Conventional pressure and differential-pressure instruments can be used in hydrostatic density and specific-gravity applications. The nature of the process fluid will determine the practical design and range to be selected. The maximum practical height of the liquid vessel and the minimum span of gravity and density changes will set the limitations of hydrostatic measurement applications.

Head type density measurement is low cost, simple, and easy to install, and can be dry calibrated. There are, however, several points that may be limitations and must be considered:

- All wet legs must be at a constant height, with seal material of constant density.
- The stratification of process fluids can result in error.
- Small differences in specific gravities or a limitation in height will result in a small-span requirement for the transmitter, although most digital transmitters can accommodate low range applications.
- Level height control is critical, or the level must be constant. The low pressure tap must be covered by the process fluid.
- The condensation of vapors in a dry leg will result in error. A means of drainage may be required when vapor condensation is expected, or a wet leg with a seal fluid may be used as required. Also, a repeater can be used to avoid the wet leg as in Figure 8–3A.

The multipurpose tank gage discussed in Chapter 9 for hydrostatic tank gaging measures density by the hydrostatic method. The operating principle of the device will be detailed in that chapter.

8.4 DISPLACER DENSITY MEASUREMENT

A detailed description of the principle and operating features of displacer level measurement was given in Chapter 5. This principle also relates to density measurement; a review of the earlier material will aid in the understanding of density measurement by displacers.

The fundamental difference between level and density displacer applications is that in the case of level measurement, the density of the process liquid remains constant and the movement of the displacer is a result of level changes. In density applications, the displacer is always

fully submerged and the change in buoyant force is a result of process density variations only.

Figure 8–4 shows the basic components of a torque-tube displacer instrument used for density measurement. The process fluid enters the chamber around the center portion through a piezometer ring, which eliminates the velocity effects of the fluid. In applications where the fluid velocity is less than about 2 ft/min, the fluid should be stable enough so that velocity effects will not affect instrument operation. When it is desired to measure the density of material flowing in a pipe, a sample is routed through the chamber. When density detection in a vessel is desired, the displacer is mounted in an appropriate flange connection, as it is suspended in the process fluid.

Displacers for density measurement are sized in accordance with the amount of buoyant force required for a particular measurement range:

$$\text{Displacer volume } (\text{in}^3) = \frac{\text{Torque tube force lb}}{(G_2 - G_1)(0.036 \text{ lb/in}^3)} \tag{8.22}$$

where the torque tube force is that required for a particular instrument and application, $(G_2 - G_1)$ is the range of measurement desired, and 0.036 lb is the weight of 1 in^3 of water.

EXAMPLE 8-3

Problem: A measurement application requires a torque tube force of 0.36 lb. The desired specific gravity range is 0.975 to 1.000. Find the volume of a displacer with a standard diameter and length for the application.

Solution: From Equation 8.22,

$$V = \frac{0.36 \text{ lb}}{(0.025)(0.036)\text{lb/in}^3} = 400 \text{ in}^3 \tag{8.23}$$

From Table 8–1, a 402 in^3 displacer for that specific gravity range corresponds approximately to one that has a diameter of 4 in. and is 32 in. long.

Figure 8–4 Displacer Type Density Sensor with Torque Tube

For density transmitters, displacer instruments can be pneumatic, analog or "smart" electronic. Temperature compensation can usually be provided as an option. Displacer density instruments are compatible with most fluid characteristics, with temperature and pressure ratings high enough for most applications. Displacers are best suited for clean, nonviscous fluids; a buildup of solids resulting from dirty liquids and slurries would result in errors caused by a change in the weight of the displacer.

8.5 RADIATION DENSITY MEASUREMENT

The principle of radiation density measurement is much like that of radiation level detection (Chapter 7). The obvious difference between

Table 8–1 Displacer Specifications (*Courtesy of CRC Press*)

Displacer Float			Minimum Specific Gravity Span	
Diameter in. (mm)	**Length in. (mm)**	**Volume in^3 (cm^3)**	**Standard Tube**	**Thin-Well Tube**
3 (76)	14 (356)	99 (1622)	0.202	0.101
3 (76)	32 (813)	226 (3703)	0.088	0.044
3 (76)	48 (1219)	340 (5572)	0.059	0.030
3 (76)	60 (1524)	425 (6964)	0.047	0.024
4 (102)	14 (356)	176 (2884)	0.114	0.057
4 (102)	32 (813)	402 (6588)	0.050	0.025
4 (102)	48 (1219)	602 (9865)	0.033	0.017
4 (102)	60 (1524)	753 (12,339)	0.027	0.014
6 (152)	14 (356)	396 (6489)	0.051	0.026
6 (152)	32 (813)	905 (14,830)	0.021	0.011
6 (152)	48 (1219)	1360 (22,286)	0.015	0.008
6 (152)	60 (1524)	1700 (27,858)	0.012	0.006

radiation level measurement and density measurement is that in level measurement, the process fluid density is constant or compensated for, and the amount of absorption of the transmitted gamma rays through the measured medium is a function of liquid level. Level measurement is based on the presence or absence of material. In radiation density measurement, the path length through the process fluid is constant and density is a variable. When gamma rays pass through a process fluid, they are absorbed in proportion to the density of the material. An increase in process fluid density will result in more of the radiation being absorbed by the fluid. This resulting attenuation is a function of density only, as the distance between the source and detector is fixed. The radiation is attenuated in accordance with the following:

$$I = I_0 e^{\mu \rho d} \tag{8.24}$$

where I is radiation striking the detector, I_0 is unattenuated radiation from the source, μ is the mass attenuation coefficient (absorption coefficient) (cm^2/g), ρ is the density of the process material (g/cm^3), and d is the thickness of the sample chamber (cm). The exponential function

of the absorption is converted to an output that is linearly proportional to density.

A radiation density instrument will generally include the following major components:

- The radioactive source
- A shielding container for the source
- The detector
- The signal-conditioning circuit

8.6 RADIATION SOURCE

Atoms that have the same chemical behavior but a different number of electrons are called isotopes. Many elements have naturally occurring stable isotopes, while many others have unstable isotopes. These unstable isotopes disintegrate to form lighter elements. Radioactive disintegration is accompanied by the emission of three kinds of rays: alpha, beta, and gamma. Alpha and beta rays consist of electrically charged particles, are deflected by an electric or magnetic field, and have reduced penetrating power compared to nondeflecting gamma rays. Gamma radiation sources, because of their greater penetration, are used in radiation density measurement.

Two common gamma radiation sources are cobalt 60 and cesium 37. The radioactive disintegration of these elements causes cobalt 60 to produce nickel, and cesium 37 to form barium. It should be noted that the decay process produces electromagnetic energy, which cannot induce other materials to become radioactive. Gamma sources are thus safe for use around food processes. Another point of interest with respect to these sources is that they lose their strength as they decay. The rate of decay is expressed as half-life, which is the period of time during which the source strength decays 50%. Cobalt 60 has a half-life of 5.3 years and will decay about 23% per year. The half-life of cesium 37 is 30 years, with a decay rate of 2.3% per year. The size of the radiation source will be in accordance with the type and thickness of the vessel walls or the pipe size and material, the process material, and the amount of process material through which the radiation must pass. The size of the source will also depend on the specific application with respect to desired precision and the desired measurement system response time.

8.7 SHIELDING

Because gamma sources radiate energy in all directions, individuals within the vicinity of a radiation source could be exposed. Short-term exposure to high-intensity gamma radiation or long-term accumulated exposure to lower radiation should be avoided because of health hazards. Radiation sources are shielded to prevent these hazards.

The (source head) shielding can consist of a lead-filled steel pipe; the radioactive source field is allowed to exit the shield through a guide tube. The radiation exit channel is normally an angle of 12°. The radiation exit channel must always be closed during installation and is usually equipped with a blocking shutter with a safety lock. Some special designs have a pneumatic lock, with switch contacts indicating its position.

8.8 RADIATION DETECTORS

There are three basic types of gamma detectors: the Geiger tube, the ionization chamber, and the scintillation detector. The Geiger tube is a low-accuracy device that measures radiation through the ionization of a halogen gas sensitized to a potential of about 500 V DC. Ionization chambers (also called ionization cells) operate by the ionization of pressurized gas between two dissimilar metals under incident radiation that generates a very low current (on the order of a nanoampere). The scintillation detector senses the light photons resulting from gamma rays incident on certain crystal materials. For density applications, both scintillation and ionization detectors are used. When the ionization chamber detector is used, it is temperature-controlled to maintain stable environmental conditions. The scintillation detector is advantageous because of its increased sensitivity; it usually allows a smaller source to be used than would be permissible with an ionization chamber detector.

8.9 SIGNAL CONDITIONING

The detector output signal requires amplification and scaling, which is done by both DC and AC amplifiers. AC amplifiers were once preferred because of better stabilization. High-gain stable DC amplification by linear operational amplifiers and digital circuits is gaining prominence and is now more common. Drift caused by component aging, temperature shifts and other factors is compensated for electronically in the signal conditioning circuitry.

Minimum full-scale span is about 0.01 g/cm^3 (or another density unit), and depends on the thickness of the material to be measured. Corresponding resolution as great as 0.0001 g/cm^3 is possible. When measuring small spans, the zero drift caused by source decay can be an important consideration, however. A means of source decay compensation, incorporated into digital signal conditioners, is now available.

8.10 DENSITY GAGE APPLICATIONS

As with any measuring instrument, careful initial selection and installation are important for reliable and precise operation of a radiation density detector. When selecting the site for installation, several criteria are critical. The pipeline or sample chamber must be completely filled with the process fluid or sample at the detecting point. Corrosion, abrasions and material deposits on pipeline walls and sample chambers must be eliminated when possible. Installation on vertical pipes is preferred. Entrained gas-forming bubbles in the product will also cause errors and should be eliminated (the product sample chamber can be operated at higher pressure to reduce bubbles). Mechanical vibration of the pipe resulting from cavitation and so forth should be reduced to avoid error and damage to the detector.

The maximum operating temperature of some detectors and related conditioning equipment is about 50°C. When conditions warrant, cooling of the detector will be required. Cooling jackets are provided by some manufacturers and should be used when needed. Water is usually the best cooling medium in high-temperature applications because of its greater cooling capacity. Careful mounting and insulation can help reduce problems caused by temperature.

Microprocessors have significantly expanded the capabilities of these density gages as well as simplified their operation. All application data can now be entered into nonvolatile memory at the factory; thus field startup and calibration consist simply of a one-step standardization procedure: the gage's response to a known material (e.g., water) is measured. Multiple readouts, digital and analog, are available in any engineering units. High- or low-relay outputs can be easily adjusted by the operator to alarm, and the time constant of the system can be adjusted to optimize process control loops.

A typical density gage is mounted externally to a process pipe as shown in Figure 8–5. Recall the radiation equation given earlier (Equation 8.24). In the density gage configuration, the material thick-

Figure 8–5 A Radiation Density Detector

ness *(d)* does not vary because the source and detector are fixed to the process pipe. Since the mass absorption coefficient (μ) is assumed to be constant, any change in the radiation intensity at the detector occurs only when the density (ρ) of the process material varies.

Nuclear density gages are employed for gases, liquids, slurries, solutions and emulsions. Because no contact is ever made with the process material, density measurement can be performed easily in caustic, corrosive and abrasive processes.

If density is to be measured inside a large vessel, it may not be practical to place both source and detector outside the vessel, as the source required would be too large. For this type of application, an insertion source can be used.

Since a density gage measures the total density of a process material, air or other entrained gases in the material may be a problem in some

applications. The user may not know that the bubbles are present until the gage is installed. Entrained gas will cause the gage to read too low and possibly cause erratic fluctuations in the output. Replacement of faulty pump seals or relocation of the gage generally will solve this problem. It should be noted, however, that some products have air injected into them as part of the manufacturing process. Air, then, is a critical part of the product, and in such instances a nuclear density gage, which measures the bulk density, cannot ensure consistent quality control.

The buildup of solids on the inner pipe wall will also introduce error into the density reading. The worst case occurs when the material builds up gradually and then suddenly flakes off. This problem is usually solved by the installation of a process pipe section lined with glass, Teflon or some other material unaffected by buildup. For slurry applications, the source and detector should be mounted on a vertical pipe section if possible. This configuration ensures a full pipe and prevents the stratification that can occur with horizontal mounting.

In most process streams, very small changes in the mass absorption coefficient of the process material are insignificant. For elements with atomic numbers 2 through 50, the mass absorption coefficient for cesium 37 radiation varies only slightly and may be assumed to be 0.077. The mass absorption coefficient increases as the atomic number goes above 50, due primarily to increased photoelectric absorption. Hydrogen, because of its high electron density, has an absorption coefficient of 0.1537. This is not a problem for solutions or slurries with a water carrier, as it is simply figured into the mathematics used to calibrate the system. However, for organic materials with varying hydrogen contents, this large difference in the absorption coefficient may introduce error into the density measurement.

The application of microprocessor-based electronics to density measurements has solved or greatly reduced the impact of many problems with analog systems that were quite formidable in the past. For example, it is well known that the density of a substance may vary significantly with fluctuations in temperature. However, the intent of the nuclear gaging system may be the measurement of density variations associated only with product makeup. It is thus essential to provide compensation for variations in process temperature. Analog systems offer limited capability for temperature compensation, but they cannot allow for the fact that the temperature coefficient of most materials is itself a function of temperature; hence, analog temperature

compensation is effective over only a very narrow temperature range. Today's microprocessor-based systems offer true temperature compensation over a wide temperature range and can compensate for both components of two-component streams, such as slurries or emulsions.

Of all the specifications pertaining to nuclear density systems, two of them—time constant and precision—are probably not considered fully by the average user. Since the two are interrelated, they will be discussed together. Precision is simply repeatability. However, recall that the amount of radiation emitted by a gamma source is a statistical phenomenon; hence, a nuclear density gage will not produce a given repeatability 100% of the time. To be meaningful, then, a statement of precision must be accompanied by a statement of confidence level. For example, if precision at one standard deviation is quoted, the confidence level is 66% and the system can be expected to measure at the quoted precision approximately two-thirds of the time. At a two-standard-deviation level, the system will measure density within the stated precision about 95% of the time. If no confidence level is given, let the user beware, because no meaningful statement of gage performance has been made.[1]

The statistical variations that affect precision appear as "noise" on the output. A filtering time constant is used to damp out the noise (statistical variations in radiation reaching the detector). The time constant is the time required for the system to provide about 63% response to a step change in process density. A 95% response requires three time constants. There are two ways to improve the precision (reduce the noise) of a given nuclear density gage configuration: increase the source size or increase the filtering time constant. Increasing the source size increases system cost, and there are limits to how large a source can be supplied. Increasing the time constant costs nothing, but this must be balanced by the response requirements of the application. Some microprocessor-based density systems provide a solution to this problem of trade-off between response time and precision, which is known as dynamic process tracking. These systems operate with a relatively long time constant when the process density is stable, thus providing good precision. When the process density changes, these systems automatically switch to a short time constant, thus providing good dynamic response.

1. The concepts of precision and confidence level apply to all types of physical measurement instrumentation, regardless of the technology used, and should always be considered when specifying such equipment.