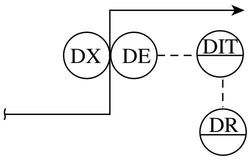
6.6 Radiation Densitometers

C. H. HOEPPNER (1982) **B. G. LIPTÁK** (1969, 1995, 2003),

REVIEWED BY A. J. LIVINGSTON (1995, 2003)



Flow Sheet Symbol

Applications:	Noncontact and nonintrusive density measurement of liquids and solids.
Radiation Sources:	The most commonly used radioisotope is cesium 137, because it decays more slowly (30 years half life). Cobalt 60 is selected when the tank/pipe walls are thick (5.3 years half life). Americum 241 (455 years half life) and radium (1602 years half life) are less frequently used.
Source Sizes:	For external types, generally a few hundred millicuries (mCi) or less. For low level applications: from 0.1 to 2 mCi. For normal applications: from 5 to 2,000 mCi with 10,000 mCi being the maximum. A curie equals 3.7×10^{10} disintegrations/s and is generated by 1 g of radium, 0.88 mg of cobalt, or 11.5 mg of cesium.
Process Pressure:	Unlimited; sensor is external to pipe.
Ambient Temperature:	External detectors are suitable for –40 to 160°F (–40 to 71°C) ambient conditions. Heaters or coolers are available for ambient temperatures outside these limits.
Materials of Construction:	Detector is normally carbon steel or aluminum; other parts are optional.
Inaccuracy:	1% of actual span
Limitations:	Errors caused by entrained air, deposits on pipe wall and stratification. The detector requires a 5% change in the detected radiation intensity as the process density changes from minimum to maximum. Therefore, when detecting narrow spans, compensation is needed for source decay and process temperature. The source decay effect with cesium 137 is 3% per year. A minimum of 6 in. (150 mm) radiation path length is required.
Range (Span):	From 0.3 to 3.0 SG
Applicable to Pipe Sizes:	2 to 30 in. (51 to 762 mm) diameter
Radiation Intensity:	Generally under 5 mR/h at 12 in. (0.3 m) from instrument
Allowable Radiation Dose:	One roentgen is received during a period of 1 h, if spent within 1 m of a 1 Ci radiation source. One receives a dose of 1 rem (roentgen equivalent man), when exposed to one roentgen in any period of time. Allowable limits for the general public are 2 mrem/h, 100 mrem/year. The allowable dose for occupational worker is 5000 mrems/year (see Table 6.6d).
Costs:	A clamp-on unit for a 6 in. (150 mm) pipe with 0.28 in. (7 mm) wall and 1 in. (25 mm) fiberglass insulation, for 80 to 120°F (27 to 49°C) ambient temperature and a range of 1.0 to 1.25 SG, cost from $ 7000 to $ 8000. For a 20 in. (0.508 m) pipe, the same unit costs from $ 12,000 to $ 14,000.
Partial List of Suppliers:	Barton Instrument Systems LLC (www.barton-instruments.com) Bedford Control Systems Inc. (x-ray)

Berthold Industrial Systems Inc. (www.berthold.com.au)
Endress + Hauser Inc. (www.us.endress.com)
Flow-Tech Inc. (www.flowtechonline.com)
Ohmartvega Corp. (www.ohmartvega.com)
Ronan Engineering Co. (www.ronanmeasure.com)
Thermo MeasurTech (www.thermomt.com)

INTRODUCTION

Radiation is caused by the spontaneous disintegration of the nucleus of an atom. Wilhelm Roentgen discovered x-rays in 1895, while radioactivity as such was discovered by Antoine-Henri Becquerel in 1896. The three forms of radiation are alpha (the emitted particle is the nucleus of helium and travels only a few centimeters in air), beta (electrons are emitted that can travel a few meters in air), and gamma. Gamma radiation consists of high-energy electromagnetic waves that can travel a couple of hundred meters in air.

The range in source sizes for density measurement applications has been lowered in recent years. This occurred partly because of changing regulations and partly because the high sensitivity sodium iodide detectors have been developed. These new detectors allow for the use of reduced (down to 0.1 mCi) source sizes, because the sodium iodide crystal detectors are larger and more stable than their predecessors.

Such density gauges are permitted under a General License, which requires no fees, no wipe tests, and no shutter check, and allows the user to do the initial start-up. These features reduce the overall cost of ownership.

Radioisotopes

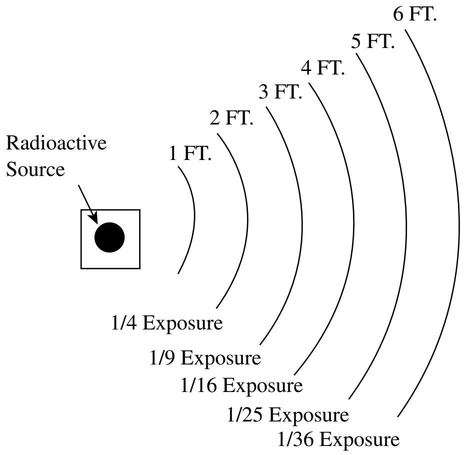
The emitters of gamma radiation and their half-lives in years are listed in Table 6.6a. The size of a radiation source is expressed in millicuries (mCi). One millicurie is defined as 37 million disintegrations. The range of source sizes for level and density applications generally ranges from 5 to 10,000 mCi. The most commonly used isotope is cesium 137. Due to its half-life, the activity of a 100-mCi cesium source will be 50 mCi after 30 years and 25 mCi after 60 years.

TABLE 6.6a
Half Lives of Radioisotopes

Isotope	*Half-Life in Years*
Americum (Am 241)	455.0
Cesium (Cs 137)	30.0
Cobalt (Co 60)	5.3
Radium (Ra 226)	1602.0

The strength of the radiation field is measured in milliroentgens (mR). In a 1-mR radiation field, 2.08 million pairs of ions are produced in a cubic centimeter of air. The intensity of the radiation field is a function of the size (activity) of the source, the distance from the source (Figure 6.6b), and the material that the radiation has to pass through. The higher the density of a material, the more radiation it is likely to absorb. Table 6.6c lists the half-value thicknesses (H) and specific gravities (SG) of some common industrial materials when exposed to radiation generated by Cs137. H is the thickness of a material necessary to reduce incident radiation by 50%.

The amount of radiation exposure received (dose) by an operator is expressed in roentgen equivalent man (rem) units.



$$D = 1000 \frac{K\ mCi}{d^2}$$

Where

D = intensity, mr/hr,
mCi = size of source in millicuries,
d = distance to source in inches, and
K= constant, 1.3 for Ra 226
0.6 for Cs 137
2.0 for Co 60.

FIG. 6.6b
Radiation intensity and therefore exposure drops with the square of distance to the radiation source.

TABLE 6.6c
Half-Value Thickness of Materials When Exposed to Radiation from a Cs 137 Source

Material	*Specific Gravity*	*Half-Value H* *Inches*	*Half-Value H* *mm*
0.5 SG bulk material	0.5	7.87	200
Water	1.0	3.9	99
Al_2O_3 refractory	2.25	1.77	45
Aluminum	2.7	1.5	38
Steel	7.86	0.6	15.2
Copper	8.96	0.47	11.9
Lead	11.4	0.25	6.35

TABLE 6.6d
Radiation Exposure Limits in Millirems (mrem)

Exposure Period	*General Public*	*Occupational Workers*
Hour	2	
Quarter		1250
Year	100	5000

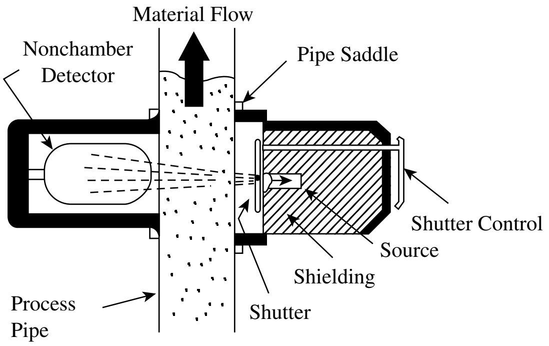


FIG. 6.6e
The gamma source is housed in a lead-shielded holder. When the shutter mechanism is opened, a collimated gamma beam passes through the pipe wall and the process material inside; its intensity at the detector is interpreted into process density.

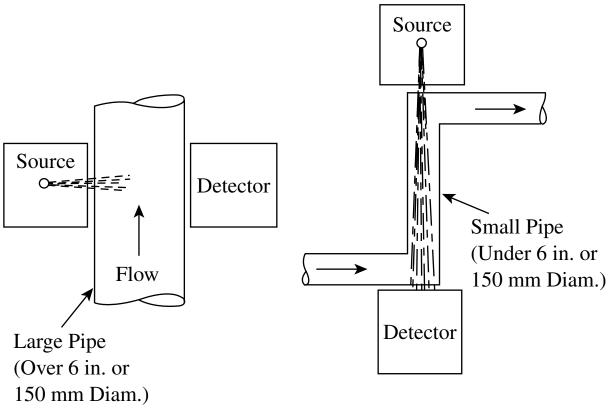


FIG. 6.6f
Radiation density sensors.

A rem is the dose received when an operator is exposed to a radiation field of 1 R. In most countries, the radiation dose limit in the workplace is 1250 mrem/calendar quarter, 100 mrem/week, or 2.0 mrem/hr. See Table 6.6d for a more complete set of data.

THE RADIATION DENSITOMETER

The basic components of the density gauge comprise a radioactive source beaming through a pipe and a detector system to measure the amount of transmitted radiation (Figure 6.6e).

When gamma rays pass through a process fluid, they are absorbed in proportion to the density of the process material (see Figure 6.6f). An increase in process density results in a reduced output current because a denser process fluid absorbs more of the gamma rays.

When the density inside large pipes (or containers) is measured, the radiation source and detector would be mounted as illustrated on Figure 6.6e. In a smaller diameter pipe (under 6 in., or 150 mm) the radiation path is not adequate to provide high accuracy and sensitivity. Therefore, the *Z* installation shown on the right side of Figure 6.6f would be used. This method of mounting lengthens the radiation path and consequently increases accuracy.

Radiation Source

For the majority of density measurement applications, cesium 137 is used as the radioisotope. Source sizes normally vary between 200 and 2000 mCi as a function of pipe diameter and specific gravity span. Gauge sensitivity is increased by the use of the collimated (narrow) beam geometry, which restricts radiation in all directions except for a direct path to the detector. This minimizes scatter and permits the use of larger sources with increased measurement sensitivity.

Most designs are such that the radiation intensity at one foot from the gauge surface in any direction will not exceed 5 mR/h. This is a safe value for any process area where the operator's occupancy is 20 hours or less per week.

The source holder is provided with a shutter mechanism to close the radiation beam port during installation. Available shutter features include the fail-safe design, which automatically closes the shutter whenever power fails; the shutter switch, which permits remote light display of shutter position; and the remote shutter control, which allows closing the radiation beam from a central control board.

Radiation Detectors

There are three basic types of gamma ray detectors: the Geiger tube, the ionization chamber, and the scintillation crystal/photomultipler tube detector.

FIG. 6.6g
Actual installation of a densitometer.

Geiger Tubes The Geiger tube is a low-accuracy device that measures radiation through the ionization of a halogen gas at about 500 V DC potential.

Ionization Cells Ionization cells operate by the ionization of pressurized gas between two dissimilar metals under incident radiation, generating a low current signal (10^{-10} A). For density gauging, the ionization chambers are used almost without exception (Figure 6.6g). They require stable amplification, but when this is provided they supply simple, accurate, and reliable measurements.

Scintillation Detectors The scintillation detector senses the light photons resulting from gamma rays incident on certain crystal materials. This is the most sensitive but least stable detector. It is particularly affected by variations in environmental conditions such as temperature.

Temperature Control and Calibration It is desirable to heat and thermostatically control the detector chamber to eliminate temperature variation and moisture condensation problems. The process temperature is of no consequence, but it is necessary to use thermal insulation between cell and process, so that detector temperature will not rise above 140°F (60°C).

Calibration checks for both zero and span can be performed by the use of equivalent absorbers. These absorbers are accurately made for the specific measurement and are inserted between source and detector with the pipe empty.

Periodic recalibration is necessary to overcome the effects of source aging and material buildup on the walls. If zeroing and calibration is to be done in place using air and some known density calibration liquid, it is necessary to install a calibration fluid sample valve near (usually below) a densitometer that is mounted in a vertical pipe.

Amplifier and Power Supply

Amplifiers are available in both digital and DC designs. Economics favor the DC design, while the digital amplifier guarantees better accuracy and less drift. The DC amplifier needs weekly or bimonthly standardization, while the solid-state, digital unit requires less frequent standardization.

Span and Error The minimum full-scale span is about 0.05 specific gravity units with a corresponding accuracy of 0.0005 SG or better. When measuring small spans, the zero drift due to source decay becomes an important consideration. The source decay compensator unit is a must for such installations. For wider ranges, it is essential only if the source is cobalt 60. The source decay effect with cesium 137 is only 3%/year.

Densitometers for applications involving process materials with high temperature expansion coefficients are provided with temperature compensation if variations in process temperature are expected.

The output signal from the detector to the amplifier is in digital pulses. Therefore, the signal should be protected by the use of two-wire, shielded cable. The maximum distance between detector and amplifier is about 5000 ft (1500 m), but should be made shorter whenever possible.

BETA RADIATION DENSITOMETERS

Beta-ray absorption has been successfully used in cryogenic density applications. The source in this unit is strontium-90 and the receiver is a silicon surface-barrier detector.

The system counts the number of beta particles that strike the detector with an energy greater than the discrimination level.

The source and receiver are packaged in a small, light, corrosion-resistant probe. In addition to detecting density, it can be used for level and other measurements.

X-RAY DENSITOMETERS

“Soft,” low-energy x-rays have also been used in density measurement applications (Figure 6.6h). x-ray systems do not require lead shielding and produce passive radiation. This means that radiation stops when the power supply to the unit is turned off. In the example shown on Figure 6.6h, safety interlocks can be provided to turn off the power supply if the hopper is empty or when either the source or the detector is removed, or if the hopper access door is opened.

The excitation voltage is about 35,000 V, and the x-rays are collimated (focused) to a beam diameter of about 3 in. (76 mm) at the end of a 40 in. (1.01 m) path through air. The supplier claims that the instrument meets both the U.S. Federal Drug Administration’s 1000 rad limit on radiation absorption of food and the 100 mrem/week limit of Occupational Safety and Health Administration on human exposure to radiation.

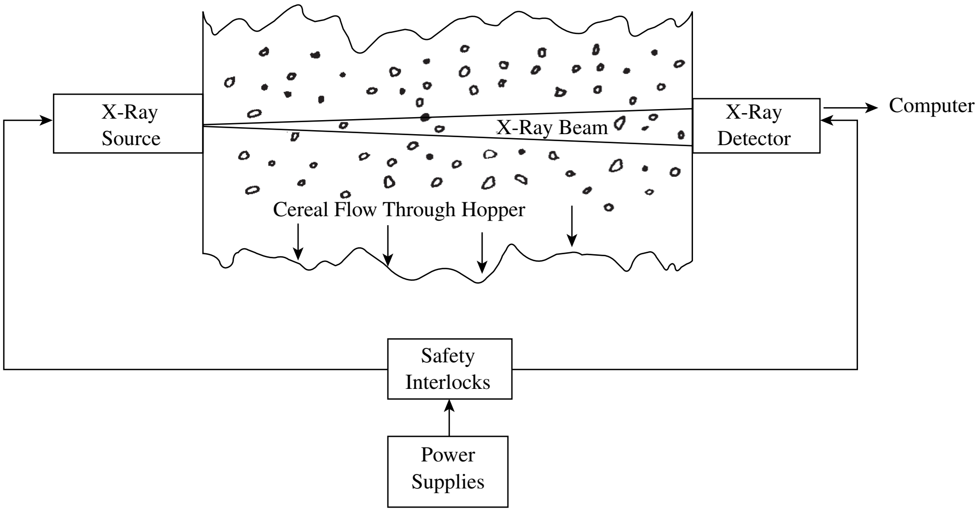


FIG. 6.6h
X-ray densitometer used on cereal hopper contents. (Courtesy of Bedford Control Systems Inc.)

LIMITATIONS

The main limitations of radiation densitometers include air entrainment, pipe wall deposits, source decay (about 3%/year for Cs 137), and stratification. Some of these problems can be minimized by installing the gauge in vertical upward flow with a positive head pressure at the location of the gauge. Other remedies include the use of glass or Teflon-lined pipes and the maintaining of a flow velocity of 5 ft/s (1.5 m/s) at the gauge. Frequent recalibration is also recommended.

Another limitation involves minimum spans, as the detector requires a 5% change in the detected radiation intensity as the process density changes from minimum to maximum. Therefore, on a 2-in. (50-mm) pipe, the minimum span is 0.2 SG, while on a 6-in. (150-mm) pipe or on a *Z* installation, the minimum span is 0.05 SG. Microprocessor-based densitometers can compensate for source decay and can also provide automatic temperature compensation (water density at 176°F [80°C] changes by 0.0005 SG/°C of temperature change).

CONCLUSIONS

For source sizing and licensing information, refer to Section 3.15. Where it is possible for the operator to get in the path of the radiation beam (when moving the gauge or when cleaning a tank), a Specific License must be obtained. In all other cases, a General License is sufficient.

The applications of radiation densitometers include the consistency control in such processes as lime kiln feeds, density measurements of sewage sludges, black and green liquors, food products, granular materials, and the detection of pipeline interfaces. While relatively high in cost, these density detectors, which have no moving parts and require no contact with the process, perform reliably on hard-to-handle (flammable, toxic, hot, corrosive, sticky, etc.) processes.

Bibliography

Boyes, W., "Non-contacting Density Instrumentation," Instrumentation, Systems, and Automation Society/93 Technical Conference, Chicago, September 19–24, 1993.

Capano, D., "The Ways and Means of Density," *InTech*, November 2000.

"Continuous Density Analyzer Records Sludge Concentration," *Wastes Engineering*, April 1959.

Cook, H.L., "Slurry Measurement and Control," *ISA Journal*, June 1964.

Haffner, J.W., "Radioisotopes for On-Stream Analysis," *ISA Journal*, May 1964.

Holzschuler, P., "Hazard Free Analysis," *Processing*, October 1989.

Livingston, A.J., "Density Measurement, Nuclear Gauge Measurement of Density," *Measurements and Control*, December 1990.

"Nuclear Disarmament," *Flow Control*, (www.flowcontrolnetwork.com), April/May 2000.

Paris, T. and Roede, J., "Back to Basics," *Control Engineering*, June 1999.

Smith, B.W., "Radioisotope Gauging in the Mining Industry," *The Canadian Mining and Metallurgical Bulletin*, January 1964.

"Standard Practice for Calibration of Transmission Densitometers," *ASTM Standard*, 1998.

U.S. Nuclear Regulatory Commission, "Working Safely With Nuclear Gauges," NUREG/BR-0133, latest edition, Washington, D.C.