action removes excitation $E_c$ from the servomotor when the system has answered to the input angle $\theta$. For small-inertia rotors typically encountered in servo systems, the shaft-angle motion for a two-phase induction motor closely approximates the

![Figure 1-15. Basic LVDT Circuit](image-url)
time integral of the excitation voltage $E_c$ and motor gain $K_m$. This relationship is described by equation (1-6).

$$\theta = \int_0^\theta K_m E_c \, dt$$

(1-6)

where

- $\theta =$ shaft angle
- $K_m =$ motor gain
- $E_c =$ excitation voltage

Acceleration measurements are principally of interest for shock and vibration sensing. Potentiometric dashpots and capacitive transducers have largely been supplanted by piezoelectric crystals. Their equivalent circuit is a voltage source in series with a capacitance as shown in Figure 1-17, which produces an output in coulombs of charge as a function of acceleration excitation. Vibratory acceleration results in an alternating output typically of very small value. Several crystals are therefore stacked to increase the transducer output. As a consequence of the small quantities of charge transferred, this transducer usually is interfaced to a low-input-bias-current charge amplifier, which also converts the acceleration input to a velocity signal. An ac-coupled integrator will then provide a displacement signal that may be calibrated, for example,
Figure 1-17. Vibration Measurement

in millinches of displacement per volt. These relationships are quantified by the following equations:

\[
\text{Acceleration} = C \cdot \Delta e \text{ coulombs} \quad (1-7)
\]
\[
\text{Velocity} \ E = \frac{C}{C_f} \cdot \Delta e \text{ volts/second} \quad (1-8)
\]
\[
\text{Displacement} \ V_o = \int_0^t E \cdot dt \text{ volts} \quad (1-9)
\]

A load cell is a transducer whose output is proportional to an applied force. Strain gage transducers provide a change in resistance due to mechanical strain produced by a force member. Strain gages may be based on a thin metal wire, foil, thin films, or semiconductor elements. Adhesive-bonded gages are the most widely used with a typical resistive strain element of 350 Ω that will register full-scale changes to 15 Ω. With a Wheatstone-bridge circuit, a 2-V excitation may therefore provide up to a 50-mV output signal change as described by Figure 1-18. Semiconductor strain gages offer high gage factors at low strain levels with outputs of 200 to 400 mV. Miniature tactile force sensors can also be fabricated from scaled-down versions of classic transducers as available from Transsensory Devices of Fremont, California. A force applied to their 80-by-80 mil device produces a one percent linear 0- to 100-mV output. A multiplexed array of these sensors can provide feedback for robotic part manipulation and teleoperator actuators.

Ultrasound ranging and imaging systems are increasingly being applied for industrial and medical purposes. A basic ultrasonic system is illustrated by Figure 1-19 consisting of a transducer element and associated signal processing circuitry. In operation, a pulse is radiated toward a target, and its return echo is detected. The elapsed time between initial emission and echo reception is converted to distance with respect to sound propagation through the inter-
vening medium. In the atmosphere at 0°C the acoustic speed of propagation is 1,087 ft/sec. Multiple frequency emissions usually are employed to prevent the possibility of single-frequency cancellation arising from specific target topographical characteristics. Automatic control of gain and bandwidth with range variation will also compensate for decreasing echo signal-to-noise ratio with increasing range. Industrial applications include robotic position sensing and fluid level determination. Ultrasonic imaging systems typically use an array of
transducers and more complex signal processing to extract the spatial information necessary for two- or three-dimensional sensing.

Hall-effect transducers, which usually are silicon substrate devices, frequently include an integrated amplifier to provide a high-level output. These devices typically offer an operating range from -40 to +150°C and a linear output. Applications include magnetic field intensity sensing, and position sensing with circuit isolation such as the Micro Switch LOHET device, which offers a 3.75-mV/Gauss response. Figure 1-20 describes the principle of Hall-effect operation. When a magnetic field $B_z$ is applied perpendicular to a current-conducting element, a force acts on the current $I_x$ creating a diversion of its flow proportional to a difference of potential. This measurable voltage $V_y$ is pronounced in materials such as InSb and InAs, and occurs to a useful degree in Si. In practice, the magnetic field usually is provided as a function of some measurand.

1-5 PHOTOMETRY AND IMAGE SENSORS

Confusion has resulted historically between photometry and radiometry as a consequence of qualitative definitions and ill-defined substitutions. Planck's basic assumption was that light is not continuous but consists of discrete quanta (photons) whose energy is frequency dependent. For this reason, energy $E$ falling on an arbitrary photosensitive material will exhibit a spectral response peak a function of the specific material according to equation (1-10). It is therefore essential to match source and sensors spectrally to maximize energy transfer. Table 1-3 presents common photometric and radiometric definitions, where a source of diameter one-tenth the separation distance is considered an area source. A sphere has a surface area of $4\pi R^2$ and a total solid angle of $4\pi$ steradians. LED devices can be fabricated to emit on wavelengths between about 560 and 910 nanometers with bandwidths to 30 nm. These devices fall into two classifications, emitters and laser diodes, both of which are photodiodes.
emitting from their valence bands. The principal difference is that laser diodes have higher peak powers and narrower spectral widths than emitters. Emitters also are usually operated continuously, whereas laser diodes are operated in a pulsed mode.

Light sensors fall into three classifications: photoemitters, photodiodes, and photoconductors. Phototubes and photomultiplier tubes are common photoemitters and operate by cathode-to-anode electron emission upon exposure to incident light. Photomultipliers have usable sensitivities down to 1 photon with gains to $10^6$. Phototubes are constant-current devices as indicated by Figure 1-21 with excellent signal-to-noise performance. Photovoltaic devices, such as the solar cell of Figure 1-22, provide an output emf of 0.5 V for silicon and 0.1 V for germanium with efficiency in the 15 percent range. Maximum power output is achieved by optimizing load resistance, which typically is 3 kΩ for silicon devices. Photodiodes are among the most widely applied electro-optical sensors, and exist as either diodes or phototransistors with characteristics as described in Table 1-4. Photodiodes are more linear than phototransistors and therefore more suitable for signal transmission, whereas position sensors and optical isolators typically employ phototransistors. Photoconductive cells are photoresistive devices that exhibit a decreasing resistance with increasing light level. Power dissipation ratings must be observed when applying all photo-

![Figure 1-21. Phototube Characteristics](image-url)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Radiometry</th>
<th>Photometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity (point source)</td>
<td>Watts/steradian</td>
<td>Candelas</td>
</tr>
<tr>
<td>Radiance (area source)</td>
<td>Watts/steradian</td>
<td>Footlamberts</td>
</tr>
<tr>
<td>Total flux</td>
<td>Watts/cm²</td>
<td>Lumens</td>
</tr>
<tr>
<td>Irradiance</td>
<td>Watts/cm²</td>
<td>Footcandles</td>
</tr>
</tbody>
</table>
sensor devices. Figures 1-23 and 1-24 describe photodiode and photoconductive device characteristics.

\[ E = hf = (6.626 \times 10^{-34} \text{ Joule/sec}) (f\text{Hz}) \]  

(1.10)

Computer vision is the construction of meaningful descriptions of physical objects from images. Digital images associated with computer vision typically are represented by discrete-valued vector functions. Continuous images are represented by samples at regularly spaced intervals with the image intensity quantized into a gray-level representation. This process is developed in Chapter 8. For a discrete image, \( f(\vec{x}) \) may represent a sampled image element with \( \vec{x} = (x, y) \) the integer coordinates of this element in a two-dimensional plane. The requirements for imaging system resources, such as memory, are determined both by the number of binary bits used to represent each gray-level sample and the tessellation or spatial pattern of image elements. Therefore, the choice of spatial and gray-level resolution for a specific computer vision task requires optimization for an efficient realization.

Television cameras are commonly used devices for computer vision applications because the image is immediate and furnished in an electrical form. Although television standards are more oriented to human viewing than to computer vision, alteration of the associated electronics to enable random access of an image rather than sequential scanning compensates for some of the limitations. A recent development in image formation is that available with

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**TABLE 1-4 PHOTODARLINGTON CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Devices</th>
<th>Gain</th>
<th>Speed</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodarlington</td>
<td>1,000</td>
<td>1 kHz</td>
<td>1 W</td>
</tr>
<tr>
<td>Phototransistor</td>
<td>1</td>
<td>100 kHz</td>
<td>100 mW</td>
</tr>
<tr>
<td>Photodiode</td>
<td>0.001</td>
<td>10 MHz</td>
<td>1 mV</td>
</tr>
</tbody>
</table>

---

**Figure 1-22. Photovoltaic Irradiance (Footcandles) Characteristics**
solid-state image sensors such as charge-coupled devices (CCDs) and charge-injection devices (CIDs). CCDs resemble MOSFETs in that they contain a source and drain coupled by a depletion channel. For imaging purposes, they operate as closely spaced MOS capacitors forming a shift register. Charges in the depletion region influenced by incident photons are transferred to an output register by application of clocking pulses between the source and drain. CIDs resemble CCDs except that each charge is confined to the image site where it was generated. These charges are injected into the substrate and detected as the video signal using a row-column addressing technique similar to memory addressing. These image sensors are described by Figure 1-25.

1-6 NUCLEAR AND CHEMICAL ANALYZERS

A property common to all nuclear radiation is its ability to interact with the atoms that constitute all matter. The nature of the interaction with any form of matter varies with the different components of radiation illustrated in Figure
Figure 1-25 (a, b). Solid-State Image Sensors
1-26. These components are responsible for the most common interactions with matter that generally produce ionization of the medium through which they pass. This ionization is the principal effect used in the detection of the presence of nuclear radiation in any of its forms. In passing through certain substances, the scintillation or luminescent effect may also be used. Alpha and beta rays often are not encountered because of their attenuation. Instrumentation for nuclear radiation detection therefore most commonly are constructed to measure gamma radiation.

The rate of ionization in Roentgens per hour is a preferred measurement unit, and represents the product of the emanations in Curies (Ci) and in the sum of their energies in Mev (E) represented as gamma energies. A distinction also should be made between disintegrations in counts per minute and ionization rate. The count-rate measurement is useful for half-life determination and nuclear detection, but does not provide exposure rate information for interpretation of its degree of hazard. The estimated yearly radiation dose to persons in the United States is 0.25 Roentgen (R). A high radiation area is defined where radiation levels exceed 0.1 R per hour, and requires posting of a caution sign. A maximum yearly exposure of 5 R is presently specified for no expected radiation sickness (National Bureau of Standards Handbook No. 59).

Methods for detecting nuclear radiation are based on means for measuring the ionizing effects of these radiations. Mechanizations fall into the two cate-

![Figure 1-26. Nuclear Radiation Characteristics](image-url)
categories of pulse-type detectors of ionizing events, and ionization-current detectors that employ an ionization chamber to provide an averaged radiation effect. The first category includes Gieger-Mueller tubes and more sensitive scintillation counters capable of individual counts. Detecting the individual ionizing scintillations is aided by an activated crystal such as sodium iodide optically coupled to a high-amplification photomultiplier tube as shown in Figure 1-27. Ionization-current detectors primarily are employed in health-physics applications such as industrial areas subject to high radiation levels. An ion chamber is followed by an amplifier whose output is calibrated in Roentgens per hour ionization rate. This method is necessary where pulse-type detectors are inappropriate because of a very high rate of ionization events. Practical industrial applications of nuclear radiation and detection include thickness gages, non-destructive testing such as X-ray inspection, and chemical analysis such as by neutron activation.

On-line measurements of industrial processes and chemical streams often require the use of dedicated chemical analyzers for the control of a process. Examples are oxygen for boiler control, sulfur oxide emissions from combustion processes, and hydrocarbons associated with petroleum refining. Laboratory instruments such as gas chromatographs generally are not used for on-line measurements primarily because they analyze all compounds present simultaneously rather than a single one of interest.

The dispersive infrared analyzer is perhaps the most widely used chemical analyzer, owing to the range of compounds it can be configured to measure. Operation is by the differential absorption of infrared energy in a sample stream in comparison to that of a reference cell. Measurement is by deflection of a diaphragm separating the sample and reference cells, which in turn detunes an oscillator circuit to provide an electrical analog of compound concentration. Oxygen analyzers usually are of the amperometric type in which oxygen is chemically reduced at a gold cathode, resulting in a current flow from a silver anode as a function of this reduction and oxygen concentration. In a paramagnetic wind device, a wind effect is generated when a mixture containing oxygen produces a gradient in a magnetic field. Measurement is derived by the thermal cooling effect on a heated resistance element forming a thermal anemometer.

![Figure 1-27. Scintillation Detector](image-url)
TABLE 1-5 CHEMICAL ANALYZER METHODS

<table>
<thead>
<tr>
<th>Compound</th>
<th>Analyzer</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO, SO&lt;sub&gt;x&lt;/sub&gt;, NH&lt;sub&gt;x&lt;/sub&gt;</td>
<td>Infrared</td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Amperometric, paramagnetic</td>
</tr>
<tr>
<td>HC</td>
<td>Flame ionization</td>
</tr>
<tr>
<td>NO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>Chemiluminescent</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;S</td>
<td>Electrochemical cell</td>
</tr>
</tbody>
</table>

Hydrocarbon analyzers usually employ the flame ionization method whereby a regulated gas sample passes through a flame fed by regulated fuel and air. Hydrocarbon compounds are accordingly ionized into ions and electrons, which are collected and totalized at polarized electrodes. Chemiluminescent reaction analyzers produce specific light emissions when electronically excited and oxygenated molecules revert to their ground state. These methods are summarized by Table 1-5, where a typical analyzer implementation is shown in Figure 1-28.

Electrochemical sensors detect the electrical potential developed in response to the presence of dissolved ionized solids in a process stream. Included

![Figure 1-28. Gas-Analyzer Sampling System](image-url)
in this group are pH, conductivity, and ion-selective electrodes. pH defines the balance between the hydrogen ions $H^+$ of an acid and the hydroxyl ions $OH^-$ of an alkali, where one type can be increased only at the expense of another. A pH probe is sensitive to the presence of $H^+$ ions in solution, thereby representing the acidity or alkalinity of a sample. All of these ion-selective electrodes are based on the Nernst equation of equation (1-11), which typically provides a 60-mV potential change for each tenfold change in the activity of a monovalent ion.

$$V_o = V + \frac{F}{n} \log (ac + sa,sc + \cdots ) \text{ volts} \quad (1-11)$$

where

- $V_o =$ voltage between sensing and reference electrodes
- $V =$ electrode base potential
- $F =$ Nernst factor, 60 mV at 25°C
- $n =$ ionic charge, 1 monovalent, 2 bivalent, etc.
- $a =$ ionic activity
- $c =$ concentration
- $s =$ electrode sensitivity to interfering ions.

### 1-7 SENSOR LINEARIZATION

An ideal linear sensor is one for which cause and effect are proportional for all values of input and output. Typical transducers are in general nonlinear, but often sufficiently linear to be useful over a limited range or span of interest. Due to the effort required in designing sensor circuits with sufficient linearity for some applications, the word nonlinear has acquired a pejorative connotation. However, there are many examples of well-defined nonlinear relationships, including logarithmic and other mathematical functions, useful in the implementation of sensor linearization.

Continuous function fitting permits the translation of an empirical relationship between an independent input variable and dependent output variable. A practical realization requires the formulation of a linearized output function $X-f(X)$ employing a nonlinear relationship appropriate for the sensor characteristic of interest. Useful relationships include natural laws such as $1/X$, $X^m$, and $\log X$, and polynomial expressions such as the cubic equation $AX + BX^3$. Solution of values for the coefficients $A$ and $B$ then permits the definition of a sensor-signal linearizing equation suitable for implementation in software or using analog circuits. In the example that follows, a Type-J thermocouple
TABLE 1-6 TYPE-J THERMOCOUPLE QUADRATIC LINEARIZATION

<table>
<thead>
<tr>
<th>Y°F</th>
<th>X mV</th>
<th>y°F</th>
<th>ε%FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0</td>
<td>32.0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>1.942</td>
<td>97.6</td>
<td>-2.4</td>
</tr>
<tr>
<td>200</td>
<td>4.906</td>
<td>197.1</td>
<td>-1.45</td>
</tr>
<tr>
<td>300</td>
<td>7.947</td>
<td>298.3</td>
<td>-0.56</td>
</tr>
<tr>
<td>400</td>
<td>11.023</td>
<td>400.0</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>14.108</td>
<td>501.0</td>
<td>0.2</td>
</tr>
<tr>
<td>600</td>
<td>17.186</td>
<td>601.0</td>
<td>0.17</td>
</tr>
<tr>
<td>700</td>
<td>20.253</td>
<td>699.9</td>
<td>0</td>
</tr>
<tr>
<td>800</td>
<td>23.317</td>
<td>797.1</td>
<td>-0.36</td>
</tr>
<tr>
<td>900</td>
<td>26.396</td>
<td>895.3</td>
<td>-0.52</td>
</tr>
<tr>
<td>1000</td>
<td>29.515</td>
<td>993.2</td>
<td>-0.68</td>
</tr>
</tbody>
</table>

Y: true temperature
X: thermocouple signal
y: linearized temperature
Slope: 35.71°F/mV
Intercept: 32°F

is linearized to a straight-line response over a 100°F to 1,000°F range by the quadratic linearizing function AX + BX². Trial coefficients are solved at one-third and two-thirds of full scale with the (0.028 mV°F⁻¹) thermocouple output signal slope and 32°F intercept. Solution of the identity of equation (1-12) provides the linearized output temperature whose values are tabulated in Table 1-6. A functional diagram of the linearizer mechanization is shown by Figure 1-29. Figure 1-30 describes the linearized thermocouple characteristic. The reader should compare these results to linearization choices of 200°F and 600°F.

![Figure 1-29. Linearizer Functional Diagram](image-url)
\[ y = \text{slope} \cdot X + \text{intercept} - \text{slope} \cdot f(X) \] 
\[ = AX + BX^2 + 32^\circ F \text{ quadratic approximation} \]

Trial 1 at \( X = 11.023 \text{ mV} \) and \( 400^\circ F \):
\[ y = AX + BX^2 + 32^\circ F \]
\[ 400^\circ F = A(11.023 \text{ mV}) + B(121.507 \text{ mV}^2) + 32^\circ F \]
\[ A = 33.385 \frac{^\circ F}{\text{mV}} - B(11.023 \text{ mV}) \]

Trial 2 at \( X = 20.253 \text{ mV} \) and \( 700^\circ F \):
\[ y = AX + BX^2 + 32^\circ F \]
\[ 700^\circ F = [33.385 \frac{^\circ F}{\text{mV}} - B(11.023 \text{ mV})](20.253 \text{ mV}) \]
\[ + B(410.184 \text{ mV}^2) + 32^\circ F \]
\[ = 676.146^\circ F + B(186.935 \text{ mV}^2) + 32^\circ F \]
Finally:

\[ A = 33.865 \frac{^\circ F}{mV} \]
\[ B = -0.044 \frac{^\circ F}{mV^2} \]

PROBLEMS

1-1. Sensor understanding is an essential requirement for the design and specification of real-time data acquisition systems. Contrast the application considerations of thermocouples, RTD devices, and semiconductor temperature sensors.

1-2. A platinum, platinum-rhodium thermocouple has an emf relationship given by the following equation where \( V_0 \) is in millivolts and \( T \) the temperature difference in degrees C between the measurement and reference junctions. Determine \( V_0 \) if the reference junction is at 27°C and the measurement junction at 1000°C.

\[ V_0 = -3.28 \times 10^{-1} + 8.28 \times 10^{-3}T + 1.5 \times 10^{-6}T^2 \text{ mV} \]

1-3. A potentiometric transducer is composed of 1800 turns equalling 1kΩ resistance. For 1V-dc excitation, determine the expected noise voltage amplitude generated by this device.

1-4. Design a linearizer function for a Type-S thermocouple employing quadratic linearization, with coefficient solutions chosen at 300°C and 600°C appropriate for the example of Figure 7-3. The intrinsic thermocouple output is described by the following table.

<table>
<thead>
<tr>
<th>°C</th>
<th>0</th>
<th>150</th>
<th>300</th>
<th>450</th>
<th>600</th>
<th>750</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>mV</td>
<td>0.016</td>
<td>1.03</td>
<td>2.32</td>
<td>3.74</td>
<td>5.23</td>
<td>6.80</td>
<td>8.45</td>
</tr>
</tbody>
</table>

REFERENCES


