INEL-96/0295
ITER/US/96/TE/SA-16

September 1996

Idaho National Engineering Laboratory

Reliability Estimates for Selected Sensors in Fusion Applications

L. C. Cadwallader

LOCKHEED MARTIN

INEL-96/0295
ITER/US/96/TE/SA-16

Reliability Estimates for Selected Sensors in Fusion Applications

L. C. Cadwallader

Published September 1996

Idaho National Engineering Laboratory
Nuclear Engineering Technologies Department
Lockheed Martin Idaho Technologies Company
Idaho Falls, ID 83415-3815

Prepared for the
U.S. Department of Energy
Office of Energy Research
Under DOE Field Office, Idaho
Contract No. DE-AC07-94ID13223

ABSTRACT

This report presents the results of a study to define several types of sensors in use, the qualitative reliability (failure modes) and quantitative reliability (average failure rates) for these types of process sensors. Temperature, pressure, flow, and level sensors are discussed for water coolant and for cryogenic coolants. The failure rates that have been found are useful for risk assessment and safety analysis. Repair times and calibration intervals are also given when found in the literature. All of these values can also be useful to plant operators and maintenance personnel. Designers may be able to make use of these data when planning systems. The final chapter in this report discusses failure rates for several types of personnel safety sensors, including ionizing radiation monitors, toxic and combustible gas detectors, humidity sensors, and magnetic field sensors. These data could be useful to industrial hygienists and other safety professionals when designing or auditing for personnel safety.

SUMMARY

This report is a review of sensor technology and sensor reliability. Several types of sensors are described; first their operating principles and then the reliability features. A qualitative reliability analysis has been carried out for five types of process sensors: temperature, pressure, flow, level, and water quality. The qualitative failure modes and effects analysis (FMEA) gives insights into what designers should consider when incorporating a sensor into a process or safety system. The qualitative reliability was approached in two stages. First, judgment was used on the sensor operating principles to identify what the possible failure modes are, then a FMEA was performed to give an exhaustive set of possible failures. The FMEA was supported by articles and reports on operating experiences.

With a firm definition of possible failures, another literature search was made to find the failure rates for these five types of sensors. Several literature sources were found to give failure rates for typically used sensors; however, these sensors represent older technology that has been in use for many years. No data were found on the reliability of digital sensors. Therefore, for the current time, it is suggested to use the average failure rates of existing equipment to bound the digital sensor failure rates. If a sensor is determined to be an important or crucial component in a risk assessment or safety analysis, then more effort can be put toward locating a data set to better describe the digital components.

Table S-1 presents an overview of the failure rate results of this report. References for the sensor failure rates given in this table are found in their respective chapters. It is noted that many of the sensor failure rates for fail to operate are the same values. This is attributed to the fact that sensors reported in the literature are reasonably matured technology, and most of the data originate from the same area, namely the fission power industry. The data for other failure modes (drift, erratic output, etc.) are given in the chapters. Repair times that were found in the literature were generally on the order of a few hours. Calibration intervals were cited to be on the order of a year or longer. Inspection times ranged from 1 to 3 months, to longer intervals. The last portion of Table S-1 presents information on personnel safety sensors from Chapter 7. These data will be useful for personnel safety assessments at fusion or related facilities (such as particle accelerators, cryogenic plants, etc.).

Table S-1. Summary of order of magnitude failure rates for selected sensors

Sensor Type	Failure mode	Failure rate (/h)	upper bound failure rate (/h)
Thermocouple	fail to operate	1E-06	3E-06
Resistance temperature detector (RTD)	fail to operate	1E-06	3E-06
Strain gauge pressure sensor	fail to operate	1E-06	3E-06
LVDT pressure sensor	fail to operate	1E-06	3E-06
Orifice or Venturi flow sensor	fail to operate	1E-05	1E-04
LVDT level sensor	fail to operate	1E-06	3E-06
pH sensor	fail to operate	5E-07	2.5E-06
Water conductivity sensor	fail to operate	1E-06	3E-06
Ionizing radiation sensors	fail to operate	1E-06	1E-05
Oxygen sensors	fail to operate	1E-05	1E-04
Combustible gas sensors	fail to operate	1E-05	3E-05
Toxic gas sensors	fail to operate	1E-05	3E-05
Ionization smoke detector	fail to operate	1E-06	3.5E-06
Humidity sensor	fail to operate	1E-05	1E-04
Noise sensor	fail to operate	1E-05	1E-04
Magnetic field sensor	fail to operate	1E-06	1E-05

CONTENTS

ACKNOWLEDGMENTS

The author wishes to thank several people for their support of this report. Mr. Dave Kraykovic allowed this failure rate data research work to proceed in a dual fashion at the University of Idaho and as a laboratory research project. Dr. Dave Petti reviewed this report and added it as an additional report to submit to the International Thermonuclear Experimental Reactor (ITER) project staff. Ms. Rebecca Cheek, industrial hygienist, offered many useful suggestions for personnel safety monitoring equipment data.

NOMENCLATURE

ASME	American Society of Mechanical Engineers
dB	decibel
DOE	US Department of Energy
DP	differential pressure
EMI	electromagnetic interference
FMEA	failure modes and effects analysis
HVAC	heating, ventilating, and air conditioning
IEEE	Institute of Electrical and Electronics Engineers
ITER	International Thermonuclear Experimental Reactor
LP	liquefied petroleum gas
LVDT	linear variable differential transformer
OREDA	Offshore Reliability Data
pH	logarithm of inverse of hydrogen ion concentration, also called potential for the hydrogen
PVDF	polyvinylidene fluoride, a polymer film
RTD	resistance temperature detector
Pa	pascals
Q	volumetric flow rate
Re	Reynolds number

RELIABILITY ESTIMATES FOR SELECTED SENSORS IN FUSION APPLICATIONS

1. Introduction

This report presents information on reliability and maintainability of selected sensors for temperature, pressure, flow, and level sensing. These sensors can be used for process control or for safety monitoring of various processes. Where possible, instruments or sensors for typical fluids (e.g., water and air) and for other fluids (e.g., cryogenic fluids) have been considered. Data on some types of related sensors for safety have been included when they were found in the literature. A representative set of personnel protection sensors is also discussed.

The four sensor types discussed above have been researched, and failure modes and effects analyses (FMEAs) have been performed on these sensors to identify the failure modes. The effects in the FMEA had to be confined to the sensor unit itself, since these units were considered as entities and not part of a larger system. The approach developed in MIL STD 1629A (1980) was used to perform the FMEAs. The FMEAs were performed in two stages. The first stage was using judgment to identify failure modes based on the discussion of sensor construction given in Johnson (1993) or other sources. Then, the literature was reviewed to learn about any other possible sensor failure modes that might occur with sensors in use. This two-stage approach was used to provide thoroughness to the qualitative reliability analysis. Failure mode distributions were sought from the literature. As the reader might expect, the failure mode of 'out of calibration' or 'drift' was the most prevalent failure mode found.

Failure rate and repair rate data for the four sensor types discussed above were collected as they were reported in the literature. These data are important to work being performed to study personnel radiation exposure in magnetic fusion reactors (Sandri and Di Pace, 1995; Sandri and Di Pace, 1996). This task of data harvesting from the literature can be useful, however the data can also be difficult to interpret and apply correctly. Without access to plant-specific performance data, such as operator logbooks, maintenance reports, calibration logs, etc., then analysts are forced to rely upon already-published data. The data will be "genericized" for future use when it is deemed appropriate. Many industries use a wide variety of sensors, but performance data are not collected on this equipment since it is costly to collect and analyze these data. Generally, only industries that are regulated by law to collect such data are found to make the effort at data collection and analysis. Primarily, the nuclear power industry collects data, however the chemical process industry is also beginning to collect plant-specific data for use in risk and safety assessment.

The data found in the literature are more abundant for older instrument technology. Both reliability and repair data for newer applications, such as fiber optic sensors and digital transducers, are not easily found in the literature. At present, the available data will provide bounding estimates of failure rates for such sensors to support safety and risk work until such time as more precise data becomes available. If the sensor becomes a highly important or even critical component, then more effort can be made to identify failure rates. The data estimation methods of inference of performance from known components and decomposition into component parts can be used (see Cadwallader and Marshall, 1996).

Any safety-related sensor data that have been found as part of the literature review, such as oxygen concentration sensors used in cryogen production plant rooms, are reported here in Chapter 7.

Some definitions (see Wheeler and Ganji, 1996; Iyengar et al., 1995) are important to note for better understanding of later chapters:

sensor - a device that senses some physical variable, such as temperature or pressure

transducer - a device that converts a physical measurement into a signal, usually an electrical signal. Sensors can be called transducers if they transform the measurement of physical variables into electrical signals.

instrument - a sensor and transducer, a device that sends a measurement signal to some type of control center or a controller

measurand - the quantity being measured, such as temperature or pressure

analog sensor - a sensor that generates a signal (usually electrical) that is proportional to the physical variable being measured, for example, a resistance temperature detector generates an electrical signal that is proportional to the temperature of the material being measured

digital sensor - a sensor that measures some parameter and then sends its signal out as a binary signal. For example, an electrical signal is only 0 or 5 volts, to represent the 0 or 1 of binary language. There is no varying electrical signal proportional to the physical property, just the binary language signal.

The chapters in this report each discuss five types of sensors: temperature, pressure, level, flow, and water quality sensors. A final chapter presents data on personnel safety monitors, such as ionizing radiation monitors, oxygen and humidity monitors, and gas detectors.

There are some concepts that should be mentioned here. While cost is always an important factor, process and personnel safety are also important. Specifying multiple sensors to gain comparative readings thereby obtaining a voting logic means added capital cost, added cost of spare parts or spare sensors to maintain capability while recalibrating units, and perhaps even additional staff personnel to perform calibrations and periodic checks. With so many sensors needed, it becomes important from a safety and cost perspective to monitor the variable that needs to be known (Kletz, 1988). For example, if the fluid flow rate from a pump is the desired measurand, then the flow rate should be measured, not the electrical current to the pump's electrical motor. While measuring electrical current might be simpler and less costly than a fluid flow meter, it is not always an adequate indication of the true measurand. In this example, the pump outlet could be clogged with debris, the liquid could be vaporized in the pump casing, some part of the flow loop could be breached or could have experienced frozen piping, etc., making current to the pump motor a poor indicator of fluid flow. When a system is working correctly, there is not a problem in using pump electrical current to estimate fluid flow. When the system is in an off-normal condition, there could be false flow readings that aggravate the situation.

Another issue is using sensors that can withstand the operating environment to give long lifetimes (i.e., decades). Sensors that experience environment stresses such as high temperature, high ionizing radiation, moisture, high vibration, high pressure, dust, etc., must have their own reliability estimates. Moss and Strutt (1993) discuss some data sources and multiplicative factors [called k factors] that weight the sensor failure rates to account for harsh conditions. The reliability data book (IEEE, 1984) gives suggested k factors for different environments. Since most of these data are for nuclear fission power plants, the high temperature and high radiation conditions are taken to be inside the containment building that houses the primary coolant loop. Containment building temperatures can reach up to 88°C, with averages around 35 to 50°C (Guyer et al., 1982). Ionizing radiation levels in containment buildings are on the order of 200 to 300 millirads/hour (Sejvar, 1977), although higher values can be seen near the coolant piping (perhaps up to 3 rads/hour) and near the reactor vessel (10^4 rads/hour). Most sensors for nuclear plant use are designed to accept a lifetime radiation dosage of 10^7 rads (Lish, 1972), which provides an adequate lifetime for sensors mounted on or near coolant piping. Other environmental conditions (e.g., humidity, vibration, etc.) must also be defined for sensors.

A design idea for analysts to be aware of is the choice of sensor zero reading. Designers generally choose to have the zero measurand reading still require an output from the sensor (Lish, 1972). For example, a flow rate of zero still requires some small milliampere output from the flow sensor. Since there is still indication, the operators know that the sensor is functional even if the indicator reads zero. If the sensor is failed to no output, the indicator will drop to a subzero reading.

Some other data were found during the literature review. Entire control systems were outside the scope of this study. However, besides the Moss and Strutt (1993) sources, some reliability data to use when fault modeling a control system are found in Trojovsky and Brown (1984), Paula (1993), Mitchell and Williams (1993), and in MIL HDBK 217F (1991).

This report is part of a series of reports to harvest reliability data for magnetic fusion usage. Previous reports covered magnets (Cadwallader, 1991), cryogenic systems (Cadwallader, 1992), vacuum systems (Cadwallader and Marshall, 1994), and fire protection systems (Cadwallader, 1995). In time, a data bank of reliability and maintainability data will be gathered to support safety assessments performed by the Fusion Safety Program at the Idaho National Engineering Laboratory. These data are shared with participants in the International Energy Agency's collaborative agreement on Environmental, Safety and Economic Aspects of Fusion Power, which has a task on failure rate collection and data bank construction. These data are also useful to fusion reactor design projects, such as the International Thermonuclear Experimental Reactor (ITER) engineering design activity.

Chapter 1 References

Cadwallader, 1991.	L. C. Cadwallader, Magnet Operating Experience Review for Fusion Applications, EGG-FSP-9977, EG&G Idaho, Inc., November 1991.
Cadwallader, 1992.	L. C. Cadwallader, Cryogenic System Operating Experience Review for Fusion Applications, EGG-FSP-10048, EG&G Idaho, Inc., January 1992.
Cadwallader and Marshall, 1994.	L. C. Cadwallader and T. D. Marshall, Vacuum System Operating Experience Review for Fusion Applications, EGG-FSP-11077, EG&G Idaho, Inc., March 1994.
Cadwallader, 1995.	L. C. Cadwallader, Fire Protection System Operating Experience Review for Fusion Applications, INEL-95/0396, Idaho National Engineering Laboratory, December 1995.
Cadwallader and Marshall, 1996.	L. C. Cadwallader and T. D. Marshall, "Component Reliability Data Estimation for Fusion Safety and Risk Assessment," to be presented at the International Conference on Probabilistic Safety Assessment (PSA '96), Park City, Utah, September 29 - October 3, 1996.
Guyer et al., 1982.	E. C. Guyer et al., Control of Containment Air Temperature: An Industry Survey and Insulation Test, EPRI NP-2694, Electric Power Research Institute, October 1982, chapter 2.
IEEE, 1984.	IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations, IEEE Std 500-1984, US Institute of Electrical and Electronics Engineers, New York, December 1983.

Iyengar et al., 1995.	S. S. Iyengar, L. Prasad, and H. Min, Advances in Distributed Sensor Technology, Prentice Hall Publishers, Englewood Cliffs, NJ, ISBN 0-13-360033-5, 1995.
Johnson, 1993.	C. Johnson, Process Control Instrumentation Technology, fourth edition, Prentice Hall Publishers, ISBN 0-13-721150-3, 1993.
Kletz, 1988.	T. Kletz, Learning from Accidents in Industry, Butterworths, London, ISBN 0-408-02696-0, 1988, page 95.
Lish, 1972.	K. C. Lish, Nuclear Power Plant Systems and Equipment, Industrial Press, New York, ISBN 0-8311-1078-3, 1972, chapter 15.
MIL HDBK 217F, 1991.	U.S. Department of Defense, Military Handbook, Reliability Prediction of Electronic Equipment, MIL HDBK-217F, December 2, 1991.
MIL STD 1629A, 1980.	Military Standard 1629A, Procedures for Performing a Failure Mode, Effects and Criticality Analysis, US Department of Defense, November 24, 1980.
Mitchell and Williams, 1993.	C. M. Mitchell and K. Williams, "Failure Experience of Programmable Logic Controllers Used in Emergency Shutdown Systems," Reliability Engineering and System Safety, 39, 1993, pages 329-331.
Moss and Strutt, 1993.	T. R. Moss and J. E. Strutt, "Data Sources for Reliability Design Analysis," Proceedings of the Institution of Mechanical Engineers, 207, E1, 1993, pages 13-21.
Paula, 1993.	H. M. Paula, "Failure Rates for Programmable Logic Controllers," Reliability Engineering and System Safety, 39, 1993, pages 325-238.
Sandri and Di Pace, 1995.	S. Sandri and L. Di Pace, "Radiological Safety During Maintenance of the Primary Heat Transfer System of the ITER Plant," Proceedings of the 16th IEEE/NPSS Symposium on Fusion Engineering, Urbana, Illinois, September 30 - October 5, 1995, IEEE Catalog number 95CH35852, pages 297-300.
Sandri and Di Pace, 1996.	S. Sandri and L. Di Pace, "Occupational Dose for the Water Cooling System of the SEAFP Project," presented at the 12th Topical Meeting on the Technology of Fusion Energy, Reno, Nevada, June 16-20, 1996.

Sejvar, 1977. J. Sevjar, "Normal Operating Radiation Levels in Pressurized Water Reactor Plants," Nuclear Technology, 36, November 1977, pages 48-55.

Trojovsky and Brown, 1984. M. Trojovsky and S. R. Brown, Data Summaries of Licensee Event Reports of Selected Instrumentation and Control Components at U.S. Commercial Nuclear Power Plants, January 1, 1976 to December 31, 1981, NUREG/CR-1740, US Nuclear Regulatory Commission, July 1984.

Wheeler and Ganji, 1996. A. J. Wheeler and A. R. Ganji, Introduction to Engineering Experimentation, Prentice Hall Publishers, Englewood Cliffs, NJ, ISBN 0-13-337411-4, 1996.

2. Temperature Sensors

2.1 Introduction

This chapter discusses sensors for temperature measurement. The most basic measuring apparatus for temperature is the thermometer, but it has limited utility in process or safety applications. This discussion will treat the two most common temperature sensors, the resistance temperature detector and the thermocouple (Gile, 1986; Weiss, 1993). Some other types of more modern temperature sensors, mainly the semiconductor sensor and fiber optic sensor applications, will also be discussed later in the chapter.

2.2 Description of sensors

Many of the descriptions are taken from Johnson (1993). The first sensor described is the resistance temperature detector (RTD). The RTD is a simple device, it is basically a piece of electrical wire made from certain elements or alloys. The wire, often platinum or nickel, is usually coiled into a cylindrical shape to allow a high surface area exposure to the material whose temperature is to be sensed, improving the thermal conductivity to the wire. This cylindrical arrangement allows faster a response time by the wire and provides a smaller, compact sensor element.

The RTD operates by the natural effect of the increasing electrical resistance in the wire with an increase in the temperature of the wire, and vice versa. For this reason, RTDs are sometimes called resistance thermometers (Considine, 1985). The RTD should reach the same temperature as the material whose temperature is to be sensed (i.e., a fluid). Quite often, a sheath or covering is put on the RTD to protect the wire from the process fluid in case the fluid is corrosive or has other detrimental properties. Sheaths could be made of metal, ceramics such as aluminum oxide, or even plastics (Gile, 1986).

The RTD functions by having a small electrical current (perhaps on a scale of a few hundredths of an ampere) passed through the wire. The change in the wire resistance is measured by comparing the incoming and outgoing electrical currents. The electrical current coming in to the RTD must be kept low so that there is no appreciable inductive self heating from current flow in the RTD wire. An RTD can be a continuous measurement sensor, or it can be pulsed with current only at discrete time intervals. Figure 2-1 is a diagram of a cryogenic RTD.

An RTD can have a response time to changing temperature on the order of 0.5 second up to 5 seconds or more. This would appear to be a slow response time when compared to other types of temperature sensors, but this time depends on the sensitivity of the process being monitored. RTDs can have a temperature range of -180°C to 300°C for nickel wire, or -100°C to 650°C for platinum wire (Johnson, 1993). Other wires can expand the RTD range to make it useful for cryogenic fluids such as liquid nitrogen (boils at -194°C at one atmosphere pressure) and liquid helium (boils at -269°C at one atmosphere pressure).

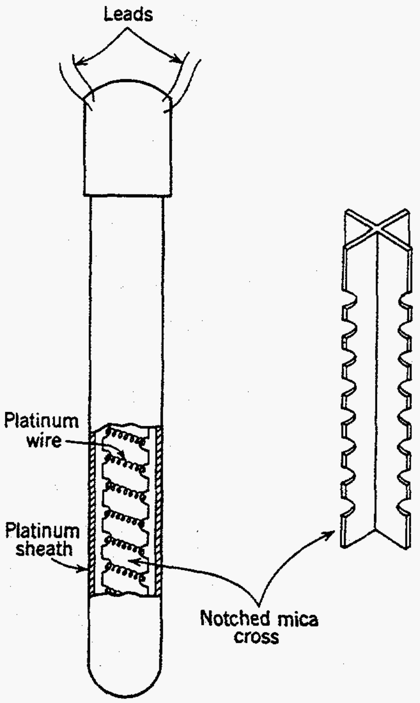
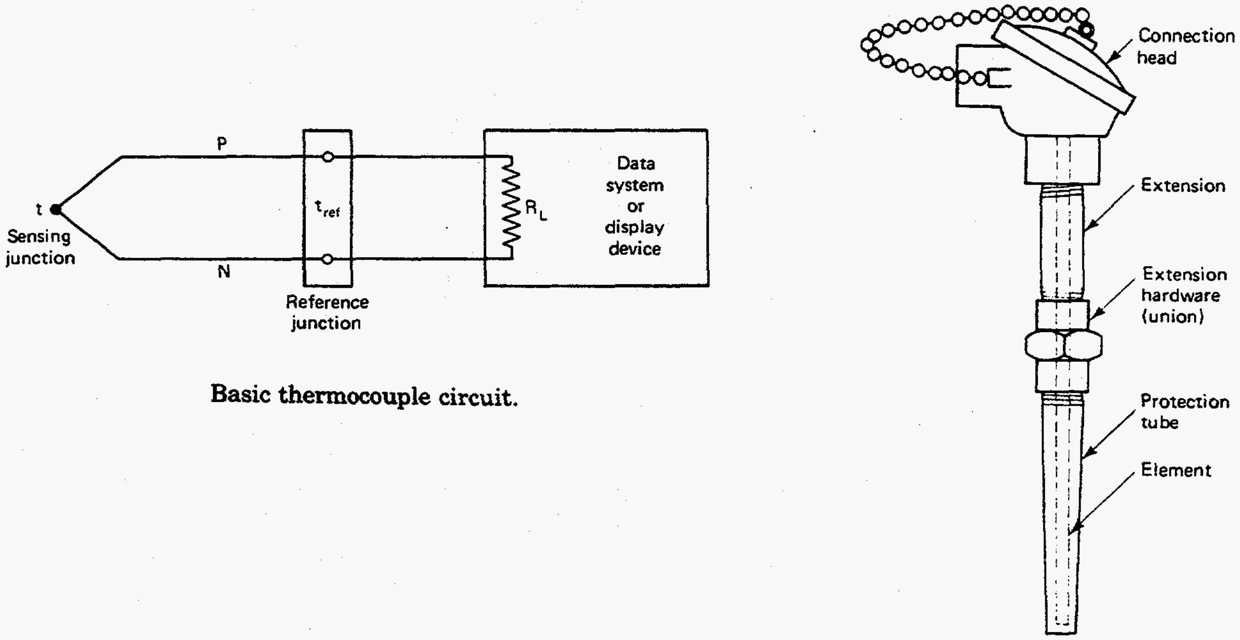


Figure 2-1. A resistance temperature detector for cryogenic service (from Barron, 1985, page 316).



Basic thermocouple circuit.

Figure 2-2. A basic thermocouple (from Norton, 1982, pages 328 and 342).

Barron (1985) and Radebaugh and Marquardt (1993) discuss platinum RTDs used for cryogenic service, sheathed in a platinum housing.

The second type of temperature sensor is the thermocouple. This device is also constructed of wire, but two kinds of wire are used, and the thermocouple is more of a probe than a coil of wire. Two different wires are joined by twisting or more likely, by welding, at the end of the probe. When the sensing junction of the two different wires is placed into changing temperature conditions, the two different wires each exhibit their own voltage potential. Since the wires are different, the voltage potentials are not equal, so this imbalance produces an effect where one wire allows electron flow more easily than the other wire, with electrons flowing from the hotter wire to the cooler wire. The generated electromotive force is very small (usually less than 50 milliVolts, often less than 10 milliVolts), and it is referred to as the thermoelectric effect. The potential difference increases with increasing temperature, so the temperature can be scaled as the voltage changes. This effect is also called the Seebeck effect, after Thomas Johann Seebeck. Angrist (1976) has a good discussion on the Seebeck effect.

An important point for a thermocouple is that a reference temperature must be maintained for comparing the voltage potentials of the two wires between the temperature to measure and the reference temperature. In that way, no voltage drops across resistive elements in the sensor circuit are considered (Johnson, 1993). The reference temperature is often taken to be the freezing point of water at one atmosphere pressure, 0°C, or it can be some other easy to maintain temperature, such as room temperature for an environment-controlled room. Another means is to use a thermistor or RTD at the reference junction (Gile, 1986).

The entire thermocouple element can be very small (such as the size of a small coin, with junctions as small as 0.08 mm), or it can be made large (many cm long). The thermocouple is usually placed inside a thermocouple well, a metal, cylindrical tube whose outer surface is in contact with the process fluid whose temperature is to be measured. The thermowell makes a better pressure seal in pressurized fluid systems. Figure 2-2 shows a sketch of a thermocouple. The thermowell can be filled with air, or with an inert gas. The clearances to the walls of the thermowell are close to allow faster transfer of heat which improves the response time of the thermocouple. Care must be taken to insure that the thermowell is intact, since its breach can lead to leaking process fluid to the environment. Figure 2-2 shows a typical thermocouple. These units can be used for fluid service, including cryogenic fluids (Barron, 1985).

One other type of temperature measurement sensor is the thermostat. This device uses to metals, sandwiched together in a strip. The strip is coiled. Since the two metals are chosen to have different linear thermal expansion, the coil will either tighten its spiral inward when heated or expand its spiral outward when heated. The outer end of the spiral is fixed to a mount in the sensor body, and the inside end is fixed to either an indicator needle, or a rotary movement arm to actuate a system response. Bimetallic strips and thermistors can be used in thermostats. Thermostats are used for heating, ventilating, and air conditioning systems (HVAC) to monitor room temperature (Haines and Wilson, 1994). Bimetallic strips can be accurate to 1% of reading (Gile, 1986) up to a limit of about 538°C (1000 F), but are most often used below 260°C (500 F).

Temperature switches are devices that activate when a certain temperature is reached. Usually, either a bimetallic strip coils enough to close a microswitch, or a mounted metal bar expands (or contracts) from thermal expansion enough to close (or open) a microswitch. The failure rate for a bimetallic strip and a microswitch is adequate to describe the failure rate for a temperature switch.

2.3 Failure Modes and Effects Analysis

A component-level failure modes and effects analysis (FMEA) was performed on RTDs and thermocouples. The effects of failures had to be judged on the component only, since no system was specified for these individual components to determine system level effects of failures. The component boundary to attribute failures to the sensors was taken to be the outer surface of the sheath or encapsulation. Any power requirements were considered to be outside the boundary and therefore faults in power supplies were not attributed to the sensors. Table 2-1 gives the RTD results and Table 2-2 gives the thermocouple results. The FMEA approach of MIL STD 1629A (1980) was used, however, the portions relating to component identifier (as from a piping and instrumentation diagram) and system level effects were deleted.

RTDs, being a length of wire, had obvious failure modes of open circuit and short circuit. A short circuit to ground might be also possible if a metallic or conductive sheath is used for the RTD. Cluley (1993, page 25) states that these two failure modes are the catastrophic failure modes for most electronic equipment. Other failure modes were found in a discussions by Lees (1973) and Johnson (1995). These included drift (which is less of a problem for RTDs than it is for thermocouples [see Hashemian and Petersen, 1989]) caused by a change in the metal chemistry, excessive heat, work hardening of the wire (by vibration or bending), contamination (from chemicals or moisture), or ionizing radiation. Electromagnetic radiation can cause noise and false signals, but this effect is small for RTDs. Contamination by chemicals or moisture can cause corrosive attack on the wires. Contaminants can enter by osmosis through the sheath, penetrating cracks in the sheath, or by cross contamination between the sheath and the individual wires (Johnson, 1995). Hashemian (1991) discusses the calibration shifts that can occur with RTDs, such as oxidation, metal ion migration from the sheath to the sensing element at high temperatures (> 500°C), and moisture content causing changes in the electrical insulation resistance value.

An important concern for safety analysts is to obtain good data that quantifies the FMEA failure mode behavior. Often, sensors are cited with 'all failure modes' failure rates.

Table 2-1. FMEA for a Resistance Temperature Detector

Function	**Failure modes and causes**	**Local effects**	**Failure detection method**	**Compensating provisions**	**Remarks**
RTD senses temperature	open circuit (flaw in sensor wire)	zero current flow	RTD registers no temperature	can set an alarm for a zero or threshold temperature	
	short circuit (flaw in support allows sensor wires to touch)	self heating, and current path is shorter so readings are inaccurate	RTD output can become erratic, readings are not true	Fluctuations should be noticeable	
	lead wire open circuit	zero current flow	RTD registers no temperature	can set an alarm for a zero or threshold temperature	
	lead wire short circuit	erratic output	Fluctuations should be noticeable to operators	perhaps multiple sensors are used	
	sheath breach	wire could short circuit or it could slowly degrade	operator should notice degradation against benchmark values	sheath is constructed to be resilient to breaching	
	scale buildup on sheath, or on well	slower response time, inaccurate readings	operator should notice degradation against benchmark values	there are many reasons to maintain system cleanliness, i.e., safety and efficiency	
	leakage past RTD fitting or connection into the process system	may not affect RTD function	may not affect RTD operation	may not be noticed except by walk downs or by technicians	this failure mode can be important for safety, but it is dependent on the process fluid
	drift, caused by many things: most notably a change in metal structure over time	RTD does not read true temperature	operator should notice degradation against benchmark values	can use multiple RTDs and average them, can use different types of RTD metal in each unit	

Table 2-2. FMEA for a Thermocouple

Function	Failure modes and causes	Local effects	Failure detection method	Compensating provisions	Remarks
Thermocouple senses temperature	open circuit (flaw in sensor wire)	zero current flow	thermocouple registers no temperature	can set an alarm for a zero or threshold temperature	
	short circuit (flaw in support allows sensor wires to touch)	thermocouple cannot function correctly	thermocouple output is greatly reduced, readings are not true	Fluctuations should be noticeable	
	lead wire open circuit	zero current flow	thermocouple registers no temperature	can set an alarm for a zero or threshold temperature	
	lead wire short circuit	erratic output	Fluctuations should be noticeable to operators	perhaps multiple sensors are used	
	sheath breach	wire could short circuit or it could slowly degrade	operator should notice degradation against benchmark values	sheath is constructed to be resilient to breaching	
	scale buildup on sheath, or on well	slower response time, inaccurate readings	operator should notice degradation against benchmark values	there are many reasons to maintain system cleanliness, i.e., safety and efficiency	
	leakage past thermocouple fitting or connection into the process system	may not affect thermocouple function	may not affect thermocouple operation	may not be noticed except by walk downs or by technicians	this failure mode can be important for safety, but it is dependent on the process fluid
	drift, caused by many things: most notably a change in metal structure or bond between metals over time	thermocouple does not read true temperature	operator should notice degradation against benchmark values	can use multiple thermocouples and average their outputs, or can use different types of metals in each unit	
	false reading from electronic noise	thermocouple does not register true temperature	difficult to detect	shield the thermocouple and its wiring	RFI and EMI are important in the plant environment

Fortunately, one report gives probabilities of the various modes of failure (RAC, 1991). For sensor transducers, the failure mode breakdown is 68% out of tolerance, 15% false response, 12% open circuit, and 5% short circuit. While this is a broad generalization for a mixture of electronic sensor types, in general, we can assume that about two-thirds of an all-modes failure rate is the out of tolerance (drift) failure mode.

2.4 Failure Rate Data

A failure rate is defined as the average probability of failure divided by unit time. Analysts regard field failure rate data (data collected on operating units in some application) as the most accurate source of data. Literature was reviewed to locate sources of finished failure rate data for temperature sensors. Reports on data analyses already performed on temperature sensors were sought since these are well regarded, and there are no raw data readily available for statistical data analysis. Several reports were found that gave suggested failure rates, some based on operations experience and some based on reference data.

One of the leading data sources is the Offshore Reliability Data Handbook (OREDA, 1992). This handbook documents data collected at offshore oil drilling platforms. The data are characterized, components are described and their boundaries defined, and the statistics are presented. The OREDA handbook gives values for resistance temperature detectors and thermocouples:

sensor	failure mode	average failure rate	90% upper bound failure rate
RTD	failed by operating without signal (spurious reading operation)	2.1E-06/hour	6.9E-06/hour
	failed to function when signaled (failed to operate)	6.6E-06/hour	1.8E-05/hour
	functioned with improper signal	7.8E-06/hour	2.1E-05/hour
Thermocouple	critical failures (no signal change when the temperature changes)	8.5E-07/hour	2.2E-06/hour
	degraded operation (drift)	1.1E-05/hour	1.7E-05/hour

The repair times for these units were an average of 4 hours for an RTD, and 4.5 hours for a thermocouple replacement, and 6 hours for thermocouple refurbishment (OREDA, 1992).

Other sources of data for these temperature resistance sensors was also found. Anyakora et al. (1971) gives 'all failure modes' faults per year for thermocouples as 0.52/year.

Assuming year round operation, this value converts to 0.52/year ÷ (8760 hours/year) = 5.9E-05/hour. Anyakora does not report error bounds on the values. Lees (1976) gave the same value. Repair times were not given in those articles.

Rogue et al. (1983) reported on thermocouples used for waste repository monitoring. Of 1310 units, 23 failed and another 25 were questionable reliability. Over 3 years, this gives a failure rate of 23 ÷ (1310 • 3 yrs • 8760 hours/yr) = 6.7E-07/hour for catastrophic failures of no output, and 25 ÷ (1310 • 3 yrs • 8760 hours/yr) = 7.3E-07/hour for degraded operation failures (probably drift). Upper bounds can be calculated using the Chi Square distribution for a 90% confidence interval. Using the formula Chi(2n+1)/2T where Chi is the Chi value at 90% confidence (see Wall, 1986), n is the number of failures, and T is the total time, we have 34.382/3.4E+07 hours = 1.0E-06/hour for failures of no output, and 36.741/3.4E+07 hours = 1.1E-06/hour for degraded operation failures. The 90% upper bound error factors are 1.49 for no output and 1.51 for degraded operation. Repair times were not given in Rogue's work.

Alber et al. (1995) give a temperature sensor failure rate of 1.7E-05/hour for drift, with an upper bound failure rate of 6.5E-05/hour. They also give a failure to operate failure rate of 1.4E-05/hour with an upper bound of 6.8E-05/hour. Blanton and Eide (1993) give a temperature sensor failure rate of 1E-06/hour for failure to operate, with an upper bound of 3E-06/hour. Blanton and Eide suggest that temperature switches have the same failure rate as thermocouples.

Since several of the most recent data sources tend to cluster at the 1E-06/hour value for failure to operate, this failure rate is chosen as the order of magnitude for thermocouples. Based on OREDA data, it would appear to be a reasonable value for RTDs, also.

While these failure rates have been calculated from plant data at chemical, nuclear, and industrial facilities, they should be generally applicable to other fluid temperature measurement applications such as water and cryogenic fluids. The sensors are built to certain specifications by similar manufacturing industries, and they should perform about equally well in the respective environments they are designed to function within. Since the failure rate for a basic copper wire circuit in a nuclear power plant is 1E-09/hour (WASH-1400, 1975), changing types of wire is probably not a dominant factor in the thermocouple or RTD reliability value. The OREDA values should be applicable to water fluids and to cryogenic service, if the analyst is positive that appropriate sensor units are chosen to meet the environmental conditions and the operational demands (i.e., temperature operating range, etc.) placed on the units.

The most recent work from the 1980's and 1990's gives lower failure rate values than the work from the 1970's. The discrepancy is almost two orders of magnitude, which is significant. Perhaps this variation in the failure rates is due to the choice of wire used as more alloys became available, and operating experience insights that have led designers to reduce vibration, positioning units to reduce scale buildup, shielding for thermocouple noise reduction, and to mitigate or avoid other potential failure mechanisms that have caused problems for temperature sensors.

2.5 Other sensor types

A relatively new type of sensor in use only since the 1980's is the fiber optic sensor (Elliot, 1986; Horn, 1988; Weiss et al., 1990). This sensor offers some advantages over electrical based sensors, such as small size and weight, explosion-proof, immunity to electromagnetic interference, secure data transmission, and others (Krohn, 1992). Some means for detecting temperatures by fiber optics are reflecting input light from one fiber optic cable onto a bimetallic strip target and then measuring the amount of reflected light into a collector fiber optic cable. The bimetallic strip warps or moves due to the differential of thermal expansion characteristics in the two metals that comprise the strip. A semiconductor crystal can also be used as the target since it is also temperature sensitive, preferentially absorbing light of infrared wavelengths at given temperatures. Unfortunately, these applications can not measure wide ranges of temperature. The fiber optic cables can also be used to microbend the light by using some junction material with a high thermal expansion coefficient. The light traversed the cable, but experiences a change in its refractive index as it passes through the area of length expansion with temperature. The change is measured as the receiving station to indicate the temperature of the junction material (Krohn, 1992; Wheeler and Ganji, 1996). While these sensors can be extremely accurate, the temperature ranges are presently limited in comparison with other types of resistance temperature sensors.

Semiconductor temperature measurement devices, also called thermistors (this name is a contraction of 'thermal resistor'), have been in service for many years. These units take advantage of the fact that as a semiconductor material warms, then electrical current flows through it more easily (Faller, 1996). Therefore, the higher the temperature, the less the resistance to current flow. These sensors can be very sensitive, and have temperature ranges in the -100°C to 300°C range. Response times are in the 0.5 to 10 second range (Johnson, 1993). These units can be useful in many applications of limited temperature range, such as heating, ventilating, and air conditioning of buildings (Liu, 1995), and as mentioned earlier, can be used on the reference temperature junction for thermocouples.

A very new type of temperature sensor is the piezoelectric sensor. The piezoelectric polyvinylidene fluoride (PVDF) polymer film sensor operates by generating a voltage when it's volume is changed - such as by vibration, acceleration, impulse, shock or temperature change (Halvorsen, 1994). It can sense people by their body heat, and it can be used for HVAC applications, although its upper temperature limit is only about 100°C. When stabilized with ceramic materials, the temperature ceiling climbs to 400°C. This sensor shows promise for many applications (thermal imaging, body heat detection, HVAC operations, heat sensor in electrical cables, and other uses).

2.6 Conclusions

In this chapter, temperature sensors were examined. The two most frequently used kinds of resistance temperature sensor, the resistance temperature detector and the thermocouple, were discussed. Failure modes were examined and failure rate data from the literature was given. Repair times are more difficult to find in the literature, but some are cited. Other sensor types, such as fiber optic sensors, are discussed at the end of the chapter. It was noted that failure rates from the 1980's and 1990's varied considerably from the earlier data, showing that continued data collection and analysis is useful to ascribe accurate values to components and to promote operating experience feedback to designers.

Chapter 2 References

Alber et al., 1995. T. G. Alber et al., Idaho Chemical Processing Plant Failure Rate Database, INEL-95/0422, Idaho National Engineering Laboratory, August 1995.

Angrist, 1976. S. W. Angrist, Direct Energy Conversion, third edition, Allyn and Bacon Publishers, ISBN 0-205-05581-8, 1976, chapter 4.

Anyakora et al., 1971. S. N. Anyakora et al., "Some Data on the Reliability of Instruments in the Chemical Plant Environment," The Chemical Engineer, No. 255, November 1971, pages 396-402.

Barron, 1985. R. F. Barron, Cryogenic Systems, second edition, Oxford University Press, ISBN 0-19-503567-4, 1985, chapter 6.

Blanton and Eide, 1993. C. H. Blanton and S. A. Eide, Savannah River Generic Database Development, WSRC-TR-93-262, Westinghouse Savannah River Company, 1993.

Considine, 1985. D. M. Considine, editor in chief, Process Instruments and Controls Handbook, third edition, McGraw-Hill Book Company, ISBN 0-07-012436-1, 1985, chapter 2.

Elliot, 1986. T. Elliot, "Cost, space, safety benefits make fiber optics commercially viable," Power, 130, August 1986, pages 45-47.

Faller, 1996. C. Faller, "NTC Thermistor Update," Sensors, 13, June 1996, pages 22-26.

Gile, 1986. D. E. Gile, Jr., "Temperature Sensors: how they work, where they are used," Power, 130, April 1986, pages 91-94.

Haines and Wilson, 1994. R. W. Haines and C. L. Wilson, HVAC Systems Design Handbook, McGraw-Hill Inc., New York, ISBN 0-07-025872-4, 1994, chapter 8.

Halvorsen, 1994. D. Halvorsen, "Putting piezo polymer film to work," Machine Design, 66, July 25, 1994, pages 47-51.

Hashemian, 1991. H. M. Hashemian, "Advanced Methods for Management of Aging of Nuclear Plant Instrumentation," Proceedings of the International Meeting on Nuclear Power Plant and Facility Maintenance, Salt Lake City, Utah, April 7-10, 1991, pages 473-489.

Hashemian and Petersen, 1989. H. M. Hashemian and K. M. Petersen, "Boosting Accuracy of Industrial Temperature Measurement," Power, 133, May 1989, pages 74-76.

Horn, 1988. D. Horn, "Optical Fibers, Optimal Sensors," Mechanical Engineering, 110, September 1988, pages 84-88.

Johnson, 1993. C. Johnson, Process Control Instrumentation Technology, fourth edition, Prentice Hall Publishers, ISBN 0-13-721150-3, 1993, chapter 4.

Johnson, 1995. F. L. Johnson, "Detecting and Preventing RTD Drift," Sensors, 12, May 1995, pages 64-78.

Krohn, 1992. D. A. Krohn, Fiber Optic Sensors, Fundamentals and Applications, second edition, Instrument Society of America, Research Triangle Park, NC, ISBN 0-55617-010-6, 1992, chapters 1, 7.

Lees, 1973. F. P. Lees, "Some Data on the Failure Modes of Instruments on the Chemical Plant Environment," The Chemical Engineer, No. 277, September 1973, pages 418-421.

Lees, 1976. F. P. Lees, "The Reliability of Instrumentation," Chemistry and Industry, Number 5, March 6, 1976, pages 195-205.

Liu, 1995. L. Liu, "Designing a Digital Temperature Controller Using a Semiconductor Sensor," Sensors, 12, September 1995, pages 69-76.

Norton, 1982. H. N. Norton, Sensor and Analyzer Handbook, Prentice Hall publishers, ISBN 0-13-806760-0, 1982.

OREDA, 1992. OREDA, Offshore Reliability Data Handbook, second edition, distributed by DNV Technica, Hovik, Norway, ISBN 82-515-0188-1, 1992, pages 414-419.

RAC, 1991.	Reliability Analysis Center, Failure Mode/Mechanism Distributions, 1991, FMD-91, Rome Air Development Center, Griffiss Air Force Base, NY, 1991.
Radebaugh and Marquardt, 1993.	R. Radebaugh and E. Marquardt, "Croygenic Instrumentation," Recent Advances in Cryogenic Engineering 1993, ASME HTD-Vol. 267, American Society of Mechanical Engineers, 1993, pages 13-27.
Rogue, 1983.	F. Rogue, E. P. Brinall, and G. A. Armantrout, "Instrument Reliability for High-Level Nuclear Waste Repository Applications," in Waste Management '83, Proceedings of the Symposium on Waste Management, Tucson, Arizona, February 27 - March 3, 1983, pages 227-234.
Wall, 1986.	F. J. Wall, Statistical Data Analysis Handbook, McGraw-Hill Book Company, ISBN 0-07-067931-2, 1986, chapter 19 and Table C.
WASH-1400, 1975.	N. C. Rasmussen et al., Reactor Safety Study, NUREG-75/014, WASH-1400, US Nuclear Regulatory Commission, October 1975, Appendix III, Failure Data.
Weiss, 1993.	J. Weiss, "More accurate sensors needed to reduce uncertainty," Power Engineering, 97, June 1993, pages 29-32.
Weiss et al., 1990.	J. Weiss, W. Esselman, and R. Lee, "Assess fiberoptic sensors for key powerplant measurements," Power, 134, October 1990, pages 55-58.
Wheeler and Ganji, 1996.	A. J. Wheeler and A. R. Ganji, Introduction to Engineering Experimentation, Prentice Hall Publishers, ISBN 0-13-337411-4, 1996, chapter 9.

3. Pressure Sensors

3.1 Introduction

This chapter discusses sensors for fluid pressure measurement. The most basic measuring apparatus for pressure is to use a mechanical element of some kind, such as a plate, shell, or a tube of some type to measure the resultant force of the fluid on the surface of the element (Norton, 1982). This discussion will treat the two most common pressure sensors for above atmospheric pressure, the Bourdon tube and the strain gauge pressure sensor (Johnson, 1993). Some other types of more modern pressure sensors, including fiber optic sensor applications, will also be discussed later in the chapter.

3.2 Description of sensors

Many of the descriptions are taken from Johnson (1993). The first sensor described is the Bourdon gauge, based on the operating principle of the Bourdon tube. This curved metal tube - whose cross-sectional area is usually more oval than circular - accepts the fluid pressure inside the tube and allows the fluid pressure to act on the inner walls of the tube. The tube will unfurl or uncoil as pressure increases in a pressure-to-position displacement energy conversion. The capped end of the tube is connected to a mechanical movement that controls a gauge needle. A schematic of a Bourdon gauge is shown in Figure 3-1. This pressure gauge is usually only used for local readings and not for control room readouts. It does have the advantages of not needing any input power (i.e., electricity or instrument air) to function, so operators can still obtain useful pressure readings at local areas during power outages. The gauge is simple and can be very rugged and long-lived; that is, it can provide years of reliable service (PE, 1980).

The Bourdon gauge has been in use over 100 years, and is found in many industrial plants and in heating, ventilating, and air conditioning (HVAC) systems (Haines and Wilson, 1994). This pressure sensor is in contact with the process fluid, so it must be corrosion resistant. Obvious failure mechanisms are a breach of the tube and disconnection of the tube and the needle mechanism. A set of two articles (PE, 1980) gives insights to field failures of Bourdon gauges. Blowout is the condition of a tube rupture, where the fluid can escape from the tube and out of the gauge body. Corrosion, both internal (from the process fluid) and external (from the plant environment), can damage the gauge so that the gauge movement is inoperable or the tube breaches. Either way, the gauge is failed and must be replaced. Pressure pulsations, defined as pressure that varies more than 0.1 percent of full-scale range per second, lead to destruction of the gauge movement and therefore the gauge accuracy is compromised. Vibration from the equipment that the gauge is mounted on leads to wear of the movement, making it sloppy and again compromising accuracy. Lens breakage - the glass or plastic lens of the gauge face can be susceptible to impacts, abrasion by particulates in the plant atmosphere, or other causes like rough handling. If the lens is broken, then the movement behind the gauge plate (i.e., the calibrated dial face) can also be compromised by plant humidity, dirt, dust, grit, or any

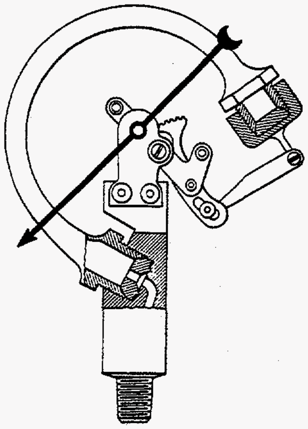


Figure 3-1. A Bourdon gauge (from Jennings, 1978, page 23).

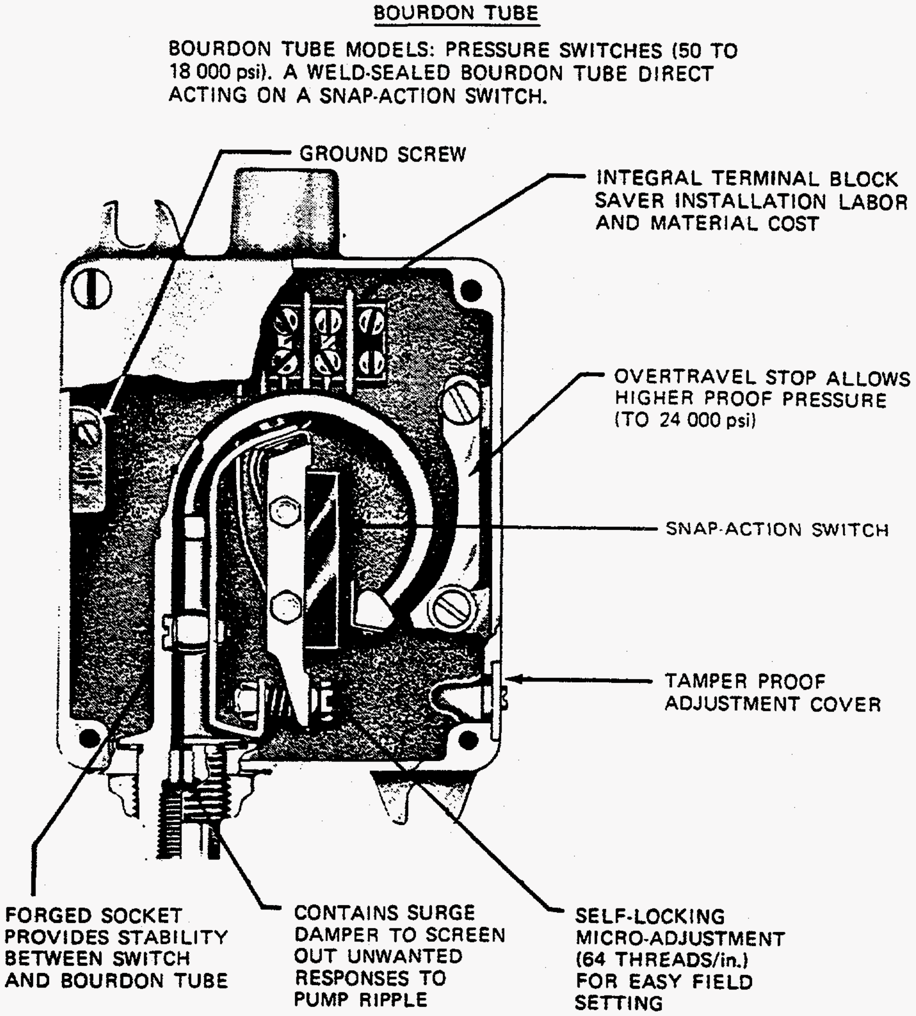


Figure 3-2. A Bourdon pressure switch (from Toepker and Kelley, 1984).

other contaminants. The last item discussed was material compatibility, to prompt the designer to ensure that the gauge materials were chemically compatible with the process fluids and the ambient atmosphere the gauge is to be used within.

The Bourdon gauge can deal with pressure ranges from slightly subatmospheric to 200 MPa, but this is dependent on the shape, wall thickness, and material of construction for the Bourdon tube. The highest pressures require stainless steel or monel, and low pressures can use brass or copper alloys. Responses are generally fast, on the order of 100 milliseconds unless the sensing line to the pressure source is a small diameter or it is very long (Considine, 1985). The Bourdon gauge often must be damped to keep the needle from bouncing or fluctuating too much to get an accurate reading (PE, 1980). Damping can retard pressure change readings by 5 to 20 seconds (PE, 1980). The American Society of Mechanical Engineers (ASME) Standard B40.1 (ASME, 1991) gives accuracy suggestions for the most robust gauges as ± 0.25% of the gauge pressure span (i.e., 0.25% of the range read from the end points on the gauge face). The Bourdon gauge is intended to measure static pressures or slowly varying pressures (i.e., variations over minutes) instead of dynamic pressures created by flowing fluids. The ASME (1991) also lists several failure modes: fatigue failure of the Bourdon tube, overpressure failure of the tube, corrosion failure of the tube, explosive failure (such as a hydrocarbon/oxygen explosion), vibration failure of the movement, and vibration-induced fatigue failure of the gauge movement and linkage.

An important use of the Bourdon tube is that it can operate as a pressure switch. In this application, the tube is designed to provide enough displacement force to close (or open) an electrical switch when a specific pressure value is reached inside the tube. The electrical switch closure allows a circuit to be completed so that a signal is sent to register that the system pressure has reached the specified value. The pressure switch is a monitor for a selected pressure level and does not monitor for a range of pressures. The pressure switch is used in many ways, to monitor underpressure or overpressure. It can be used for safety warnings, or for process monitoring and control. One example of pressure switch use is to notify operators that pressure in a tank is beginning to exceed the safety design margin, so that they can take action to reduce pressure before relief valves open or rupture disks open to relieve the tank pressure. A pressure switch is shown in Figure 3-2. Since the pressure switch used the Bourdon tube as its basic operating principle, then Bourdon tube failure modes are applicable. Electrical switch failure modes of fail to open, fail to close, fail to remain in position, spurious transfer of position, etc., are also applied to the electrical switch inside the pressure switch. There are other types of pressure switches that do not use Bourdon tubes, such as the pressure sensitive diaphragm to electrical switch.

Another type of pressure sensor is the simple manometer, where the pressure of the ambient atmosphere is used as the reference pressure on one leg of a u-shaped tube. The other leg of the tube is attached to the system whose pressure is to be measured, and a

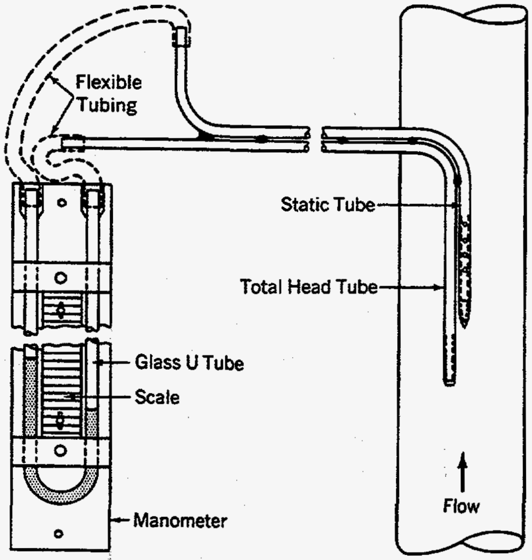


Figure 3-3. A pitot tube manometer for fluid velocity measurement based on pressure (B&W, 1978).

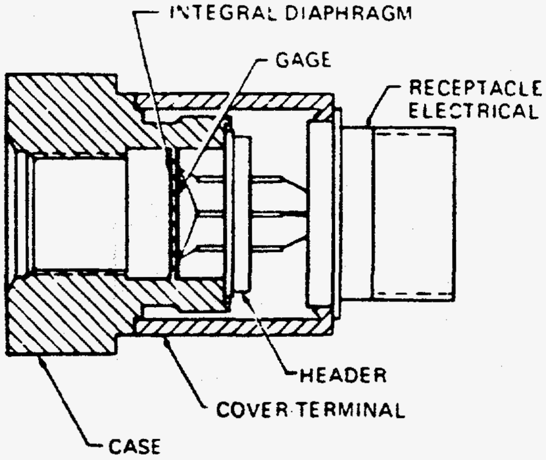


Figure 3-4. A strain gauge pressure sensor (Norton, 1982, page 259).

liquid (either mercury, glycol, or another liquid that is compatible with the process gas or liquid) resides inside the u-tube. The tube can be made of plastic, glass, or any other clear material that is compatible with the fluids it contacts. When under pressure, the change in height of the two sides of the measuring fluid determines the pressure above ambient (i.e., density of measuring fluid x acceleration due to gravity x height difference of the two fluid columns in the u-tube). Only low pressures can be read with a manometer, usually only slowly varying pressures between 0.1 MPa and 0.67 MPa (Beckwith and Buck, 1969), but this is dependent on the fluid used in the u-tube and the length of the sides of the u-tube. Too much system pressure can cause the measuring fluid to escape from the atmospheric pressure side of the u-tube. The pressure to be measured should not pulsate or fluctuate rapidly, since the manometer cannot give a good reading with the column height in constant change. U-tube manometers can be used in heating, ventilating, and air conditioning (HVAC) systems (Jennings, 1978) because the pressures are usually small (usually less than $\sim 10^4$ Pa or a few pounds/inch^2) and usually do not vary greatly. However, the manometer only measures static pressure, unless it is configured to measure impact pressure (that is, the force created by a moving fluid when it impacts a stationary object). Impact pressure force is given by 0.5(density)(velocity)^2. The pitot tube used for fluid velocity indication measures the impact pressure of moving fluid in one tube and the static or base pressure of the fluid in a second tube. Figure 3-3 shows one measuring fluid (mercury, ethylene glycol, water, or some other liquid that is immiscible version of a pitot tube.

Other pressure sensors use integrated circuits. A semiconductor diaphragm is used with a semiconductor strain gauge and temperature compensation sensor attached to the reference pressure side (Johnson, 1993). The other side of the diaphragm is in contact with the fluid whose pressure is to be measured. This sensor outputs a direct current voltage proportional to the deflection of the diaphragm (the strain on the diaphragm), which is proportional to the fluid pressure acting on the diaphragm. An example sensor is shown in Figure 3-4. These sensors need input power to the strain gauge, a ground line, and an output signal line (Johnson, 1993). The output is in the ten's of milliVolts region. The strain gauge is arranged in a Wheatstone bridge circuit, where the pressure on the diaphragm induces strain on the resistor components of the Wheatstone bridge circuit. The electrical resistance changes in proportion to the strain of the wires (which is caused by the pressure on the diaphragm). A constant voltage is needed across the Wheatstone bridge circuit to measure the resistance change. Semiconductors are generally very reliable, but they can be sensitive to temperature and other environmental effects (temperature, vibration, etc.). This type of pressure sensor is widely used (Wheeler and Ganji, 1996; Haines and Wilson, 1994). Diaphragm materials vary, they could be made of silicon or metals such as thin steel. Failures could be diaphragm leakage or rupture (the silicon usually only experiences rupture rather than leakage). Strain gauge debonding can occur with a diaphragm that the integrated circuit strain gauge was not grown upon (i.e., the metal diaphragms). These gauges can also suffer from a hysteresis effect induced by thermo-elastic strain; that is, the diaphragm does not return to its original shape after repeated use so the unit must be calibrated more and more often until it is easier to simply replace it. Other failure modes could be that the sensing line to the process piping plugs, leaks, or ruptures. The semiconductor could stop functioning by radiation damage, vibration, or increased temperature. These units can be configured to measure low pressure levels of a few atmospheres or they can measure high pressures up to hundreds of atmospheres. The response time is usually very fast, less than one-tenth of a second.

The bellows pressure sensor is another pressure to displacement sensor. The fluid pressure inside a metal bellows forces it to move. The capped end of the bellows is connected to a linear variable differential transformer (LVDT). Johnson (1993) describes this unit as a device that converts displacement to voltage. The LVDT is built by using a metal rod and three wire coils. The center wire coil around the metal rod is called the primary excitation coil. The other two secondary coils are on either side of the primary coil. As the metal rod (also called the core) moves, the change in magnetic flux in the two secondary coils causes one of the secondary voltages to decrease and the other to increase. The voltage change is linearly proportional to the metal core displacement, which is proportional to the pressure experienced by the metal bellows. This sensor needs input power to the primary excitation coil, and there must also be an output signal. A Bourdon tube could also be attached to the LVDT metal rod.

Metal bellows can either be hydroformed or precision welded (Conway, 1995). The bellows wall thickness, the number and depth of convolutions, the type of construction (hydraulically formed or precision welded), the bellows diameter, and the bellows parent material (stainless steel, monel, inconel, brass, copper, and other metals) all affect the bellows deflection under pressure. Some bellows failure modes are leakage, rupture, separation from the mounting flange, and a bellows-specific failure called 'squirm', where a convolution bulges radially outward from overpressure or some internal weakness (Becht, 1981). The bellows can then buckle if the pressure increases any further. If the bellows does breach, then the process fluid can leak out to the facility environment. Some failure mechanisms for bellows are corrosion in the convolutions, material flaws in the bellows walls, overpressure squirm or underpressure collapse, weld flaws (either sealing a hydroformed unit to a flange or in the convolutions of a precision welded bellows), and cyclic failures (wear-out fatigue, vibration fatigue, see McCulloch, 1981). In general, pressure sensor bellows can vary from 1.5 mm diameter to 150 mm, and the bellows walls are usually over 1 mm thick (Considine, 1985).

Considine (1985) discusses the so-called 'smart' sensor, which is an integrated circuit sensor for force. A piezoelectric quartz crystal is under the force from the end of a bellows or diaphragm, and this crystal gives out an electrical signal proportional to the amount of (bellows pressure) force exerted on the crystal. The units can be small (perhaps 25 mm diameter) and can be very sensitive, up to 5.8 milliVolts per kiloPascal. The cultured quartz crystals are insensitive to temperature, have high elasticity and stability, and are modestly priced. These are very popular transducers for pressure measurement. Only two wires, signal out and ground, are needed for this sensor. The crystals are rugged, and can be used for applications with high impact, shock, or vibration. However, these crystals cannot continuously provide a reading. The piezoelectric sensor measures pressures as they change from the average pressure already established by the sensor itself. Considine (1985) notes that impatient operators have mistaken the slow action of re-zeroing the discharge circuit as no change in the average pressure reading.

The obvious failure modes of the piezoelectric sensor are a problem with the quartz crystal, such as fracture. However, the crystal is stated to be very rugged (Considine, 1985) and used for measuring shocks and impacts; therefore, fracture failures are expected to be rare. Inherent flaws in a crystal or Mechanical overstress might be the only reasons for crystal failure. Problems with the wires (open circuit, short circuit) can also be expected. The bellows or the diaphragm used to apply pressure to the crystal could also have several failure modes. These were discussed above.

3.3 Failure Modes and Effects Analysis

A component-level failure modes and effects analysis (FMEA) was performed on Bourdon tube pressure gauges and strain gauge pressure sensors. The effects of failures had to be judged on the component only, since no system was specified for these individual components to determine system level effects of failures. The component boundary to attribute failures to the sensors was taken to be the outer surface of the gauge body. Power requirements for the pressure sensor were considered to be outside the boundary and therefore faults in power supplies were not attributed to the sensor. The FMEA approach of MIL STD 1629A (1980) was used; however, the portions relating to component identifier (as from a piping and instrumentation diagram) and system level effects were deleted. Table 3-1 gives the Bourdon gauge results and Table 3-2 gives the strain gauge pressure sensor results.

Other failure modes were found in a discussions by Lees (1973). These included drift caused by wear of the gauge's mechanical movement (overpressure, vibration, thermal cycling, foreign material intrusion, poor lubrication, or other factors) and contamination (from chemicals or moisture). Ionizing radiation could cause embrittlement of the metal if the unit is subjected to high fluences. Electromagnetic radiation is unlikely to damage a Bourdon gauge, unless it generates electrical currents and heating in the gauge movement occurs. If magnetic fields are a concern, then choosing a non-magnetic Bourdon tube material (inconel, monel, stainless steel, etc.) is prudent. If the fluid of concern must be kept contained because of toxic, radioactive, or other hazardous properties, then choosing the smallest instrument line possible is also prudent because any breach will result in only a small leak rate. Using an thin interior coating of perhaps plastic on the Bourdon tube may also be prudent.

Table 3-1. FMEA for a Bourdon gauge

Function	**Failure modes and causes**	**Local effects**	**Failure detection method**	**Compensating provisions**	**Remarks**
Bourdon gauge senses and displays pressure	rupture, from flaw in metal tube, from vibration or corrosion fatigue, from embrittlement or fatigue, or overpressure	depressurization of the Bourdon tube	Gauge does not register pressure	conservative design of gauge, solid front gauge body or blowout plug, install isolation valve in sensing line	This situation could be hazardous if the process fluid is toxic, explosive, or radioactive
	leakage, from flaw in metal tube, from corrosion, or from vibration fatigue	process fluid leaks out into gauge body, could make readings inaccurate	Gauge output can become erratic, readings are not true, leakage from body may be noted as well	install isolation valve in sensing line	
	fitting rupture, same causes as rupture above	depressurization of the Bourdon tube	Gauge does not register pressure	use high quality tube fitting	rupture could be hazardous if fluid is toxic
	fitting leakage, same causes as leakage above	process fluid leaks out into gauge body, could make readings inaccurate	Gauge output can become erratic, leakage from body may be noted as well	install isolation valve in sensing line	
	linkage detachment, due to vibration or poor assembly	tube detached from gauge movement	Gauge registers no pressure		
	plugging, due to foreign material buildup in the tube	steady output that does not change with system pressure changes	Lack of change should become suspicious to operators	perhaps multiple sensors are used, fluid cleanliness should be monitored	

Table 3-2. FMEA for a strain gauge pressure sensor

Function	**Failure modes and causes**	**Local effects**	**Failure detection method**	**Compensating provisions**	**Remarks**
strain gauge sensor detects pressure	open circuit (flaw in sensor lead wire)	zero current flow	sensor registers no pressure	can set an alarm for a zero or threshold pressure	
	short circuit (sensor lead wires touch)	sensor cannot function correctly	sensor output is erratic, readings are not true	Fluctuations should be noticeable	
	strain gauge fails to operate, open circuit or debonding from diaphragm	sensor cannot function	sensor does not read pressure	Multiple sensors? Frequent testing?	
	diaphragm fails due to leakage, rupture, foreign material plating on surface, or metal changes its ductility from thermal or chemical exposure	zero output	sensor does not read pressure	Multiple sensors? Diverse pressure sensing methods?	
	erratic reading, electromagnetic interference (EMI)	instrument readings are inaccurate	operators notice fluctuations	shield for electromagnetic fields	These units operate in the mV range, can be susceptible to EMI
	scale buildup in instrument sensing line to diaphragm	slower response time, inaccurate readings	operator should notice degradation against average values	there are many reasons to maintain system cleanliness, i.e., safety and efficiency	preventive maintenance must check for this buildup of materials
	leakage past pressure sensor fitting or in sensing line to the process system	small leak may not affect pressure sensor function; large leak will show decreased pressure	may affect pressure sensor operation	small leak may not be noticed during walk downs or by system technicians; large leak will be noticed by dropping pressure readings	this failure mode can be important for safety, but it is dependent on the process fluid

An important concern for safety analysts is to obtain good data that quantifies the FMEA failure mode behavior. It is usually true that the FMEA gives more failure modes than are found in the field, since the FMEA is not concerned with probabilities of occurrence and field data usually treats the most probable events. Sometimes, the data are lumped into one category, the so-called 'all failure modes' failure rates. Fortunately, one report gives probabilities of the various modes of failure (RAC, 1991). For sensor transducers, the failure mode breakdown is 68% out of tolerance, 15% false response, 12% open circuit, and 5% short circuit. While this is a broad generalization for a mixture of electronic sensor types, in general, we can assume that about two-thirds of events are out of tolerance (drift). When no better information is available, these data can be used to guide analysts and to make inquiries to experts, plant operations personnel, etc.

3.4 Failure Rate Data

A failure rate is defined as the average probability of failure divided by unit time. Analysts regard field failure rate data (data collected on operating units in some application) as the most accurate source of data (Green, 1983) since units operating in the field are subjected to the operating environment - they are exposed to all factors of the environment simultaneously. These factors can include heat, cold, vibration, foreign material intrusion, corrosion, poor maintenance, wear (i.e., maintainers or operators using the sensor as a hand hold or foot hold, etc.) and other causes. Often, these causes can aggravate each other. For example, heat and corrosion, or vibration and foreign material intrusion can aggravate each other. Literature was reviewed to locate sources of finished failure rate data for pressure sensors. Reports on data analyses already performed on pressure sensors were sought since these are well regarded, and there are no raw data readily available for statistical data analysis. Several reports were found that gave suggested failure rates, some based on operations experience and some based on reference data.

One of the leading data sources is the Offshore Reliability Data Handbook (OREDA, 1992). This handbook documents data collected at offshore oil drilling platforms. The data are characterized, components are described and their boundaries defined, and the statistics are presented. The OREDA handbook gives values for pressure sensors:

sensor	failure mode	average failure rate	90% upper bound failure rate
Bourdon pressure switch	function without pressure signal	1.9E-06/hr	6.2E-06/hr
	failed to function with pressure signal	1.9E-06/hr	6.2E-06/hr

Bourdon pressure switch (con't)	function at improper pressure level (drift)	2E-06/hr	5.8E-06/hr
Pressure transducer	failed to operate	5.4E-07/hr	1.4E-06/hr
	drift	4.1E-05/hr	5.9E-05/hr

The repair times for these units were an average of 8 hours for a pressure switch with a high time of 48 hours. The testing frequency was given as weekly alarm tests and 1 to 3 month service intervals for cleaning and maintenance (OREDA, 1992). Repair times were not given for the electrical analog signal pressure transducers. Test frequencies for the pressure transducers were monthly for an alarm test and visual inspection (OREDA, 1992). Other sources of data for pressure sensors was also found. Anyakora et al. (1971) gives 'all failure modes' faults per year for pressure sensors as 1.41/year. Assuming year round operation, this value converts to 1.41/year ÷ (8760 hours/year) = 1.6E-04/hour. Anyakora does not report error bounds on the values. Lees (1976) gave the same value. Anyakora gave a value of 0.34/year for pressure switches, which converts to 3.9E-05/hour. Repair times were not given in those articles.

Melvin and Maxwell (1974) gave a Bourdon tube failure rate of 1E-06/hour with an upper bound of 7E-06/hour. The failure mode was failure to operate, and the repair time was 4 man-hours per year. They gave a manometer failure to operate of 2E-07/hour with an upper bound of 8E-07/hour, and a repair time of 4 to 5 man-hours per year.

Alber et al. (1995) gave failure rates for pressure sensors as 2.3E-05/hour, drift, with an upper bound of 7.1E-05/hour. For failure to operate, they gave 1.7E-05/hour with an upper bound of 1.8E-04/hour.

Blanton and Eide (1993) gave a general pressure transducer failure rate of 1E-06/hour with an upper bound of 3E-06/hour for failure (no output). These data come from the Savannah River facilities.

All of these failure rate values are in the 1E-05 to 1E-06 per hour range. The 1E-06/hour value seems to be a reasonable average value for strain gauge pressure sensors. The LVDT units are generally regarded to be rugged as well (Herceg [1996] boasts that the LVDT is rugged and can have an unlimited mechanical lifetime because the core does not physically contact the coil housing), and are given the same generic failure rate value until operations and maintenance data are found that give the type of pressure sensor and failure rates. One source gave a suggested recalibration and response time test for pressure sensors as every 18 to 24 months (Weiss et al., 1990), while some facilities strive to test yearly.

While these failure rates have been calculated from plant data at chemical and industrial facilities, they should be generally applicable to other fluid temperature measurement applications such as water and cryogenic fluids. The sensors are built to certain specifications by similar manufacturing industries, and they should perform about equally well in the respective environments they are designed to function within. The OREDA values should be applicable to water fluids and to cryogenic service, if the analyst is positive that appropriate sensor units are chosen to meet the environmental conditions and the demands placed on the units. That is, designers will make use of appropriate technology and design principles for each sensor application (see this concept discussed by Thaggert and Jacobs, 1983).

The most recent work from the 1980's and 1990's gives lower failure rate values than the work from the 1970's. The discrepancy is almost two orders of magnitude, which is significant. Perhaps this variation in the failure rates is due to the choices of sensors being used over the different decades. Or, if it is the same unit, such as a Bourdon gauge, then the choice of materials can be a factor. Also, the feedback from operating experiences has given designers insights that have led them to reduce or dampen vibration, positioning units to reduce scale buildup, shielding for EMI protection, and to mitigate or avoid other potential failure mechanisms that have caused problems for pressure sensors.

3.5 Other sensor types

A relatively new type of sensor in use only since the 1980's is the fiber optic sensor (Horn, 1988). This sensor offers some advantages over electrical based sensors, such as small size and weight, explosion-proof, immunity to electro-magnetic interference, secure data transmission, and others (Krohn, 1992). Some means for detecting pressures by fiber optics are shining input light from one fiber optic cable through a small chamber that houses a bellows. As pressure increases, the bellows pushes a small metal plate up into the light beam. The amount of direct light collected at the other side of the chamber is inversely proportional to the fluid pressure. The change in collected light is measured at a fiber optic receiving station to indicate the pressure (Krohn, 1992; Wheeler and Ganji, 1996). Another means of pressure sensing is to have a reflective coating on a diaphragm. Light shines onto the diaphragm and is reflected into another fiber optic cable. As the diaphragm bulges from increased pressure, the amount of light reflected into the pickup cable is reduced, making light captured inversely proportional to the pressure in the system. These sensors can be very accurate.

Vacuum gauges, for rough vacuum and for high vacuum, were not discussed here. These sensors have been briefly discussed in Cadwallader and Marshall (1994).

3.6 Safety applications of pressure sensors

Some pressure sensors are used for safety functions in engineered systems. For example, pressure switches can actuate backup pumps to boost system pressure, or they can actuate valves that open to relieve mild pressure transients. Sensors for room pressure can signal if an overpressure condition is occurring (i.e., escape of pressurized gas into room). A special application of pressure sensors is that they can be used to actuate explosion suppression systems (Catalano, 1986). One such unit is described as a low mass, stainless steel diaphragm pressure transducer. The description is more of a diaphragm pressure switch. Byran (1982) describes these pressure sensors and pressure-rate-of-rise sensors for explosion suppression systems. A tentative 'failure to function' upper bound failure rate of 0.01/demand was assigned to these units (Cadwallader, 1995). Besides the pressure sensor, light sensors (such as infrared sensors) are also used to actuate explosion suppression systems.

3.7 Conclusions

In this chapter, pressure sensors were examined. The two most frequently used kinds of pressure sensor, the Bourdon gauge and the strain gauge pressure sensor, were discussed. Failure modes were examined and failure rate data from the literature was given. Repair times are more difficult to find in the literature, but some are cited. Other sensor types, such as fiber optic sensors, are discussed at the end of the chapter. It was noted that failure rates from the 1980's and 1990's varied considerably from the earlier data, showing that continued data collection and analysis is useful to ascribe accurate values to components and to promote operating experience feedback to designers.

Chapter 3 References

Alber et al., 1995.	T. G. Alber et al., Idaho Chemical Processing Plant Failure Rate Database, INEL-95/0422, Idaho National Engineering Laboratory, August 1995.
Anyakora et al., 1971.	S. N. Anyakora et al., "Some Data on the Reliability of Instruments in the Chemical Plant Environment," The Chemical Engineer, No. 255, November 1971, pages 396-402.
ASME, 1991.	American Society of Mechanical Engineers, Standard B40.1, "Gauges - Pressure Indicating Dial Type, Elastic Element," ASME, New York, 1991.
B&W, 1978.	Babcock and Wilcox, Steam, Its Generation and Use, thirty-ninth edition, Babcock and Wilcox Company, New York, 1978, chapter 33.
Barron, 1985.	R. F. Barron, Cryogenic Systems, second edition, Oxford University Press, ISBN 0-19-503567-4, 1985, chapter 6.
Becht, 1981.	C. Becht, "Root Bulge of Bellows," in Metallic Bellows and Expansion Joints, ASME PVP Vol. 51, American Society of Mechanical Engineers, 1981, pages 105-117.

Beckwith and Buck, 1969. T. G. Beckwith and N. L. Buck, Mechanical Measurements, second edition, Addison-Wesley Publishing Co., Reading, MA, ISBN 0-201-00454-2, 1969, chapter 13.

Blanton and Eide, 1993. C. H. Blanton and S. A. Eide, Savannah River Generic Database Development, WSRC-TR-93-262, Westinghouse Savannah River Company, 1993.

Bryan, 1982. J. L. Bryan, Fire Suppression and Detection Systems, second edition, MacMillan Publishing Company, New York, ISBN 0-02-471300-7, 1982, chapter 8.

Cadwallader and Marshall, 1994. L. C. Cadwallader and T. D. Marshall, Vacuum System Operating Experience Review for Fusion Applications, EGG-FSP-11037, Idaho National Engineering Laboratory, March 1994.

Cadwallader, 1995. L. C. Cadwallader, Fire Protection System Operating Experience Review for Fusion Applications, INEL-95/0396, Idaho National Engineering Laboratory, December 1995.

Catalano, 1986. L. Catalano, "Plants Opt for Explosion Protection as Insurance Costs Rise," Power, 130, July 1986, pages 49-51.

Considine, 1985. D. M. Considine, editor in chief, Process Instruments and Controls Handbook, third edition, McGraw-Hill Book Company, ISBN 0-07-012436-1, 1985, chapter 3.

Conway, 1995. D. Conway, "Cutting Emissions with Metal Bellows," Machine Design, 67, August 24, 1995, pages 52-58.

Green, 1983. A. E. Green, Safety Systems Reliability, John Wiley & Sons Publishers, Chichester, ISBN 0-471-90144-X, 1983, page 101.

Haines and Wilson, 1994. R. W. Haines and C. L. Wilson, HVAC Systems Design Handbook, McGraw-Hill Inc., New York, ISBN 0-07-025872-4, 1994, chapter 8.

Herceg, 1996. E. E. Herceg, "An LVDT Primer," Sensors, 13, June 1996, pages 27-30.

Horn, 1988. D. Horn, "Optical Fibers, Optimal Sensors," Mechanical Engineering, 110, September 1988, pages 84-88.

Jennings, 1978. B. H. Jennings, The Thermal Environment, Conditioning and Control, Harper & Row, Publishers, New York, ISBN 0-06-043311-6, 1978, chapter 1.

Johnson, 1993.	C. Johnson, Process Control Instrumentation Technology, fourth edition, Prentice Hall Publishers, ISBN 0-13-721150-3, 1993, chapter 4.
Krohn, 1992.	D. A. Krohn, Fiber Optic Sensors, Fundamentals and Applications, second edition, Instrument Society of America, Research Triangle Park, NC, ISBN 0-55617-010-6, 1992, chapters 1, 7.
Lees, 1973.	F. P. Lees, "Some Data on the Failure Modes of Instruments on the Chemical Plant Environment," The Chemical Engineer, No. 277, September 1973, pages 418-421.
Lees, 1976.	F. P. Lees, "The Reliability of Instrumentation," Chemistry and Industry, Number 5, March 6, 1976, pages 195-205.
McCulloch, 1981.	D. R. McCulloch, "Preventing Failure of Bellows Expansion-Joints," Chemical Engineering, 88, November 16, 1981, pages 259-263.
Melvin and Maxwell, 1974.	J. G. Melvin and R. B. Maxwell, Reliability and Maintainability Manual, Process Systems, AECL-4607, Atomic Energy of Canada Limited, January 1974.
Norton, 1982.	H. N. Norton, Sensor and Analyzer Handbook, Prentice Hall publishers, ISBN 0-13-806760-0, 1982, chapter 2.
OREDA, 1992.	OREDA, Offshore Reliability Data Handbook, second edition, distributed by DNV Technica, Hovik, Norway, ISBN 82-515-0188-1, 1992, pages 406-410.
PE, 1980.	Engineering Staff, "Tips for Preventing Pressure Gauge Problems, Part I - Blowout and Corrosion Failures," Plant Engineering, 34, March 6, 1980, pages 287-289; and "Tips for Preventing Pressure Gauge Problems, Part II - Pulsating Pressure, Vibration, and Lens Failures," Plant Engineering, 34, April 3, 1980, pages 91-93.
RAC, 1991.	Reliability Analysis Center, Failure Mode/Mechanism Distributions, 1991, FMD-91, Rome Air Development Center, Griffiss Air Force Base, NY, 1991.
Thaggert and Jacobs, 1983.	H. L. Thaggert and I. M. Jacobs, "Component Failure Rates Applicable to LMFBRs as Derived from LER Data," Nuclear Safety, 24, November-December 1983, pages 801-809.
Toepker and Kelley, 1984.	T. P. Toepker and J. J. Kelley, "Environmental Effects on a Pressure-Activated Switch," Nuclear Technology, 67, October 1984, pages 178-181.

Weiss et al., 1990.	J. Weiss, W. Esselman, and R. Lee, "Assess fiberoptic sensors for key powerplant measurements," Power, 134, October 1990, pages 55-58.
Wheeler and Ganji, 1996.	A. J. Wheeler and A. R. Ganji, Introduction to Engineering Experimentation, Prentice Hall Publishers, ISBN 0-13-337411-4, 1996, chapter 9.

4. Flow Sensors

4.1 Introduction

This chapter discusses sensors for fluid flow measurement. The most basic measuring apparatus for flow is to restrict the flow at a known cross-sectional area and measure its pressure at that point (Norton, 1982). Johnson (1993) describes the main methods of flow measurement, restriction flow and obstruction flow devices. This discussion will treat three of the most common flow sensors for liquids and gases, the orifice and venturi flow sensors and the turbine flow sensor (Gilbert, 1987) out of the over 100 types of flow sensors (Miller, 1983). Some other types of more modern flow sensors, including fiber optic sensor applications, will also be discussed later in the chapter.

4.2 Description of sensors

Many of the descriptions are taken from Johnson (1993). The first sensor described is the orifice flow meter, which is a restriction type of flow sensor. Orifice meters are used for liquids, usually clean liquids (i.e., no slurries or liquids with suspended particulates). This type of flow sensor is widely used (Battye et al., 1985). The orifice flow sensor is very simple, it is a metal disk with a central hole of a pre-calculated size. The disk is mounted into a long, straight pipe run, usually at a flange, to make a flow restriction. The pressure of the flow is measured on each side of the orifice. An equation predicts the volumetric flow, Q, as $Q = K\sqrt{\Delta p}$, where K is a constant and conversion factor, and the Δp is the pressure drop between the two pressure readings (Johnson, 1993). Often, a manometer or two diaphragms can be used to make these pressure readings, and electronics are used to convert to flow rates. Johnson (1993, page 218) describes the 'DP cell', or differential pressure cell instrument that is connected to the two pressure tap lines. The two pressures are routed to the two sides of a single diaphragm, and the diaphragm is connected to an LVDT that sends a signal out for conversion into a flow rate reading.

A schematic diagram of an orifice flow meter is shown in Figure 4-1. The advantages of the orifice flow meter are that it is inexpensive, it can be accurate for a wide variety of flow rates (although the flow should be turbulent; if the flow is only laminar then the equation for flow is $Q = c\Delta p$, where c is a constant (see Anderson, 1972, pg. 23) that is not equal to the constant K above), and if mounted at a flange these metal plates can be easy to replace. Turbulence of the flow depends on the fluid being moved, the fluid velocity, the pipe diameter, and the fluid viscosity. A dimensionless number called the Reynolds number, Re, is used to measure the turbulence of fluid flow. The Reynolds number is equal to the (pipe diameter)(fluid density)(fluid velocity)/(fluid viscosity). If only the fluid velocity is varied (i.e., the fluid temperature, and piping diameter are constant) then the transition from laminar to turbulent flow is often seen around Re = 2300 (Fox and McDonald, 1978). Since most flows of liquids are high velocity to improve heat transfer or mass transfer, Re values for liquids can be high, such as in the 1E+04 to 1E+05 range, and most flows in engineering systems are highly turbulent. Therefore, care must be taken to choose a material (usually metal) for the orifice plate that will withstand the flow environment. Orifice flow sensors are generally given accuracy of ±0.8% to 5% of the indicated flow rate, depending on the fluid and the Reynolds number. The highest experienced Reynolds number has been 3.3E+07 (Miller, 1983).

The obvious failure modes for the orifice flow sensor are the pressure sensor failure modes described in the previous chapter, as well as orifice plugging and deterioration of the metal plate. Usually, plugging is not thought to be a concern when flow velocities are high since the high speed and turbulence will keep any particulates in solution so that they do not easily plate out, and the friction of the high speed fluid passage will tend to keep the pipe walls 'scoured clean' so that few precipitates will cling to the walls. However, high fluid velocity can increase corrosion, erosion-corrosion, and abrasion (Fontana, 1986) of the orifice plate, especially the actual hole where velocity will be the highest. Orifices are not thought to be very stable at high flow velocities (over 30 m/s), and flow nozzles are used at these high flows (Miller, 1983).

The venturi flow sensor is a variation of the orifice plate flow sensor. The venturi is also a restriction flow device, but it has a more gradual tapering to the reduced flow area, shaped very much like an hourglass. The fluid static pressure is measured at the inlet and at the vena contracta (also called the throat; the smallest diameter flow area) and the pressures are compared like the orifice flow sensor. One of the important features of the venturi is that the pressure decrease, that is, the flow energy lost due to friction and the restriction, is less for this unit than for the more blunt orifice plate. While this pressure loss is system and fluid dependent, in an orifice the loss might be 20,000 Pa or more. Venturis are used where large pressure drops cannot be tolerated, such as in cryogenic systems where high pressures must be maintained to keep the fluid subcooled. Barron (1985), and Radebaugh and Marquardt (1993) discuss the use of orifices and venturi flow sensors. Orifice sensors can be used in cryogenic systems, but generally venturi sensors are preferred. For most cryogens, the water calibration values can be used with less than 1% error. Venturis are also simple and generally reliable (they must be installed so that the pressure tap is placed at the inlet), and can measure two-phase flow adequately (Huang and Van Sciver, 1996). Venturi accuracy usually varies between ±0.5% and 2% (Miller, 1983). Measuring two-phase flow can be especially important with cryogens. A venturi sensor is shown in Figure 4-2.

The obvious failure modes for the venturi are the same as those for the orifice. Throat plugging, erosion-corrosion that could lead to wall thinning and through cracking, and pressure tap plugging or leaking are reasons that this unit might not function correctly.

The other type of flow sensor discussed here is the turbine flow sensor. This is one of the obstruction type sensors. This unit places a small propeller, or turbine, mounted axially in a pipe section. Flow straighteners are ahead of the turbine blades to prevent turbulent flow from giving a false reading by extra concurrent impulse to the blades or by countercurrent

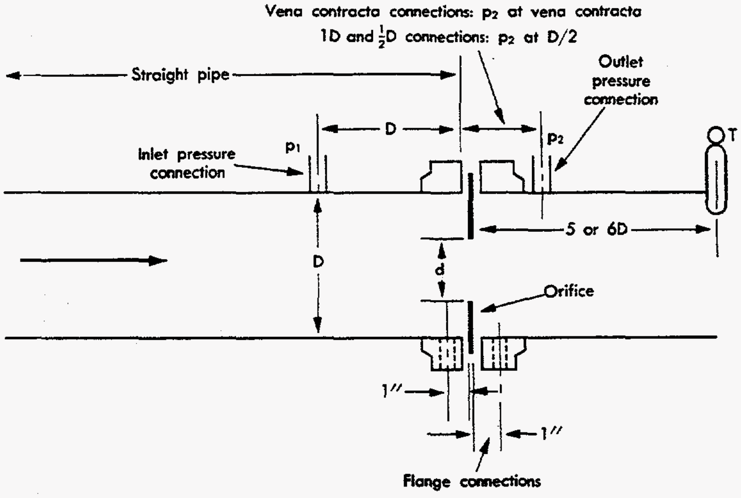
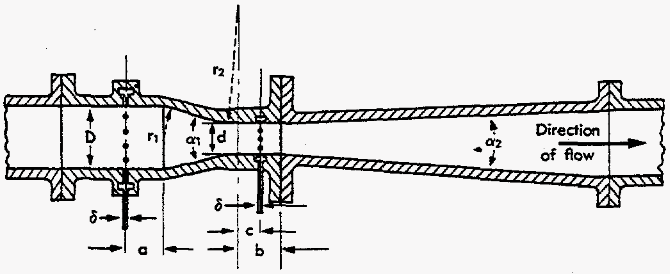


Figure 4-1. An orifice flow sensor (from Beckwith and Buck, 1969, page 419).



D = Pipe diameter inlet and outlet
d = Throat diameter as required
$a = 0.25\ D$ to $0.75\ D$ for $4'' \leqq D \leqq 6''$
$0.25\ D$ to $0.50\ D$ for $6'' < D \leqq 32''$
$b = d$
$c = d/2$
$\delta = \frac{3}{16}$ in. to $\frac{1}{2}$ in. according to D
Annular pressure chamber with at least 4 piezometer vents
$r_2 = 3.5\ d$ to $3.75\ d$
$r_1 = 0$ to $1.375\ D$
$\alpha_1 = 21° \pm 2°$
$\alpha_2 = 5°$ to $15°$

Figure 4-2. A venturi flow sensor (from Beckwith and Buck, 1969, page 416).

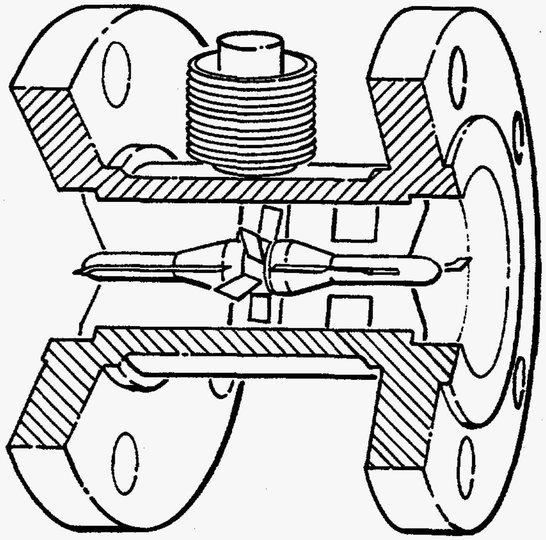


Figure 4-3. A turbine flow sensor for liquids (from Miller, 1983, page 6-16).

impulse that incorrectly slows the turbine blades. A small permanent magnet is mounted in the turbine shaft or outer wall, so that when a blade passes by, a small current is generated. As the blades pick up speed, more and more electrical pulses are sent per minute. Another means to transmit the turbine blade revolutions per minute (rpm) is to attached the turbine shaft to a tachometer (Johnson, 1993). Gears can also be used to transmit the turbine rpm, usually ventilation system sensors (called rotating vane anemometers but really are turbine flow sensors) use gears to get the rpm signal out (ACGIH, 1995). These meters can handle air flow velocities from 1 to 15 m/s and have very fast (ms) response times. The turbine meter is not a square root of pressure dependent sensor, so it can have a greater range. Obvious failures would be bearing problems, signal transmission faults (i.e., short or open circuit), and concerns about the obstruction sensor getting foreign object fouling or impacts. For example, many foreign objects have been found in piping systems - paint brush, nuts and bolts, gaskets (Mueller, 1969), and hand tools, pieces of wood, workman's glove, etc. The turbine flow sensor is best used for clean gases and liquids, and even steam; although the turbine blade shape is changed to accommodate the different fluids (Miller, 1983). The major problems with turbine flow meters are the effects of overspeed when a liquid flashes to vapor [or slugs of air or vapor enter the piping, etc.], shifts in calibration with blade wear (it is best to use this sensor only with clean fluids), bearing friction and bearing lifetime, and large calibration shifts for liquids containing small amounts of air (Miller, 1983). Turbine flow meters are said to be accurate to ±0.25% to 1% of the indicated flow rate. A magnetic pickup turbine flow meter is sketched in Figure 4-3.

Much has been discussed above about using these sensors with clean fluids. If a particular process fluid is known to carry suspended solids or is actually a slurry, then a magnetic flow sensor may be used. The suspension or slurry does not need to exhibit large magnetic properties, small effects can be measured well. Johnson (1993) discusses these flow sensors. If the fluid is a conductor, although it does not have to be a good conductor, of electricity, then the moving fluid passing through a magnetic field will induce a voltage potential. The pipe section must be a non-conductor, and electrical leads serve as the pickups for the voltage potential. Usually an electromagnetic field will be created instead of using a permanent magnet to create a magnetic field. These sensors will probably have only very limited application in magnetic fusion, since the fringe fields from the poloidal field magnets tend to induce currents of their own, making any voltage readings problematic.

An important aspect of flow sensors is the flow switch, where a certain flow rate will trigger a sensor to send an alarm. This sensor monitors continuously, but it only signals when the pre-selected flow rate value is reached by the fluid in the system. For example, a high flow rate value might be monitored in situations of possible tank overfill or overpressurization, or if a chemical reaction is supposed to proceed at a certain pace. A low flow signal might be needed for cooling water flow or for other applications. A flow switch can use the DP cell discussed earlier, with either an orifice or a venturi sensor.

4.3 Failure Modes and Effects Analysis

A component-level failure modes and effects analysis (FMEA) was performed on orifice flow sensors, venturi sensors, and turbine flow sensors. The effects of failures had to be judged on the component only, since no system was specified for these individual components to determine system level effects of failures. The component boundary to attribute failures to the sensors was taken to be the outer surface of the gauge body, in this case, it included the piping section that houses the sensor. Power requirements for the flow sensor were considered to be outside the boundary and therefore faults in power supplies were not attributed to the sensor. The FMEA approach of MIL STD 1629A (1980) was used; however, the portions relating to component identifier (as from a piping and instrumentation diagram) and system level effects were deleted. Table 4-1 gives the orifice sensor results, Table 4-2 gives the venturi sensor results, and Table 4-3 gives the turbine flow sensor results.

Some failure modes were found in a discussions by Lees (1973). These included drift caused by wear of the gauge's mechanical movement (overpressure, vibration, thermal cycling, foreign material intrusion, poor lubrication, or other factors) and contamination (from chemicals or moisture). Ionizing radiation could cause embrittlement of the metal if the unit is subjected to high fluences. Electromagnetic radiation is unlikely to damage a flow sensor, unless it generates electrical currents and heating in the sensor.

An important concern for safety analysts is to obtain good data that quantifies the FMEA failure mode behavior. It is usually true that the FMEA gives more failure modes than are found in the field, since the FMEA is not concerned with probabilities of occurrence and field data usually treats the most probable events. Sometimes, the field data are lumped into one category, the so-called 'all failure modes' failure rates. Fortunately, one report gives probabilities of the various modes of failure (RAC, 1991). For sensor transducers, the failure mode breakdown is 68% out of tolerance, 15% false response, 12% open circuit, and 5% short circuit. While this is a broad generalization for a mixture of electronic sensor types, in general, we can assume that about two-thirds of events are out of tolerance (drift). When no better information is available, these data can be used to guide analysts and to make inquiries to experts, plant operations personnel, etc.

4.4 Failure Rate Data

Failure rates were defined in Chapters 2 and 3. In this section, the results of a literature review to locate sources of finished failure rate data for flow sensors are presented. Reports on data analyses already performed on flow sensors were sought since these are well regarded (Green, 1983), and there are no raw data readily available for statistical data analysis. Several reports were found that gave suggested failure rates, some based on operations experience and some based on reference data.

Table 4-1. FMEA for an orifice flow sensor

Function	Failure modes and causes	Local effects	Failure detection method	Compensating provisions	Remarks
Orifice sensor measures fluid pressure, converts to flow rate	orifice plate crack or rupture, from flaw in metal, from vibration or corrosion fatigue, erosion-corrosion, abrasion, or from embrittlement	fluid flow is not constrained to pass through present diameter hole, false low reading	Sensor registers false low flow rate	frequent inspection of sensor,	
	pipe leakage, from flaw in pipe wall, from corrosion, or from vibration fatigue, etc.	process fluid leaks out into plant environment, could make readings inaccurately low	Sensor output not true, leakage from body may be noted	install isolation valves in process pipe line	Isolation valves will help with maintenance as well as isolating leaks
	pressure taps leak, due to vibration, poor assembly, or material flaws	with pressure drops, sensor gives erroneous readings of flow	Sensor does not register correct flow rate	Use multiple sensors and average the readings? Frequently inspect sensors	
	plugging pressure taps, due to foreign material buildup in the lines	near steady output that does not change with system flow changes	Lack of change should become suspicious to operators	perhaps multiple sensor outputs are averaged?	
	orifice accumulates crud	crud buildup could affect pressure reading	inspect piping	water cleanliness to reduce scale and crud	
	orifice plugging, due to foreign object or crud buildup	flow stops, sensor shows no flow	alarm, or note since it is a process upset	unlikely to plug with crud, keep foreign objects out of piping	
	orifice abrasion, due to particles in liquid	orifice hole enlarges, gives false low reading	sensor registers a false low reading	frequent inspection to verify orifice plate is intact	

Table 4-2. FMEA for a venturi flow sensor

Function	Failure modes and causes	Local effects	Failure detection method	Compen-sating provisions	Remarks
venturi flow sensor converts pressure readings into flow rate	pipe leakage, from flaw in pipe wall, from erosion-corrosion, or from abrasion, or material flaw	process fluid leaks out into plant environment, could make readings inaccurately low	Sensor output not true, leakage from body may be noted	install isolation valves in process pipe line, specify extra thickness walls for venturi	Isolation valves will help with maintenance as well as isolating leaks, thick walls will make venturi more expensive
	pressure taps leak, due to vibration, poor assembly, or material flaws	with pressure drops in taps, sensor gives erroneous readings of flow	Sensor does not register correct flow rate	Use multiple sensors and average the readings? Frequently inspect sensors	
	plugging pressure taps, due to foreign material buildup in the lines	near steady output that does not change with system flow changes	Lack of change should become suspicious to operators	perhaps multiple sensor outputs are averaged?	
	venturi throat plugs, foreign material buildup or foreign object in piping	flow goes to zero, flow reading goes to zero	operators should notice flow drop to zero, pump heatup, pressure increase at pump outlet	strainers or screens in piping, use demineralization?	
	erratic reading, electromagnetic interference (EMI)	instrument readings are inaccurate	operators notice fluctuations	shield for electromagnetic fields	These units operate in the mV range, can be susceptible to EMI
	scale buildup in instrument sensing line to diaphragm	slower response time, inaccurate readings	operator should notice degradation against average values	there are many reasons to maintain system cleanliness, i.e., safety and efficiency	preventive maintenance must check for this buildup of materials
	leakage past pressure sensor fitting or in sensing line to the process system	small leak may not affect pressure sensor function; large leak will show decreased pressure	may affect pressure sensor operation	small leak may not be noticed during walk downs or by system technicians; large leak will be noticed by dropping pressure readings	this failure mode can be important for safety, but it is dependent on the process fluid

Table 4-3. FMEA for a turbine flow sensor.

Function	**Failure modes and causes**	**Local effects**	**Failure detection method**	**Compen-sating provisions**	**Remarks**
turbine flow sensor senses flow rate from rotational velocity of turbine blades	blade wear, due to particulates in fluid, cavitation pitting, or simply long service life	accuracy of flow rate is decreased	difficult to detect. Over time, reading will not agree with other system parameter values, i.e., heat or mass transfer readings	choice of blade materials for the expected operating environment	
	blade obstruction, foreign material intrusion	if turbine stops, flow reading goes to zero	could be alarmed parameter	screens or strainers in the piping system?	
	bearing freeze-up	if turbine stops, flow reading goes to zero	could be alarmed parameter	choice of bearing in the flow sensor	
	extra turbulence in process fluid	turbine blades either turn at an artificially low or high rpm	flow readings will not agree with other indications, i.e., pump power or others	flow straightener vanes should be sized to be able to stop any problem of this type	
	output wiring open circuit	no signal of flow sent out	operators should be suspicious of zero flow while system is operating	multiple flow sensors	
	output wiring short circuit	no signal of flow sent out	operators should be suspicious of zero flow while system is operating	multiple flow sensors	
	casing leakage, from material flaw or impact, or corrosion pitting	leakage of process fluid to the plant environment	walkdowns spot leakage, or system pressure decrease alerts operators	choice of material for flow meter body	pin hole leakage should not have a large effect on the turbine flow sensor

One of the leading data sources is the Offshore Reliability Data Handbook (OREDA, 1992). This handbook documents data collected at offshore oil drilling platforms. The data are characterized, components are described and their boundaries defined, and the statistics are presented. The OREDA handbook gives values for flow sensors:

sensor	failure mode	average failure rate	90% upper bound failure rate
orifice flow switch with DP cell	failed to function when required	3E-06/hour	9.6E-06/hour
	sent signal at improper flow value	1.5E-06/hour	7.2E-06/hour
turbine flow meter	failed to function when required	1.7E-05/hour	5.7E-05/hour

The repair times for these units were an average of 12 hours for a flow switch with a high time of 24 hours. The testing frequency was given as weekly alarm tests and 1 to 3 month service intervals for cleaning and maintenance (OREDA, 1992). Test frequencies for the turbine flowmeter was monthly for routine servicing and maintenance, but no testing or calibration intervals were given (OREDA, 1992).

Other sources of data for flow sensors was also found. Anyakora et al. (1971) gives 'all failure modes' faults per year for flow sensors as 1.73/year. Assuming year round operation, this value converts to 1.73/year ÷ (8760 hours/year) ≈ 2E-04/hour. Anyakora does not report error bounds on the values. Lees (1976) gave the same value. Repair times were not given in those articles. They did cite an overall failure rate of 2.18/year for magnetic flow sensors, which converts to 2.5E-04/hour.

Melvin and Maxwell (1974) gave a venturi flow sensor failure rate of 4E-07/hour with an upper bound of 2E-06/hour. The failure mode was failure to operate, and no maintenance time was cited. They gave a pitot tube failure to operate of 5E-07/hour with an upper bound of 1E-06/hour, and no repair time was given. They also gave a magnetic flow detector overall failure rate of 2E-06/hour with an upper bound of 6E-06/hour, and a maintenance time of 8 man-hours per year.

Alber et al. (1995) gave failure rates for gas flow sensors as 4E-05/hour, drift, with an upper bound of 1.3E-04/hour. For failure to operate, they gave 2.7E-05/hour with an upper bound of 1.8E-04/hour. For liquid flow sensors, they gave a failure rate for drift of 3.2E-05/hour, with an upper bound of 2.2E-04/hour. For failure to operate, they gave a failure rate of 3.3E-05/hour, with an upper bound of 1.5E-04/hour.

Blanton and Eide (1993) gave a general flow sensor failure rate of 3E-06/hour with an upper bound of 9E-06/hour for failure (no output). These data come from the Savannah River facilities. Unfortunately, the analyst has to infer which sort of flow sensor these data sources use in calculating their failure rates. Often, the analyst uses any system description information to find the answer. Failing that, the age of the facility is used to decide which sort of technology was used for sensors. Obviously, none of these sensors are fiber optic.

All of these failure rate values are in the 1E-05 to 1E-06 per hour range. The 1E-05/hour value seems to be a reasonable average value for flow sensors of the restriction type. The turbine flow meter value from the OREDA (1992) handbook, the 1.7E-05/hour value, is reasonable to use until better data are found. It is reasonable to assume yearly calibration checks unless better data or plant-specific procedures are found to contradict this suggested value.

While these failure rates have been calculated from plant data at chemical and industrial facilities, they should be generally applicable to other fluid temperature measurement applications such as water and cryogenic fluids. The sensors are built to certain specifications by similar manufacturing industries, and they should perform about equally well in the respective environments they are designed to function within. The OREDA values should be applicable to water fluids and to cryogenic service, if the analyst is positive that appropriate units are chosen to meet the environmental conditions and the demands placed on the units.

The most recent work from the 1980's and 1990's gives lower failure rate values than the work from the 1970's. The discrepancy is about an order of magnitude, which can be significant. Perhaps this variation in the failure rates is due to the choices of sensors being used over the different decades. Or, if it is the same unit, such as a manometer, then the choice of fluids or materials can be a factor. Also, the feedback from operating experiences has given designers insights that have led them to reduce or dampen vibration, positioning units to reduce scale buildup, understanding the effects of particulates in the fluid to be measured, shielding electrical portions of the sensors for EMI protection, and to mitigate or avoid other potential failure mechanisms that have caused problems for flow sensors.

4.5 Other sensor types

A relatively new type of sensor in use only since the 1980's is the fiber optic sensor (Horn, 1988). This sensor offers some advantages over electrical based sensors, such as small size and weight, explosion-proof, immunity to electro-magnetic interference, secure data transmission, and others (Krohn, 1992). Some means for detecting flows by fiber optics are shining input light from one fiber optic cable through a small chamber that houses a turbine, allowing the turbine to turn in the fluid flow. The turbine blades are reflective, so light reflection back to a pickup fiber optic cable can count the rpm's. Another method for fiber optics to measure flow is to use fiber optic pressure sensors as described in the previous chapter, connecting them to pressure taps on an orifice or venturi flow sensor. As pressure increases in the pressure tap lines, metal bellows expand and push a small metal plate up into the light beam. The amount of direct light collected at the other side of the chamber is inversely proportional to the fluid pressure. The change in collected light is measured at a fiber optic receiving station to indicate the pressure (Krohn, 1992; Wheeler and Ganji, 1996). Another means of pressure sensing is to have a reflective coating on a diaphragm rather than a bellows. Light shines onto the diaphragm and is reflected into another fiber optic cable. As the diaphragm bulges from increased pressure, the amount of light reflected into the pickup cable is reduced, making light captured inversely proportional to the pressure in the system. These sensors can be very accurate.

4.6 Safety applications of flow sensors

Some flow sensors are used for safety functions in engineered systems. For example, flow switches can actuate a signal that fluid is flowing in systems where the fluid is normally stagnant, such as in a wet pipe fire sprinkler system. These fire protection systems often use a vane or flap flow sensor that moves (is pushed by flow) as the flow pressure acts on it; thereby moving a displacement lever that actuates a switch to close a flow alarm electrical circuit (Coon, 1991). These flow switch or flow valve devices are given a very low failure rate of 4E-05/year in Cadwallader (1995). Such a low failure rate can sometimes be found in standby equipment. There are other safety applications of flow sensors, but these are dependent on the process system. For example, over flow or under flow can be sensed by flow switches and alarmed. Continuous sensing of a cooling water flow rate can also be important to safety.

4.7 Conclusions

In this chapter, flow sensors were examined. It is interesting to note that flow sensors can make use of pressure readings to convert a signal into a flow rate. The two most frequently used kinds of flow sensor, the orifice and the venturi differential pressure sensors, were discussed. The turbine flow sensor was also discussed. Failure modes were examined and failure rate data from the literature was given. Repair times are more difficult to find in the literature, but a few are cited. Other sensor types, such as fiber optic sensors, are discussed at the end of the chapter. It was noted that failure rates from the 1980's and 1990's varied considerably from the earlier data, showing that continued data collection and analysis is useful to ascribe accurate values to components and to promote operating experience feedback to designers.

Chapter 4 References

ACGIH, 1995.	American Conference of Governmental Industrial Hygienists, Industrial Ventilation, a manual of recommended practice, twenty-second edition, Cincinnati, OH, ISBN 1-882417-09-7, 1995, pages 9-12 to 9-13.
Alber et al., 1995.	T. G. Alber et al., Idaho Chemical Processing Plant Failure Rate Database, INEL-95/0422, Idaho National Engineering Laboratory, August 1995.
Anderson, 1972.	N. A. Anderson, Instrumentation for Process Measurement and Control, second edition, Chilton Company, Philadelphia, 1972.
Anyakora et al., 1971.	S. N. Anyakora et al., "Some Data on the Reliability of Instruments in the Chemical Plant Environment," The Chemical Engineer, No. 255, November 1971, pages 396-402.
Barron, 1985.	R. F. Barron, Cryogenic Systems, second edition, Oxford University Press, ISBN 0-19-503567-4, 1985, chapter 6.
Battye et al., 1985.	J. S. Battye et al., editors, Shell flow meter engineering handbook, second edition, McGraw-Hill Book Company, New York, ISBN 0-07-084798-3, 1985.
Beckwith and Buck, 1969.	T. G. Beckwith and N. L. Buck, Mechanical Measurements, second edition, Addison-Wesley Publishing Co., Reading, MA, ISBN 0-201-00454-2, 1969, chapter 13.
Blanton and Eide, 1993.	C. H. Blanton and S. A. Eide, Savannah River Generic Database Development, WSRC-TR-93-262, Westinghouse Savannah River Company, 1993.
Cadwallader, 1995.	L. C. Cadwallader, Fire Protection System Operating Experience Review for Fusion Applications, INEL-95/0396, Idaho National Engineering Laboratory, December 1995.
Considine, 1985.	D. M. Considine, editor in chief, Process Instruments and Controls Handbook, third edition, McGraw-Hill Book Company, ISBN 0-07-012436-1, 1985, ch. 3.
Coon, 1991.	J. W. Coon, Fire Protection, Design Criteria, Options, Selection, R. S. Means Company, Inc., Kingston, MA, ISBN 0-87629-215-5, 1991, chapter 3.

Fontana, 1986.	M. G. Fontana, Corrosion Engineering, third edition, McGraw-Hill, Inc., New York, ISBN 0-07-021463-8, 1986, chapter 2.
Fox and McDonald, 1978.	R. W. Fox and A. T. McDonald, Introduction to Fluid Mechanics, second edition, John Wiley & Sons Publishers, New York, ISBN 0-4 71-01909-7, 1978, chapter 2.
Gilbert, 1987.	G. Gilbert, "Three ways to measure flow in powerplant ducts," Power, 131, June 1987, p. 63-72.
Green, 1983.	A. E. Green, Safety Systems Reliability, John Wiley & Sons Publishers, Chichester, ISBN 0-471-90144-X, 1983, page 101.
Haung and Van Sciver, 1996.	X. Haung and S. W. Van Sciver, "Performance of a venturi flow meter in two-phase helium flow," Cryogenics, 36, 1996, pages 303-309.
Horn, 1988.	D. Horn, "Optical Fibers, Optimal Sensors," Mechanical Engineering, 110, September 1988, pages 84-88.
Johnson, 1993.	C. Johnson, Process Control Instrumentation Technology, fourth edition, Prentice Hall Publishers, Englewood Cliffs, NJ, ISBN 0-13-721150-3, 1993, chapter 4.
Krohn, 1992.	D. A. Krohn, Fiber Optic Sensors, Fundamentals and Applications, second edition, Instrument Society of America, Research Triangle Park, NC, ISBN 0-55617-010-6, 1992, chapters 1, 9.
Lees, 1973.	F. P. Lees, "Some Data on the Failure Modes of Instruments on the Chemical Plant Environment," The Chemical Engineer, No. 277, September 1973, pages 418-421.
Lees, 1976.	F. P. Lees, "The Reliability of Instrumentation," Chemistry and Industry, Number 5, March 6, 1976, pages 195-205.
Melvin and Maxwell, 1974.	J. G. Melvin and R. B. Maxwell, Reliability and Maintainability Manual, Process Systems, AECL-4607, Atomic Energy of Canada Limited, 1974.
Miller, 1983.	R. W. Miller, Flow Measurement Engineering Handbook, McGraw-Hill Book Company, New York, ISBN 0-07-042045-9, 1983, chapter 6.

Mueller, 1969.	R. E. Mueller, "Objects Found in Power Reactor Systems," *ANS Conference on Reactor Operating Experience*, American Nuclear Society, October 1-3, 1969, *ANS Transactions*, supplement to volume 12, 1969, pages 42-44.
Norton, 1982.	H. N. Norton, *Sensor and Analyzer Handbook*, Prentice Hall publishers, Englewood Cliffs, NJ, ISBN 0-13-806760-0, 1982, chapter 2.
OREDA, 1992.	*OREDA, Offshore Reliability Data Handbook*, second edition, distributed by DNV Technica, Hovik, Norway, ISBN 82-515-0188-1, 1992, pages 420-430.
RAC, 1991.	Reliability Analysis Center, *Failure Mode/Mechanism Distributions, 1991*, FMD-91, Rome Air Development Center, Griffiss Air Force Base, NY, 1991.
Radebaugh and Marquardt, 1993.	R. Radebaugh and E. Marquardt, "Cryogneic Instrumentation," *Recent Advances in Cryogenic Engineering 1993*, ASME HTD Vol. 267, American Society of Mechanical Engineers, 1993, pages 13-27.
Wheeler and Ganji, 1996.	A. J. Wheeler and A. R. Ganji, *Introduction to Engineering Experimentation*, Prentice Hall Publishers, Englewood Cliffs, NJ, ISBN 0-13-337411-4, 1996, chapter 9.

5. Level Sensors

5.1 Introduction

This chapter discusses sensors for fluid level measurement. These sensors can have safety importance in facility operations. For example, level sensors can be used to determine if there is pipe leakage by monitoring a sump level underneath a piping system, monitor the level of fuel in the tank for an emergency diesel generator, or monitor the water level in an overhead storage tank for fire water. The level of surge tanks, or the pressurizer in a fission reactor, can be important to safety as well. Process safety can also depend on level sensors to provide indication of levels of reactants in reactor vessels. There are many kinds of level sensors, such as: simple dip sticks, sight glasses, mechanical float sensors, pressure sensors configured to measure level and dielectric-type level sensors. Level switches indicate one particular level of fluid, while other sensors are continuous reading (Norton, 1982). Reason (1984) describes many types of electronic level sensors. Johnson (1993) describes several methods of level measurement, the mechanical float devices, electrical conductivity, ultrasonic reflection, and pressure methods. This discussion will treat the two most common level sensors for liquids, the float and the differential pressure sensors. Capacitance means will also be discussed. Some other types of more modern flow sensors, including fiber optic sensor applications, will also be discussed later in the chapter.

5.2 Description of sensors

Many of the descriptions are taken from Johnson (1993). The first sensor described is the float sensor. As the name implies, this sensor is in contact with the liquid, and a part of the sensor floats on the surface of the liquid. If the liquid is often agitated, readings could become very erratic. The float is attached to a linear variable differential transformer (LVDT), which was described in Chapter 3. The float could also be attached to a rotary potentiometer (Wheeler and Ganji, 1996), which is the system often used in automobile gasoline tanks. However, newer automobiles also use other sensors, such as an electronic capacitance sensor, to measure the gasoline level in the fuel tank. Nonetheless, the float sensor is still used, and it is described here. The float sensor operates in the following manner. As the float rides with the level changes, the LVDT core metal rod moves, generating a small current electrical signal as described in Chapter 3. This signal is conditioned to indicate the liquid level in the tank. A float level sensor is shown in Figure 5-1.

The obvious failure modes for the float level sensor are float detachment from the LVDT, so much fluid agitation that the reading varies too much for any accuracy, and any LVDT faults (short circuit, open circuit).

The differential pressure cell, described in Chapter 4, can be used as a level sensor. Based on the principle that static head pressure is equal to (liquid density)(gravitational acceleration)(height), the height of a column of liquid can be estimated. Pressure readings from the top and bottom of a tank are routed via sensing lines to either side of the pressure diaphragm. Some other means must be used to determine the liquid density, possibly measuring temperature to determine the density. With the differential pressure between the top and bottom of the tank known, and the liquid density known, then the liquid height can be determined. If the tank is open to the atmosphere on top, then only a single pressure diaphragm at the base of the tank is needed to get a level height estimate (when the density is known) (Norton, 1982). The DP cell level sensor is shown in Figure 5-2. This type of sensor is used in many process applications (Weiss, 1993), including cryogenic tank level measurement (Barron, 1985).

The obvious failure modes for the DP cell are diaphragm leakage and rupture, LVDT becoming jammed or bound, and the wiring faults (short circuit or open circuit). Wheeler and Ganji (1996) point out that the upper sensing line could become filled with liquid rather than the air or cover gas in the tank if the tank was overfilled. If both lines are filled with liquid, a consistently false low reading will result. The sensing lines could also become blocked by particulate plate out if the liquid is not clean.

The capacitance level sensor is a continuous level sensor. It operates by measuring the capacitance of the liquid between a vertical probe inserted into the liquid and the tank wall. As the liquid level rises, the dielectric between the two capacitor plates (the probe and the tank wall) changes, and this dielectric capacitance change is used to generate the voltage signal that is converted to a level signal (Reason, 1984). Wheeler and Ganji (1996) state that the dielectric constant (a unitless number) of air, and many vapors, will be unity. They also state that liquid dielectric constants can range from 2 to 100. The probe can be made of stainless steel for non electrical conductor liquids, and it must be insulated with an appropriate insulating material for electrically conducting liquids. This probe can have an accuracy of ± 0.2% of the gauge span. The principal disadvantage of these sensors is that some liquids or particulates suspended in liquids tend to build up on the probe, causing a change in the dielectric value (Reason, 1984).

An important point level sensor is the level switch. In its simplest form, the level switch is a float type device mounted on the side wall of a tank. The float hangs downward on its hinge until the liquid level rises. When the liquid level reaches the level switch, the float buoyant force moves the float upward. The float pivots on its hinge, and when the liquid level moves the float, it pivots 90° and actuates an electrical switch. The switch closure completes a circuit that alarms or annunicates that the liquid level is at that particular height in the tank.

5.3 Failure Modes and Effects Analysis

A component-level failure modes and effects analysis (FMEA) was performed on float level sensors and DP sensors. The effects of failures had to be judged on the component only,

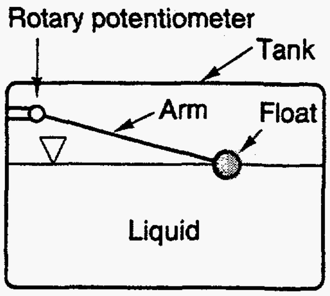


Figure 5-1. A float level sensor (Wheeler and Ganji, 1996, page 312).

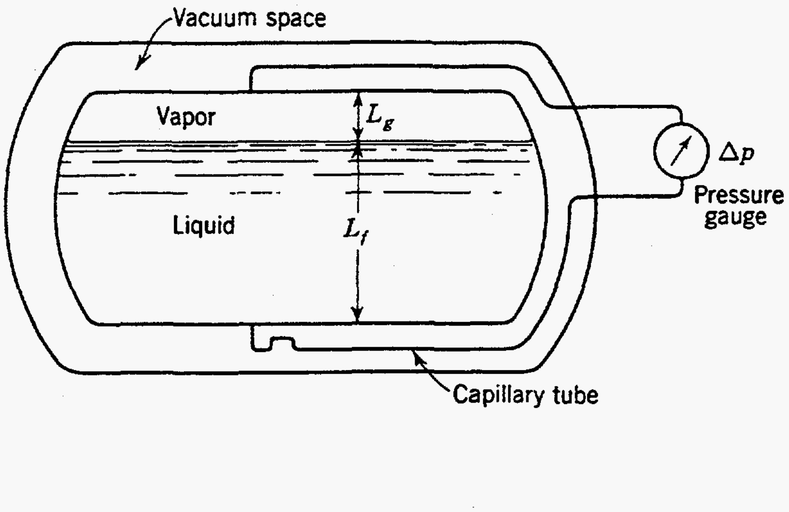


Figure 5-2. A differential pressure level sensor for a cryogenic tank (from Barron, 1985, page 341).

Table 5-1. FMEA for a float level sensor

Function	**Failure modes and causes**	**Local effects**	**Failure detection method**	**Compensating provisions**	**Remarks**
Float level sensor measures fluid level in a tank	float loses buoyancy, float breached from crack, corrosion, or other causes	float does not follow liquid level or it follows only sluggishly	operators notice that level in tank does not vary although it should as part of a process	frequent inspections, multiple sensors, choice of materials	
	float detachment from wand, due to impact or corrosion, or other causes	sensor reads zero level output as wand sags to lowest point of travel	sensor output is zero level	choice of materials to negate corrosion	float in piping system can cause flow blockage
	float wand overstress, due to tank overfilling or impact event	level sensor reads false level since the wand is bowed	Sensor does not register correct liquid level, operators must cross check level value	prudent operation to avoid tank overfill, frequent maintenance to verify sensor is intact	
	LVDT open circuit, wiring fault	level output drops to zero, does not change with system level changes	Zero level and lack of change should become suspicious to operators	perhaps multiple sensor outputs are averaged?	
	LVDT short circuit, wiring fault	erratic reading	operators should become suspicious of rapidly changing level readings	perhaps multiple sensor outputs are averaged?	
	erratic reading, electromagnetic interference (EMI)	instrument readings are inaccurate	operators notice fluctuations	shield for electromagnetic fields	These units operate in the mV range, can be susceptible to EMI
	LVDT binding, due to foreign material buildup	level sensor reads a constant value	constant level should be suspicious to operators	frequent maintenance to verify that sensor is intact	
	leakage from sensor seal to tank wall, due to corrosion, thermal cycling, gasket wear, or other causes	does not affect level sensor unless liquid causes an electrical problem	leakage should be detected during walkdown inspections	choose seal materials with care	liquid leakage might be a hazard to personnel or to facility safety

Table 5-2. FMEA for a differential pressure cell level sensor

Function	Failure modes and causes	Local effects	Failure detection method	Compensating provisions	Remarks
DP cell measures pressure in a tank, converts pressure readings into level	sensing line leakage, from flaw in tube wall, from erosion-corrosion, or from abrasion	process fluid leaks out into plant environment, could make readings inaccurately low	Sensor output not true, leakage from lines may be noted during a walkdown	install isolation valves in sensing lines, specify extra thickness walls for sensing lines	Isolation valves will help with maintenance as well as isolating leaks, thick walls will make instrument more expensive
	sensing lines plug up with particulates from the process liquid	the differential pressure cell does not register changes in pressure, so level appears to be constant	level lack of change should become suspicious to operators	perhaps multiple sensor outputs are averaged?	
	diaphragm chamber leakage, due to corrosion or a material flaw	the DP cell response could become erratic, depending on which side the leakage is on	operators may not notice the fluctuating readings very quickly	frequent calibration checks are needed	leakage to the plant environment could be hazardous
	diaphragm leakage, from pin hole flaw, corrosion, or other cause	differential pressure reading is not true, level reading is falsely low	over time, low readings should be suspicious to operators	frequent calibration, average output of several sensors	could overfill tank until operators recognize sensor gives incorrect level
	diaphragm rupture, from flaw or overpressure	no differential pressure reading	Zero level and lack of change should become suspicious to operators	perhaps multiple sensor outputs are averaged?	
	erratic reading, electromagnetic interference (EMI)	instrument readings are inaccurate	operators notice fluctuations	shield for electromagnetic fields	These units operate in the mV range, can be susceptible to EMI
	scale buildup in instrument sensing line to diaphragm	slower response time, inaccurate readings	operator should notice degradation against average values	there are many reasons to maintain system cleanliness, i.e., safety and efficiency	preventive maintenance must check for this buildup of materials

since no system was specified for these individual components to determine system level effects of failures. The component boundary to attribute failures to the sensors was taken to be the outer surface of the gauge body. Power requirements for the level sensor were considered to be outside the boundary and therefore faults in power supplies were not attributed to the sensor. The FMEA approach of MIL STD 1629A (1980) was used; however, the portions relating to component identifier (as from a piping and instrumentation diagram) and system level effects were deleted. Table 5-1 gives the float level sensor results, and Table 5-2 gives the DP cell sensor results.

Some failure modes were found in a discussions by Lees (1973). These included drift caused by wear of the gauge's mechanical movement, such as the rotary potentiometer (overpressure, vibration, thermal cycling, foreign material intrusion, poor lubrication, or other factors) and contamination (from chemicals or moisture). Ionizing radiation could cause embrittlement of the metal if the unit is subjected to high fluences. Some level sensor types (such as those using the LVDT) could have false currents generated by electromagnetic radiation, which would lead to false level signals.

An important concern for safety analysts is to obtain good data that quantifies the FMEA failure mode behavior. It is usually true that the FMEA gives more failure modes than are found in the field, since the FMEA is not concerned with probabilities of occurrence and field data usually treats the most probable events. Sometimes, the data are lumped into one category, the so-called 'all failure modes' failure rates. Fortunately, one report gives probabilities of the various modes of failure (RAC, 1991). For sensor transducers, the failure mode breakdown is 68% out of tolerance, 15% false response, 12% open circuit, and 5% short circuit. While this is a broad generalization for a mixture of electronic sensor types, in general, we can assume that about two-thirds of events are out of tolerance (drift). When no better information is available, these data can be used to guide analysts and to make inquiries to experts, plant operations personnel, etc.

5.4 Failure Rate Data

Failure rates were defined in Chapters 2 and 3. The results of a literature review to locate sources of finished failure rate data for level sensors are presented here. Reports on data analyses already performed on level sensors were sought since these are well regarded field experiences (Green, 1983), and there are no raw data readily available for statistical data analysis. Several reports were found that gave suggested failure rates, some based on operations experience and some based on reference data.

One of the leading data sources is the Offshore Reliability Data Handbook (OREDA, 1992). This handbook documents data collected at offshore oil drilling platforms. The data are characterized, components are described and their boundaries defined, and the statistics are presented. The OREDA handbook gives values for level sensors:

sensor	failure mode	average failure rate	90% upper bound failure rate
level sensor	no change of output with change of input	2.2E-07/hour	1.0E-06/hour
	low output	2.2E-07/hour	1.0E-06/hour
	erratic output	4.3E-07/hour	1.4E-06/hour
	contaminated sensor	5.7E-07/hour	2E-06/hour
level switch (float with switch)	fail to function when needed	6.0E-07/hour	2.1E-06/hour
	function without need	2.8E-07/hour	1.1E-06/hour

The repair times for these units were an average of 4 hours for a flow sensor with a high time of 31 hours, and 2 hours for the level switch with a high time of 13 hours. The testing frequency was given as weekly alarm tests and 1 to 3 month service intervals for cleaning and maintenance for the level switch, and 3 month visual inspection intervals for the level sensors (OREDA, 1992).

Other sources of data for level sensors was also found. Anyakora et al. (1971) gives 'all failure modes' faults per year for level sensors as 1.71/year. Assuming year round operation, this value converts to 1.71/year ÷ (8760 hours/year) ≈ 2E-04/hour. Anyakora does not report error bounds on the values. Lees (1976) gave the same value. Repair times were not given in those articles. They did give an overall failure rate of 1.64/year for float-type level transducers.

Melvin and Maxwell (1974) gave a differential pressure type of level sensor a failure rate of 8E-06/hour with an upper bound of 5E-05/hour. The failure mode was failure to operate, and the repair time was 5 man-hours per year. They gave a level sight glass failure to operate of 1E-06/hour with an upper bound of 3E-06/hour, and no maintenance times were given for sight glasses.

Alber et al. (1995) gave failure rates for level sensors as 2.3E-05/hour, drift, with an upper bound of 7.1E-05/hour. For failure to operate, they gave 1.7E-05/hour with an upper bound of 1.8E-04/hour.

Blanton and Eide (1995) gave a general level transducer failure rate of 1E-06/hour with an upper bound of 3E-06/hour for failure (no output). These data come from the Savannah River facilities.

All of these failure rate values are in the 1E-04 to 1E-07 per hour range. Looking at the most recent data narrows the range down to 1E-06 to 1E-07/hour. The 1E-06/hour value is conservative for level sensors. The LVDT-based DP cell units are generally regarded to be rugged (Herceg, 1996), so perhaps the values from the OREDA handbook are applicable for most units.

While these failure rates have been calculated from plant data at chemical and industrial facilities, they should be generally applicable to other fluid temperature measurement applications such as water and cryogenic fluids. The sensors are built to certain specifications by similar manufacturing industries, and they should perform about equally well in the respective environments they are designed to function within. The OREDA values should be applicable to water fluids and to cryogenic service, if the analyst is positive that appropriate units are chosen to meet the environmental conditions and the demands placed on the units.

The most recent work from the 1980's and 1990's gives lower failure rate values than the work from the 1970's. The discrepancy is very wide. Perhaps this variation in the failure rates is due to the choices of sensors being used over the different decades. Or, if it is the same unit, such as a DP cell, then the choice of materials can be a factor. Also, the feedback from operating experiences has given designers insights that have led them to reduce or dampen vibration, positioning units to reduce scale buildup, add shielding for electromagnetic interference (EMI) protection, and to mitigate or avoid other potential failure mechanisms that have caused problems for pressure sensors.

5.5 Other sensor types

Boyes and Jean (1994) discuss several methods of non-invasive level measurement, such as radar and microwave reflection from the top of the liquid, gamma radiation continuous level measurement, and others. The non-invasive techniques are thought to be more reliable than other traditional sensors since they are not contaminated with particulates or process liquids and can be kept away from the liquid pressure and temperature. Another relatively new type of sensor in use only since the 1980's is the fiber optic sensor (Horn, 1988). This sensor offers some advantages over electrical based sensors, such as small size and weight, explosion-proof, immunity to electro-magnetic interference, secure data transmission, and others (Krohn, 1992). Some means for detecting liquid level by fiber optics are to use fiber optics on the DP cell, and to use photoelectric switches. Fiber optic pressure sensors are described in Chapter 3.

5.6 Conclusions

In this chapter, level sensors were examined. The two most frequently used kinds of level sensor, the float sensor and the differential pressure level sensor, were discussed. Failure modes were examined and failure rate data from the literature was given. Repair times are more difficult to find in the literature, but some are cited. Other sensor types, such as microwave and fiber optic sensors, are discussed at the end of the chapter. It was noted that failure rates from the 1990's varied considerably from the earlier data, showing that continued data collection and analysis is useful to ascribe accurate values to components and to promote operating experience feedback to designers.

Chapter 5 References

Alber et al., 1995.	T. G. Alber et al., Idaho Chemical Processing Plant Failure Rate Database, INEL-95/0422, Idaho National Engineering Laboratory, August 1995.
Anyakora et al., 1971.	S. N. Anyakora et al., "Some Data on the Reliability of Instruments in the Chemical Plant Environment," The Chemical Engineer, No. 255, November 1971, pages 396-402.
Barron, 1985.	R. F. Barron, Cryogenic Systems, second edition, Oxford University Press, ISBN 0-19-503567-4, 1985, chapter 6.
Blanton and Eide, 1995.	C. H. Blanton and S. A. Eide, Savannah River Generic Database Development, WSRC-TR-93-262, Westinghouse Savannah River Company, 1995.
Boyes and Jean, 1994.	W. Boyes and R. Jean, "Look at Your Process Non-invasively," Chemical Engineering, 101, June 1994, pages 84-88.
Bryan, 1982.	J. L. Bryan, Fire Suppression and Detection Systems, second edition, MacMillan Publishing Company, New York, ISBN 0-02-471300-7, 1982, chapter 8.
Green, 1983.	A. E. Green, Safety Systems Reliability, John Wiley & Sons Publishers, Chichester, ISBN 0-471-90144-X, 1983, page 101.
Herceg, 1996.	E. E. Herceg, "An LVDT Primer," Sensors, 13, June 1996, pages 27-30.
Horn, 1988.	D. Horn, "Optical Fibers, Optimal Sensors," Mechanical Engineering, 110, September 1988, pages 84-88.
Johnson, 1993.	C. Johnson, Process Control Instrumentation Technology, fourth edition, Prentice Hall Publishers, Englewood Cliffs, NJ, ISBN 0-13-721150-3, 1993, chapter 5.
Krohn, 1992.	D. A. Krohn, Fiber Optic Sensors, Fundamentals and Applications, second edition, Instrument Society of America, Research Triangle Park, NC, ISBN 0-55617-010-6, 1992, chapters 1, 7.

Lees, 1973. F. P. Lees, "Some Data on the Failure Modes of Instruments on the Chemical Plant Environment," The Chemical Engineer, No. 277, September 1973, pages 418-421.

Lees, 1976. F. P. Lees, "The Reliability of Instrumentation," Chemistry and Industry, Number 5, March 6, 1976, pages 195-205.

Melvin and Maxwell, 1974. J. G. Melvin and R. B. Maxwell, Reliability and Maintainability Manual, Process Systems, AECL-4607, Atomic Energy of Canada Limited, January 1974.

Norton, 1982. H. N. Norton, Sensor and Analyzer Handbook, Prentice Hall publishers, ISBN 0-13-806760-0, 1982, chapter 2.

OREDA, 1992. OREDA, Offshore Reliability Data Handbook, second edition, distributed by DNV Technica, Hovik, Norway, ISBN 82-515-0188-1, 1992, pages 434-437.

RAC, 1991. Reliability Analysis Center, Failure Mode/Mechanism Distributions, 1991, FMD-91, Rome Air Development Center, Griffiss Air Force Base, NY, 1991.

Reason, 1984. J. Reason, "Level measurement: Wide variety of sensors fit many control needs," Power, 128, May 1984, pages 97-99.

Weiss, 1993. J. Weiss, "More Accurate Sensors Needed to Reduce Uncertainty," Power Engineering, 97, June 1993, pages 29-32.

Wheeler and Ganji, 1996. A. J. Wheeler and A. R. Ganji, Introduction to Engineering Experimentation, Prentice Hall Publishers, Englewood Cliffs, NJ, ISBN 0-13-337411-4, 1996, chapter 10.

6. Water Quality Sensors

6.1 Introduction

The sensors already discussed in previous chapters usually have process safety aspects, and they can also have personnel safety aspects. Water quality sensors are important when water is used as a coolant. Water coolant must be very pure to prevent corrosion and fouling of heat transfer surfaces (Cohen, 1980). If steam is generated from the water coolant, then the water should be pure to avoid contaminating the steam (Baumeister, 1978). The chapter discusses two of the most basic sensors for water quality, the pH and electrical conductivity sensors. The term pH refers to the negative logarithm of the hydrogen ion concentration (p is the mathematical symbol for the logarithm and H is the chemical symbol for hydrogen), and can be thought of as the 'potential of the hydrogen' in the liquid (Kinnard, 1956). When the pH is 0 to 7, the liquid is acidic, and more acidic the closer to zero. At a pH of 7 exactly, the liquid is neutral (as many hydrogen ions as hydroxyl ions, at 1E-07 ion moles/liter at 25°C). With a pH of 7 to 14, the liquid is alkaline (basic), with a stronger alkaline being closer to 14. The basic pH sensor measures the hydrogen ion concentration. The other sensor is the electrical conductivity sensor. This sensor uses plates with a potential difference across them, the plates are immersed in the liquid to be tested. If the liquid has many impurities, then a process of electrolytic conduction (Norton, 1982) causes electrical current to flow between the voltage potential between the plates. Typically, water has many salts dissolved within it, namely the magnesium and calcium salts that carry Ca^{2+} and Mg^{2+} ions. These ion-containing salts are the chief cause of scale buildup in water piping (El-Wakil, 1984). The conductivity sensor measures the amount of all ions in a water sample; the pH sensor specifically measures the amount of hydrogen ions.

6.2 Description of sensors

pH sensors. The basic sensor for pH compares the pH of a known solution to the process liquid. Two electrodes are used, both housed in glass tubes. Figure 6-1 shows the basic sensor. The reference electrode is immersed in the known solution, usually potassium chloride. Then the reference electrode glass tube is immersed in the process liquid. This reference electrode maintains a constant voltage, and the varying hydrogen ion concentration on the sensing or pH electrode causes a change in the voltage of that electrode. Monitoring the voltage difference shows the amount of hydrogen ion concentration in the process liquid. The reference electrode is made of either silver wire coated with silver chloride, or a platinum wire coated with calomel (mercuous chloride) (Kinnard, 1956; Norton, 1982). The reference electrode is designed to very slowly leak the known solution (the potassium chloride) out of its glass tube into the liquid to be measured. The other electrode, the sensing electrode (also called the glass electrode or pH electrode), has a varying voltage with respect to the hydrogen ion concentration. The glass tube has a membrane that allows hydrogen ions to migrate into the tube from the process liquid being measured. Voltage on the glass tube changes with the concentration of hydrogen ions in the liquid it is immersed in. Since that voltage changes, the voltage on the electrode wire also changes (in the millivolts region). The wire electrode in the tube is made of silver. The slight leakage of potassium chloride from the reference electrode is also needed to complete the voltage circuit between the glass electrode and the reference electrode (Omega, 1989). Without the potassium chloride migration, there is no measurement.

These sensors can be mounted in a piping system, or they can be used in a laboratory (with periodic sampling from instrument lines carried into the lab). Some applications require frequent or even continuous monitoring, so the mounted units are often chosen.

As an illustrative example of pH values, fission reactors usually operate with primary coolant at a pH of about 6.8 or slightly higher. They can operate with a higher pH of 7.4 to reduce crud deposits in the system (Shah and MacDonald, 1993).

Conductivity sensors. This sensor is quite simple. The sensor element is two parallel plates or other shaped panels. The plates are held at a constant distance apart (such as 1 cm) and are sometimes referred to as a conductance cell when the plates and gap form a fixed volume. These plates are immersed in the process liquid. When ions are present, these will migrate to one of the plates when a voltage difference is placed across the gap between the two plates. An alternating current voltage is used to avoid localized distortions of the ion concentration in the liquid. Even in a flowing liquid, there will be a current reading across the two plates. This electrical conductivity is measured in either siemens or mhos (a mho is the reciprocal of resistance, which is measured in ohms). Since hydrogen ions are generally more mobile than the ions from salts, comparing the pH and conductivity values will give a good indication of the hardness of the water or process liquid being measured.

A thermistor (see Chapter 2) is attached to one of the plates. It is used to compensate the current reading since there is higher ion mobility at higher temperatures. The high ion mobility can lead to falsely high readings. The plates are often coated with a platinum clad for its catalyst effect and to reduce polarization of ions. The plates are wired in a Wheatstone bridge fashion (Norton, 1982).

The conductivity sensor can operate with other configurations besides the two plates. Two parallel wires or two annular electrodes are often used. Figure 6-2 shows a diagram of a two wire conductivity probe. The electrode wires can be made of nickel, carbon, stainless steel, or ferrous-nickel alloys (Norton, 1982). Past sensor used direct current, but alternating current is now used to set up the voltage difference for making measurements, so that polarity is reversed before electrolysis becomes significant. Alternating current is used to also reduce the polarization effect (Anderson, 1972).

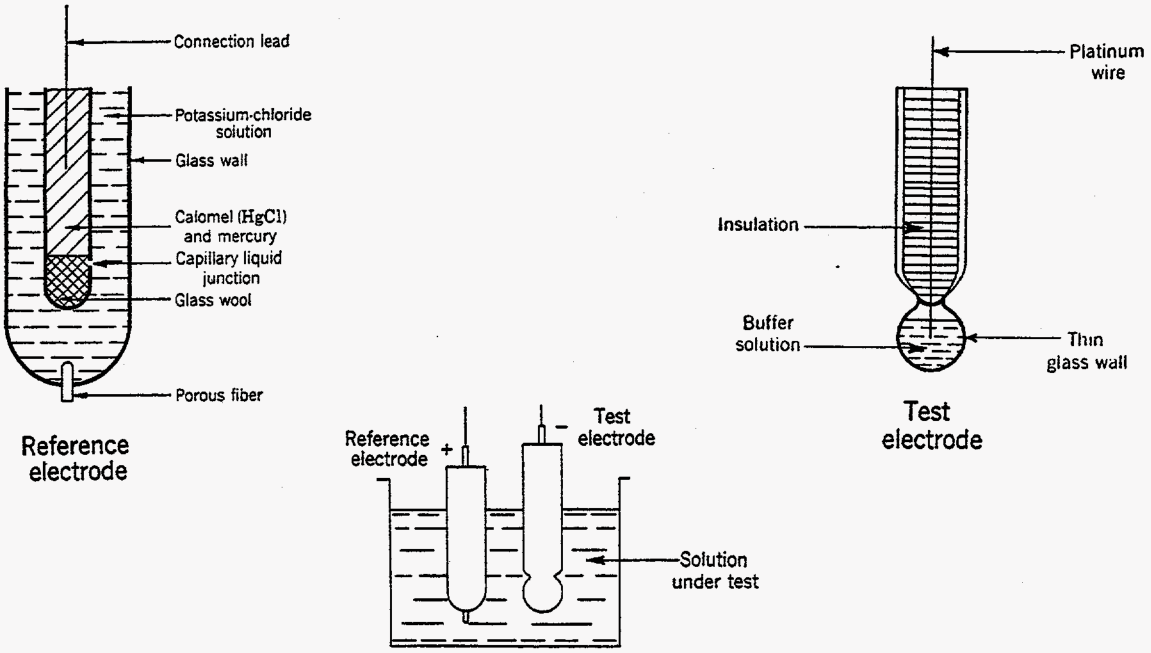


Figure 6-1. A pH sensor (from Kinnard, 1956, pages 546-548.)

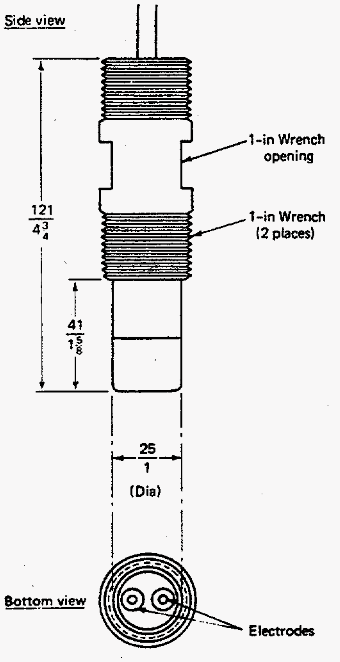


Figure 6-2. A conductivity sensor (from Norton, 1982, page 499).

An interesting use of a conductivity probe is to monitor the annulus of double-walled piping (Ziu, 1995). If water intrudes into a dry annulus, then a current signal will be sent from the conductivity probe. Therefore, a conductivity probe can be a leakage monitor.

6.3 Failure Modes and Effects Analysis

From the description of the pH sensor, several possible failure modes are noted. Glass can be brittle, therefore the sensor probe can crack or break. Electrodes can have material flaws that could lead to breakage (open circuit) or insulation flaws that could lead to short circuits. The glass membrane could become coated or otherwise plug up, leaving a stagnant sample of water or other process liquid to compare to the reference liquid. Lees (1973) gives several failures of pH analyzers. These failures are water in electrode head, glass broken, electrode damp or wet, electrode not covered, and loose connection on electrode.

The conductivity sensor would have problems of electrical wiring, such as open circuit, short circuit, and plugging (buildup) that reduces ion contact with the electrodes. Norton (1982) states that mass increases of ions on the voltage collectors (the plates) will cause non-linearities between the conductivity and ion concentration. This non-linearity is considered to be the drift of a conductivity sensor.

Table 6-1 gives the FMEA for a pH sensor. Table 6-2 gives the FMEA for a conductivity sensor. The list of failure modes is longer than many of the other sensors discussed in this report, since the pH sensor is a more complicated piece of equipment.

6.4 Failure Rate Data

Failure rates were described in Chapters 2 and 3. The results of a literature review to locate sources of finished failure rate data for water quality are presented here. Reports on data analyses already performed on pH and conductivity sensors were sought since these are well regarded (Green, 1983). A few reports were found that gave suggested failure rates, some based on operations experience and some based on reference data.

pH sensors. Lees (1976) gave a failure rate for pH sensors as 5.88/year, without any confidence interval. Assuming full time operation (8760 hours/year) this is a failure rate of 6.7E-04/hour. However, these units are not always kept in the process piping. Sometimes they are only used in labs (water samples are drawn and carried to the lab for analysis) or are fed by a regularly opened instrument tap line from the process piping. In either case, these instruments may not run continuously, but the failure rate is still rather high. Omega (1989) discusses some of the past failure mechanisms for pH sensors - dry out of the reference electrode, wiring faults and failure to keep the pH electrode immersed. Blanton and Eide (1993) give a pH sensor failure rate of 5E-07/hour for failure to operate, with an upper bound of 2.5E-06/hour. The discrepancy in failure rates could be due to improvements in the pH sensor. Early units had to be kept immersed in liquid to maintain their functionality (the pH electrode responded best when there was a hydrated layer on the glass surface [Omega ,1989]). If the units were not immersed, then they could fail to function quite easily. Otherwise, material improvements in glass and wire are credited for the decrease in the failure rate between the values presented here (more than a factor of 250 difference in failure rates). The Blanton and Eide value should be used unless the analyst has reason to believe a higher failure rate is more appropriate for the specific application.

Conductivity sensors. Lees (1976) gave a value of 16.70/year for an overall failure rate for electrical conductivity meters. Using 8760 hours/year, this gives 1.9E-03/hour. This is a very high failure rate, the highest found thus far in this review of published failure rates. Lees did not explain the high value, but there is speculation that the plates become covered with foreign material or plateout of ion material, thus reducing their effectiveness. Better choice of collectors and improved alternating current operations will decrease the build up of material on the collectors. Blanton and Eide (1993) gave a general failure rate of 1E-06/hour for a sensor failing to operate, with an upper bound of 3E-06/hour. The IEEE (1984) gave a water conductivity sensor failure rate of 5.6E-07/hour for all failure modes. No upper bound was given, but an average repair time of 1.2 hours was cited. While the Blanton and Eide value is only a general value, it is within a factor of 2 of the IEEE value. To be slightly conservative with the failure rate, the Blanton and Eide value is recommended for use with conductivity sensors.

6.5 Conclusions

In this chapter, water quality sensors were discussed. The types discussed were pH and electrical conductivity sensors to determine the hydrogen ion concentration and the total ion concentration in the liquid. Basic failure modes were listed and failure rate data from the literature was given. Repair times are more difficult to find in the literature, but some are cited. It was noted that failure rates from the 1980's and 1990's varied considerably from the earlier data, showing that continued data collection and analysis is useful to ascribe accurate values to components and to promote operating experience feedback to designers.

Table 6-1. FMEA for a pH sensor.

Function	**Failure modes and causes**	**Local effects**	**Failure detection method**	**Compensating provisions**	**Remarks**
pH sensor measures hydrogen ion concen-tration in a liquid sample	reading is incorrect, liquid sample contaminated at collection point or in container	there may be no local effects, this failure mode applies only to units in lab rooms	trend of readings over time shows anomalous reading	frequent maintenance keeps sample lines clean	good practices and cleanliness will give accurate readings
	sensing lines plug up with particulates from the process liquid	the pH sensor will not have a sample of liquid to read	inability to draw a liquid sample will be obvious to operators	frequent maintenance keeps sample lines clean	good practices and cleanliness will give accurate readings
	incorrect reading, reference electrode glass contaminated by scale or other material	reference voltage is incorrect	since the reference voltage should be constant, it can be compared to recent readings	voltage changes can be monitored and noted	
	no reading, reference electrode does not release reference liquid (KCl) into process fluid, either from scale or plugging in reference electrode permeable junction	no reading	The system being unresponsive should give an indication of the problem	reference electrode can be refilled or repaired to release solution to the process stream	see Omega (1989) Another possible failure cause would be depletion of potassium chloride inventory in reference electrode glass casing
	reference electrode wire open circuit, due to vibration, corrosion, material flaw	no reading	the system being unresponsive should give an indication of the problem	reference electrode can be replaced, choose an electrode more robust for the environment	
	pH electrode wire open circuit, due to vibration, corrosion, material flaw	no reading	the system being unresponsive should give an indication of the problem	pH electrode can be replaced, choose an electrode more robust for the environment	
	pH electrode wire coated, due to foreign material intrusion	no reading or false reading	only comparison to past readings will alert operators to false readings	logs or records should be kept for comparing the readings from various system operating modes	

Table 6-1. Continued

Function	Failure modes and causes	Local effects	Failure detection method	Compensating provisions	Remarks
	pH electrode permeable glass membrane coated, due to foreign material	false reading based on what is trapped within glass electrode	only comparison to past readings will alert operators to drift in readings	logs or records should be kept for comparing the readings from various system operating modes	
	pH electrode leakage to the plant environment, due to threaded fitting leak	leakage may not affect reading	operator walkdowns will detect leakage, or monitoring of system inventory will detect leakage	good practices in installation will avert leaks, and frequent walkdown inspections will find leaks in early stages	
	open circuit in either electrode, caused by air bubble entrapment	no reading when there is no current flow	the system being unresponsive should give an indication of the problem	good maintenance practices should preclude air admission into glass tube around electrode	dry out and subsequent refill could lead to air bubbles in the glass tube around the electrode
	open circuit in either electrode, caused by chemical attack of incorrect cleaning bath	sensor is inoperative	post-maintenance testing will reveal faulty sensor	clear maintenance procedures will preclude soaking in incorrect chemical bath	
	glass casing cracking for either electrode, due to abrasion of process fluid, impact from foreign object in fluid stream, thermal stresses, or other causes	no reading when current is disrupted by fluid leakage	the system being unresponsive should give an indication of the problem	replace glass cover, choose a glass more robust for the environment	

Table 6-2. FMEA for a conductivity sensor

Function	Failure modes and causes	Local effects	Failure detection method	Compensating provisions	Remarks
Electrical conduc-tivity sensor measures ion concen-tration in liquid	fails to conduct ions between plates, due to collector plate fouling or scale buildup	no signal out, or reduced signal	alarm on loss of signal	use multiple units, or specify frequent cleaning	this is a hazard for this type of sensor, if the water has high particulates, this sensor is needed but it will also stop working
	fails to conduct ions between plates, due to collector plate ion buildup	no signal out, or reduced signal	alarm on loss of signal; operators must notice a reduced signal as deviating more than expected	use multiple units, or specify frequent cleaning	alternating current is supposed to greatly reduce ion buildup on collector plates
	collector plate loss of continuity, due to material degradation (corrosion, abrasion, or cracking)	no signal out	alarm on loss of signal	specify frequent inspections, choice of materials to withstand environment	
	wiring open circuit, from wire flaw, impact or abrasion of solid particles in the fluid system	no signal out	alarm on loss of signal	specify frequent inspections	
	wiring short circuit, from insulation flaw	erratic signal out from sensor	operators should notice erratic signal	frequent testing of sensor	

Chapter 6 References

Anderson, 1972.	N. A. Anderson, Instrumentation for Process Measurement and Control, second edition, Chilton Company, Philadelphia, PA, 1972, Chapter 4.
Angrist, 1976.	S. W. Angrist, Direct Energy Conversion, third edition, Allyn and Bacon, Inc., Boston, MA, ISBN 0-205-05581-8, 1976, pages 130-136.
Baumeister, 1978.	T. A. Baumeister, editor-in-chief, Marks' Standard Handbook for Mechanical Engineers, eighth edition, McGraw-Hill Book Company, New York, ISBN 0-07-004123-7, 1978, page 9-31.
Blanton and Eide, 1995.	C. H. Blanton and S. A. Eide, Savannah River Generic Database Development, WSRC-TR-93-262, Westinghouse Savannah River Company, 1995.
Cohen, 1980.	P. Cohen, Water Coolant Technology of Power Reactors, American Nuclear Society, ISBN 0-84948-020-0, 1980, chapter 3.
Considine, 1985.	D. M. Considine, editor in chief, Process Instruments and Controls Handbook, third edition, McGraw-Hill Book Company, New York, ISBN 0-07-012436-1, 1985, chapter 6.
Dexter and Perkins, 1982.	A. H. Dexter and W. C. Perkins, Component Failure-Rate Data with Potential Applicability to a Nuclear Fuel Reprocessing Plant, DP-1633, Savannah River Laboratory, July 1982.
El-Wakil, 1984.	M. M. El-Wakil, Powerplant Technology, McGraw Hill Book Company, New York, ISBN 0-07-019288-X, 1984, pages 250-254.
Green, 1983.	A. E. Green, Safety Systems Reliability, John Wiley & Sons Publishers, Chichester, ISBN 0-471-90144-X, 1983, page 101.
IEEE, 1984.	IEEE guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations, IEEE Std 500-1984, US Institute of Electrical and Electronics Engineers, New York, December 1983, page 626.
Kinnard, 1956.	I. F. Kinnard, Applied Electrical Measurements, John Wiley & Sons, New York, 1956, pages 288-290.

Norton, 1982. H. N. Norton, Sensor and Analyzer Handbook, Prentice Hall publishers, Englewood Cliffs, NJ, ISBN 0-13-806760-0, 1982, chapter 8.

Omega, 1989. The pH and Conductivity Measurement Handbook and Encyclopedia, volume 27, Omega Engineering, Inc., Stamford, CT, 1989, section Z.

RAC, 1991. Reliability Analysis Center, Failure Mode/Mechanism Distributions, 1991, FMD-91, Rome Air Development Center, Griffiss Air Force Base, NY, 1991.

Shah and MacDonald, 1993. V. N. Shah and P. E. MacDonald, editors, Aging and Life Extension of Major Light Water Reactor Components, Elsevier Publishers, Amsterdam, ISBN 0-444-89448-9, 1993, page 261.

Ziu, 1995. C. G. Ziu, Handbook of Double Containment Piping Systems, McGraw-Hill Book Company, New York, ISBN 0-07-073012-1, 1995, chapter 15.

7. Personnel Safety Sensors

7.1 Introduction

The sensors already discussed in previous chapters can have personnel safety applications. For example, pressure indication for piping and tanks is important to the personnel working around the piping system, as well as monitoring rooms to actuate explosion suppression systems in process plants. Temperature measurements for habitable rooms or zones have an important safety function to indicate when workers could encounter heat stress. This chapter discusses the reliability of other types of sensors that monitor the human environment to provide safety functions. These functions can be protection from ionizing radiation or radioactive contamination, monitoring the volume percentage of oxygen, detecting smoke from fires, detecting toxic gases, detecting combustible gases, sensing high humidity, noise, and electromagnetic radiation. There are more personnel protective sensors that just these, for example, proximity sensors that can shut down automated equipment if people enter into equipment exclusion areas (see Graham, 1991), air sampling to detect metal or other aerosols, and interlock systems to de-energize equipment if rooms are entered or access panels opened while equipment is in operation. This chapter will focus on the sensors first listed: ionizing radiation, oxygen, gas, humidity, noise, and electromagnetic radiation. A good reference for descriptions of many kinds of personnel protection instruments is Herig (1989).

7.2 Description of sensors

Radiation sensors. There are a variety of radiation sensors for personnel protection. One of the most widespread methods of protection is to monitor the indoor atmospheric air to determine if there are airborne radioactive materials (aerosols, radioactive gases) in the breathing air. These monitors are called continuous air monitors, or cam's. The most basic monitor uses the gas ionization principle to detect radiation. Incoming ionizing radiation (alpha, beta, or gamma radiation) will cause ionization in the gas that is housed in the detector chamber (Tsoulfanidis, 1983). The ion pairs created in this gas will migrate to opposite sides of the detector chamber since a voltage potential is set up across the chamber. For that reason, the chamber is called an ionization chamber. The continuous air monitor requires a metered air pump for a constant volume of air inflow, the power supply for the ionization chamber, the electronics to register the chamber output current from the collected ions, setpoint comparison and alarm circuitry, and many chambers are also fitted with local alarms (i.e., an audible alarm such as a horn or bell, and a visual alarm such as a flashing light).

Depending on the facility, there can also be criticality monitors to detect neutrons from the criticality of fissile materials. These are not a concern for the majority of energy technology experiments, such as fusion technology. Nonetheless, Alber et al. (1995) give some data on criticality monitors.

Other radiation monitors detect radioactive contamination on surfaces, or on people's clothing. Usually hand-held meters (small counters using the gas ionization method) are used for surface surveys, or swipe samples on small cloths are taken by health physicists and measured in a scintillation counter. The small cloths are immersed in a liquid inside small vials. The liquid, called 'scintillation cocktail' and usually made of a benzene compound, will fluoresce when irradiated. The light given off is very small, and is amplified in a photomultiplier tube to be counted as a radioactive decay from material on the cloth. Scintillation counters are sensitive to low energy radiation, such as the low energy beta particle given off by tritium decay.

Personnel at nuclear facilities survey themselves for radioactive contamination by passing through gas ionization counters called portal monitors or by standing in front of large area detectors. These names are given to the monitors since the first is shaped like a doorway or portal that a person walks through, and the second since the set of monitoring window openings to the gas chambers are large by detector standards (on the order of 0.1 m^2 each). Personnel monitors for detecting contaminated clothing are usually gas ionization counters.

An important aspect of using radiation survey meters is the environment that they operate in. Liu et al. (1993) determined that magnetic fields of up to 10 milliTesla will not affect some meters, but these magnetic fields can cause some meters to read low by a factor of 10. This is an important effect to consider for magnetic fusion facilities and particle accelerator facilities.

Oxygen sensors. Gas analyzers are used to monitor gas concentrations in the atmosphere. Oxygen monitors are used in areas where there is the possibility of another gas displacing the normal air concentration of oxygen, such as cryogenic production facilities, liquefied petroleum (LP) gas distribution centers, etc. Oxygen can be sensed using an electrometric method (Norton, 1982). The sensing element is a zirconium-dioxide tube, shaped like a test tube. Electrodes are fixed to the inside and outside of the tube, and the tube is electrically heated. The atmospheric gas is flowed over the outside of the tube, and a specific concentration of oxygen is contained inside the tube. At high temperatures, over 400°C, the side of the tube having a higher oxygen concentration (higher oxygen partial pressure) will become the better electrolytic conductor (the anode) because of the higher number of oxygen ions present. A voltage will be produced according to the Nernst equation, voltage = (constant)(temperature of the tube)(log [oxygen reference pressure/oxygen pressure in atmospheric gas]). The output voltage is converted to read as parts per million of oxygen in the atmospheric gas (Norton, 1982). Considine (1985) states that the response time is typically 3 seconds, and the output signal is in the milliVolt region.

Parry et al. (1993) and Herig (1989) also discuss the use of electrochemical cells for oxygen sensing. The electrochemical cell (a fuel cell) reacts oxygen with hydrogen to produce electricity and water. The amount of electricity produced is proportional to the oxygen concentration. Electrodes are coated with a catalyst (perhaps nickel, silver, or platinum) and immersed in an electrolyte (such as aqueous potassium hydroxide). Air flows over the catalyst, reacting oxygen with an inflow of hydrogen (fuel) gas, with reactions being induced by the catalyst. The cell runs at room temperatures as opposed to the heated methods described above (Considine, 1985). Another type of oxygen sensor that is used by industrial hygienists is the galvanic cell sensor (NSC, 1988; Considine, 1985). The oxygen makes this cell produce an electrical current in proportion to the partial pressure of oxygen present.

Oxygen sensor placement is important to give timely notification of a possible problem. For example, if dealing with liquid helium, any escape of this cryogen will result in a gas cloud at the ceiling; even though the helium is very cold its natural buoyancy still causes it to rise, pool at the ceiling, and then move horizontally down back into the room as it expands upon warming (Parry et al., 1993; Blyukher, 1995). Oxygen sensors 60 m apart on the ceiling could be adequate to protect occupants for helium releases in large rooms. Cryogenic nitrogen behaves the opposite from helium. Nitrogen is about the same molecular weight as air, so its cold temperature causes it to sink to the floor and then rise and mix with the atmospheric air as it warms. Four sensors near the floor, and four mid way up the room walls were used to protect one room housing a cryogenic system for possible nitrogen leaks (Blyukher, 1995), and the monitors were set to alarm at 19.5% by volume of oxygen (see NSC, 1992). Parry et al. (1993) discussed that the lifetime of the electrochemical cells in oxygen sensors is 9 to 24 months, and that the sensors are wired for two-out-of-three voting logic. A total of 21 sensors was used in a magnet testing lab. The setpoint value of 19.5% is also cited in the Code of Federal Regulations for oxygen deficient atmospheres. The normal volume concentration of oxygen in air at atmospheric pressure and sea level is approximately 20.95%.

The obvious failure modes of these instruments are that they have a finite lifetime due to the electrolytic effect by which they sense oxygen, the sensing tube can become fouled with foreign material deposits to yield false readings, electrodes can fail (open circuit, short circuit), the resistance heater can fail (also by open circuit or short circuit), or the converter circuitry can fail. Another issue with these detectors is that they can only sample air in local areas, so if there is a release of an oxygen-displacing gas, it will take time to register with the sensor. Multiple sensors are important to reduce this time to notification. Miller and Mazur (1984) note that instrument drift with oxygen monitors can be over 1% oxygen concentration, so they choose to set the alarm level at 1% higher than the hazardous level. At FermiLab, they cited 18% as the alarm level. Miller and Mazur (1984) also noted that personal oxygen monitors (chosen for their warning of oxygen deficiency in proximity to the worker, high reliability, and low cost) have failure probabilities less than 1E-04 [assume per demand to alert worker], but the worker error-of-omission rate in failing to don the monitor or turn the monitor on was 1E-02 per oxygen deficiency event. In their analysis, Miller and Mazur (1984) neglected the monitor failure rate in favor of the much larger human error rate of failure to use the personal monitor.

Toxic gas detectors. These sensors can also operate in much the same way as the oxygen sensors (Norton, 1982). Herig (1989) describes many kinds of these sensors, both hand held and wall mounted units that use thermal catalyst methods, infrared scanning methods, and others. Thin metal film-oxide materials are used because their electrical resistance properties will change when gas molecules diffuse into them, such as the tin-oxide sensor for nitrogen oxides. A platinum-activated tungsten-oxide sensor measures hydrogen concentrations (Norton, 1982). Other materials are used as catalysts to sense sulfur oxides, hydrogen sulfide, and other contaminant gases. Scanning Herig (1989) shows that most units have response times in the seconds range, nearly all being under one minute. The detector catalyst may only last on the order of 6 months before requiring replacement. Calibration intervals vary from one month up to calibration only at the time of catalyst changeout. The possible failure modes for these sensors are the same as those for the oxygen monitors.

Another means to detect toxic gases is to use the wheatstone bridge, with one of the wires covered in a catalyst that will speed up reactions of the gas with oxygen in air. Air contaminated with the gas to be analyzed is moved across the catalyst coated wire. Heat from the reaction will be noted in the resistance change of the wire in the wheatstone bridge. The resistance change is proportional to the concentration of gas in the air. This method is discussed below in the section on combustible gas detection.

There are other reasons to sample gases besides personnel protection. For example, one application for sensing toxic gases is to give an alert of combustion. Sensing carbon monoxide (White, 1993) can alert fossil fueled power plant operators of possible fires in the coal being processed for combustion in the boiler. Since carbon monoxide is an intermediate molecule formed in the combustion process, its presence signifies combustion occurring. These detectors compare the content of carbon monoxide in inlet and outlet air for coal pulverizers or other coal handling equipment. The early units experienced maintenance problems, such as clogged probes and filters (from coal dust) and filter degradation. Newer air collection probes are screened and filtered more highly to reduce plugging and abrasion from coal dust.

Combustible gas sensors. Sensors that detect hydrocarbon gases typically use a heat of combustion approach. A sample of the atmosphere is drawn into a chamber where a catalyst resides. Catalyst materials are chosen based on the combustible gas to be measured. The catalyst reacts a small amount of the combustible gas that has been ingested with the inlet atmospheric air, and the temperature increase of the catalyst due to the combustion heat is measured against the inlet air temperature. Usually, a platinum wire resistance temperature detector is used for this temperature measurement (see Chapter 2). The temperature change is proportional to the concentration of the combustibles in the inlet gas stream. Many of these sensors are calibrated to report the percentage relative to the lower explosive limit or the lower flammability limit of the combustible gas to be measured

(Norton, 1982; Herig, 1989). There is design guidance for combustible gas sensors (ISA, 1987). The failure modes for these sensors are the same as those for oxygen sensors.

Humidity sensors. Humidity sensors can have safety implications in facilities that require low moisture, such as chemical handling facilities. Humidity can also have a direct effect on personnel when they are working at very demanding physical labor, or in high temperatures. The human body uses the heat transfer of evaporating perspiration to regulate temperature when exerting itself. When the air is very humid, it is more difficult for the perspiration to evaporate into the air. Relative humidity above 60% makes perspiration a poor cooling mechanism, and relative humidity over 75% nullifies any cooling effect (Vincoli, 1995). It is important to measure humidity in facilities that are not climate controlled so that personnel are not exposed to undue heat stress.

Humidity sensors are based on two principles. The first is using a hygroscopic, or moisture absorbent, material such as lithium chloride and putting a small electrical current through the material. When moisture is absorbed by the lithium chloride, a high resistance circuit is created and the material heats up by resistance heating until an equilibrium is created. The temperature of the lithium chloride is measured and is interpreted to be the dew point temperature (Haines and Wilson, 1994). The dew point temperature is the temperature where moisture will start to condense out of the air. Using the dew point and comparing to the ambient condition will give the relative humidity, that is, the existing humidity compared to saturated air humidity at the ambient temperature. The lithium chloride sensor has to be cleaned at frequent intervals because dirt in the system will diminish its accuracy.

The more accurate chilled-mirror sensor operates by using a thermoelectric cooler (see Angrist, 1976, for a description of the Thomson effect) on a small glass mirror. Atmospheric air is allowed to contact the mirror, and as the mirror reaches the dew point, moisture begins to condense on the mirror. Light shining on the mirror is not reflected well through the condensation, and an optical balance notes this change. The temperature of the thermoelectric cooler is taken to be the dew point temperature when the optical balance first changes. This system is very accurate, to less than ± 1°F, which allows a relative humidity calculation to within ± 2 to 3%. This device can be mounted in a ventilation duct or in a room. It requires little maintenance, simply cleaning the mirror occasionally (Haines and Wilson, 1994; Wiederhold, 1996).

These sensors can be susceptible to dirt intrusion, and any heavy hydrocarbon will foul the mirror and distort any reading the optics attempt to yield. Most foreign materials will cause diminished accuracy. When using the hygroscopic material sensors, the sensor will have a finite lifetime as the sensing element becomes saturated with water vapor. It may be able to undergo regeneration, but there will be hysterisis effects to where the sensor needs recalibration more and more frequently.

Noise sensors. These sensors detect the levels of sound in a building or at a job site. Noise can be important because of its debilitating effect on worker hearing. The compressors at an ammonia liquefaction plant have decibel (dB) readings in the 100 range (Cadwallader, 1992), which is not as loud as a turbofan jet engine spooling up for takeoff. Other plant equipment - large pumps, fans and blowers, and other items - can also make an environment much noisier than normal conversation range of 60 to 70 dB.

Sound level meters are composed of a microphone (probably piezoelectric) to detect sound pressure variations, an amplifier to increase the microphone output gain, an electrical network to vary the scale the meter is reading, and a meter circuit (NSC, 1988). The typical measurement range is 40 to 140 dB. The sensors are usually hand held, battery-operated units for ease in taking multiple readings throughout a room or work area.

Failure modes could be battery depletion, microphone failure to function, electrical faults (short or open circuit), moisture intrusion, or other failures.

Magnetic field sensors. For fusion experiments and particle accelerators, there can be large magnetic fields (i.e., in the milliTesla range) in the facility some distance away from the magnets. These fields must be measured to ensure that workers are not exposed to high fields in excess of suggested guidelines (DOE, 1996). Most magnetic field sensors for high fields use the Hall effect to sense the field strength (Kinnard, 1956). The Hall effect is a phenomenon where a magnetic field passing through certain materials will alter a small, milliampere electrical current flowing through the material. For example, Germanium is a material that responds to the magnetic field by altering current flow to generate a small voltage (millivolts region) between two leads. Hall probe accuracies have been noted to be within 0.1%. Failure modes could be short or open circuit, and thermal or vibration degradations of the magnetic field-sensitive material.

7.3 Failure Rate Data

A failure rate is defined as the average probability of failure divided by unit time. Analysts regard field failure rate data (data collected on operating units in some application) as the most accurate source of data (Green, 1983) since units operating in the field are subjected to the operating environment - they are exposed to all factors of the environment simultaneously. These factors can include heat, cold, vibration, foreign material intrusion, corrosion, poor maintenance, wear (i.e., maintainers or operators using the sensor as a hand hold or foot hold, etc.) and other causes. Often, these causes can aggravate each other. For example, heat and corrosion, or vibration and foreign material intrusion can aggravate each other. Literature was reviewed to locate sources of finished failure rate data for flow sensors. Reports on data analyses already performed on flow sensors were sought since these are well regarded, and there are raw data on only a few sensors readily available for statistical data analysis. Several reports were found that gave suggested failure rates, some based on operations experience and some based on reference data.

Katzel (1996) suggests that a routine time interval for sensor checks should be monthly - to replenish any consumable materials and clean the sensor so it is free of obstructions.

Radiation sensors. Blanton and Eide (1993) give a radiation sensor failure rate for failure to operate as 5E-06/hour, with an upper bound of 2.5E-05/hour. The sensor is assumed to be a typical gas counter. Earlier work by Dexter and Perkins (1982) gave a failure rate of 1.39E-05/hour for a gas counter, without giving an upper bound. Alber et al. (1995) gave a radiation meter drift failure rate of 2.3E-05/hour (with an upper bound of 1.2E-04/hour) and a failure to operate failure rate of 3.4E-05/hour (with an upper bound of 7.4E-05/hour). A specialized tritium monitor was analyzed for its reliability by Cadwallader et al. (1991) and found to have failure rates of 2.2E-06/hour for high readings (a 95% upper bound failure rate of 1E-05/hour) and 2.2E-06/hour for reading low (a 95% upper bound of 1E-05/hour). Each of the tritium monitors is out of service for recalibration about 672 hours each year.

These failure rates do not account for loss of electrical power to the radiation sensors. In general, it would appear that the proper order of magnitude for a radiation sensor failure rate is 1E-05/hour for failure to operate.

Oxygen sensors. Anyakora et al. (1971) gave a value of 5.65/year for an overall oxygen analyzer failure rate. Using 8760 hours/year, this gives 6.5E-04/hour. This is a rather high value. As noted in previous chapters, the early data from the 1970's often has higher values than later studies. Blanton and Eide (1993) gave a failure to operate failure rate of 1E-05/hour with an upper bound of 1E-04/hour. The type is not known, but the Blanton and Eide data are probably a newer type of sensor, perhaps the electrochemical cell that operates at modest temperatures. The Blanton and Eide data is suggested for use on oxygen sensors. The repair times are probably similar to the gas detectors discussed below.

Combustible gas sensors. One of the leading data sources is the Offshore Reliability Data Handbook (OREDA, 1992). This handbook documents data collected at offshore oil drilling platforms. The data are characterized, components are described and their boundaries defined, and the statistics are presented. The OREDA handbook gives values for gas detectors:

sensor	failure mode	average failure rate	90% upper bound failure rate
catalyst method for hydrocarbon gas detection	maximum or zero output	1.7E-05/hour	3.5E-05/hour
	no output	8.5E-06/hour	1.5E-05/hour
	high output	3.7E-05/hour	5.5E-05/hour

hydrocarbon detectors (con't)	low output	3.3E-05/hour	6.1E-05/hour
	erratic output	5.5E-07/hour	8.4E-07/hour

The repair times for these units were an average of 9 hours, with a high time of 68 hours. The testing frequency was given as 1 to 3 month test and service intervals for cleaning and maintenance (OREDA, 1992). The detector head was usually changed to solve failure problems. The 1 to 3 month service interval agrees with the suggestion by Katzel (1996).

Another source of data for hydrocarbon gas sensors was found. Bodsberg (1994) gave a total failure rate for these catalytic units of 1.1E-05/hour, where 91% of the failure rate was non-critical failures, 4.5% (that is, ~5E-07/hour) were critical failures of failing to operate when needed, and the other 4.5% was spurious operation. The upper bound failure rate could vary by perhaps up to a factor of up to ten, but is more likely to be in the range of 3 because the data set is large.

Scanning these data, it appears that the order of magnitude for a generic failure rate to apply to gas detectors is 1E-05/hour for the critical failures. The OREDA data could be used on other sensors if they are the catalyst type.

Smoke detectors. Bukowski and O'Laughlin (1994) give a design failure rate for ionization smoke detectors of 3.5E-06/hour, as an upper bound failure rate for these units. Bukowski and O'Laughlin do not give a failure mode, but it is evident from their discussion that they are considering only the failure to operate mode. The useful life of these detectors is thought to be on the order of five years due to dust and dirt buildup on the two potential difference (ion collector) plates. These plates must be in contact with atmospheric air, so they tend to accumulate dust and moisture over time. If the ion conductance drops enough because of the foreign material on the collector plates, the detector will have repeated false alarms. Yearly tests are suggested for individual units. If the detector is part of an addressable fire alarm control panel system, the detector is electronically queried on a continuous basis (i.e., hourly or greater) for its temperature, cleanliness, and other operational factors. Detectors can be cleaned, but are often simply replaced.

Cadwallader (1995) reported some additional data on smoke detectors. Some researchers quote smoke detectors failing on demand (0.13/fire demand), and others have the typical hourly failure rates: detector zero output, 5.4E-07/hour (error factor of 2.4), detector erratic output, 2.4E-07/hour (error factor of 1.75), and contaminated detector, 5.5E-07/hour (error factor of 2.2). After reviewing the failure rates, an order of magnitude value would be 1E-06/hour for a smoke detector failing to operate.

It is important to note that radiation exposure can interfere with ionization detector operation. Capaul et al. (1989) noted that a field of 4 roentgens/hour caused a high level of nuisance alarms with one brand of ionization smoke detector. Also, similar to what was explored by Liu et al. (1993) for radiation sensors, high magnetic fields could also prevent ionization smoke detectors from operating correctly by altering paths of ionized smoke particles. It is noted that magnetic installations (magnetic resonance imaging magnets, magnetic fusion experiments, etc.) are usually protected by photoelectric smoke detectors.

Humidity sensors. Blanton and Eide gave a failure to operate failure rate for a humidity sensor of 1E-05/hour, with a 95% upper bound of 1E-04/hour. The sensor was probably the absorption type. RAC (1991) lists open circuit (50%) and short circuit (50%) as the failure modes for an optoelectronic sensor, such as the thermoelectric humidity sensor. If the Blanton and Eide data is applicable to this sensor, then a preliminary failure mode partitioning is also known.

Noise sensors. No data were found on noise sensors. These sensors generally are hand-held units, and they appear to be reasonably simple. Reviewing data on the series of components that comprise the sensor (microphone, comparator circuit, etc.) and considering the generic reliability values of other sensors, a judgment is made that the 'failure to operate' failure rate should be 1E-05/hour. The failure modes reported for typical meters by the Reliability Analysis Center (RAC, 1991) likely apply to the circuit of a sound level meter: faulty indication (51%), unable to adjust (23%), open circuit (14%) and no indication (12%).

Magnetic field sensors. These sensors are rather simple, just passing a milliAmpere current through a magnetic field sensitive material and reading the voltage. Some discussions of Hall probes were found in the literature (CERN, 1985; IFVE, 1982), but there were no quantitative estimates of reliability given in those reports. The reliability was reported to be high over long time periods, with good repeatability. An analyst judgment is made to consider use of 1E-06/hour for a generic 'fail to operate' failure rate, using a factor of 10 for the error factor to estimate the upper bound.

7.4 Conclusions.

In this chapter, safety sensors for personnel protection were discussed. The types discussed were radiation sensors, gas (oxygen, toxic gas, and combustible gas) sensors, and humidity sensors. Basic failure modes were listed and failure rate data from the literature was given. Repair times are more difficult to find in the literature, but some are cited. It was noted that failure rates from the 1970's and 1990's varied considerably from the earlier data, showing that continued data collection and analysis is useful to ascribe accurate values to components and to promote operating experience feedback to designers.

Chapter 7 References

Alber et al., 1995.	T. G. Alber et al., Idaho Chemical Processing Plant Failure Rate Database, INEL-95/0422, Idaho National Engineering Laboratory, August 1995.
Angrist, 1976.	S. W. Angrist, Direct Energy Conversion, third edition, Allyn and Bacon, Inc., Boston, MA, ISBN 0-205-05581-8, 1976, pages 130-136.
Anyakora et al., 1971.	S. N. Anyakora et al., "Some Data on the Reliability of Instruments in the Chemical Plant Environment," The Chemical Engineer, No. 255, November 1971, pages 396-402.
Blanton and Eide, 1995.	C. H. Blanton and S. A. Eide, Savannah River Generic Database Development, WSRC-TR-93-262, Westinghouse Savannah River Company, 1995.
Blyukher, 1995.	B. Blyukher, "Oxygen Deficiency Hazard (ODH) Analysis for Pressure and Cryogenic Systems Facilities," Structural Integrity of Pressure Vessels, Piping, and Components - 1995, PVP-318, American Society of Mechanical Engineers, ISBN 0-7918-1349-5, 1995, pages 169-175.
Bodsberg, 1994.	L. Bodsberg, "Optimal Voting Logic of Hydrocarbon Gas Detectors Based on Field Data," presented at the Second International Conference on Probabilistic Safety Assessment and Management (PSAM II), San Diego, CA, March 20-25, 1994, paper 55-19.
Bukowski and O'Laughlin, 1994.	R. W. Bukowski and R. J. O'Laughlin, Fire Alarm Signaling Systems, second edition, National Fire Protection Association, Quincy, MA, ISBN 0-87765-399-2, 1994, chapter 14.
Cadwallader et al., 1991.	L. C. Cadwallader, M. A. Stolpe-Gavett, and L. Quintana, Tritium Room Air Monitor Component Failure Data Analysis from January 1, 1984 to December 31, 1990, EGG-FSP-9450, EG&G Idaho, Inc., May 1991.
Cadwallader, 1992.	L. C. Cadwallader, Cryogenic System Operating Experience Review for Fusion Applications, EGG-FSP-10048, EG&G Idaho, Inc., January 1992.
Cadwallader, 1995.	L. C. Cadwallader, Fire Protection System Operating Experience Review for Fusion Applications, INEL-95/0396, Idaho National Engineering Laboratory, December 1995.

Capaul et al., 1989.	T. Capaul et al., "Radiation Effects on the Reliability of Fire Detection Systems," Fire Protection and Fire Fighting in Nuclear Installations, Proceedings of an IAEA Symposium, Vienna, Austria, February 27-March 3, 1989, paper IAEA-SM-305/49, ISBN 92-0-020489-9, pages 171-176.
CERN, 1985.	Center for European Research Nucleaire, Digital Micro-Teslameter, CERN-8513, Geneva, Switzerland, September 1985.
Considine, 1985.	D. M. Considine, editor in chief, Process Instruments and Controls Handbook, third edition, McGraw-Hill Book Company, New York, ISBN 0-07-012436-1, 1985, chapter 6.
Dexter and Perkins, 1982.	A. H. Dexter and W. C. Perkins, Component Failure-Rate Data with Potential Applicability to a Nuclear Fuel Reprocessing Plant, DP-1633, Savannah River Laboratory, July 1982.
DOE, 1996.	U.S. Department of Energy, Safety of Magnetic Fusion Facilities: Requirements, DOE-STD-6002-96, May 1996; and Safety of Magnetic Fusion Facilities: Guidance, DOE-STD-6003-96, May, 1996.
Graham, 1991.	J. H. Graham, Safety, Reliability, and Human Factors in Robotic Systems, Van Nostrand Reinhold, New York, ISBN 0-442-00280-7, 1991, pages 119-121.
Green, 1983.	A. E. Green, Safety Systems Reliability, John Wiley & Sons Publishers, Chichester, ISBN 0-471-90144-X, 1983, page 101.
Herig, 1989.	S. V. Herig, editor, Air Sampling Instruments for Evaluation of Atmospheric Contaminants, seventh edition, American Conference of Governmental Industrial Hygienists, Cincinnati, OH, ISBN 0-936712-82-1, 1989.
IFVE, 1982.	State Committee for Utilization of Atomic Energy in the USSR, Hall Pulse Magnetometer, IFVEOP-8277, Serpukhov Institute of High Energy Physics, Russia, 1982.
ISA, 1987.	International Society for Measurement and Control (ISA), Installation, Operations and Maintenance of Combustible Gas Detection Instruments, RP 12.13 Part II-87, recommended practice, ISA, Research Triangle Park, North Carolina, 1987.

Katzel, 1996.	J. Katzel, "What you need to know about fixed gas detection systems," Plant Engineering, 50, July 1996, pages 54-58.
Kinnard, 1956.	I. F. Kinnard, Applied Electrical Measurements, John Wiley & Sons, New York, 1956, pages 288-290.
Liu et al., 1993.	J. C. Liu et al., "The Effect of the Static Magnetic Field on the Response of Radiation Survey Instruments," Health Physics, 64, 1993, pages 59-63.
Miller and Mazur, 1984.	T. M. Miller and P. O. Mazur, "Oxygen Deficiency Hazards Associated with Liquefied Gas Systems: Derivation of a Program of Controls," American Industrial Hygiene Association Journal, 45, 1984, pages 293-298.
Norton, 1982.	H. N. Norton, Sensor and Analyzer Handbook, Prentice Hall publishers, Englewood Cliffs, NJ, ISBN 0-13-806760-0, 1982, chapter 8.
NSC, 1988.	National Safety Council, Fundamentals of Industrial Hygiene, third edition, NSC, Itasca, IL, ISBN 0-87912-082-7, chapter 9.
NSC, 1992.	National Safety Council, Accident Prevention Manual for Business and Industry, Engineering and Technology, tenth edition, NSC, Itasca, IL, ISBN 0-87912-156-4, page 489.
OREDA, 1992.	OREDA, Offshore Reliability Data Handbook, second edition, distributed by DNV Technica, Hovik, Norway, ISBN 82-515-0188-1, 1992, pages 420-430.
Parry et al., 1993.	R. Parry et al., A High Reliability Oxygen Deficiency Monitoring System, SSCL-preprint 430, Superconducting Super Collider Laboratory, May 1993.
RAC, 1991.	Reliability Analysis Center, Failure Mode/Mechanism Distributions, 1991, FMD-91, Rome Air Development Center, Griffiss Air Force Base, NY, 1991.
Tsoulfanidis, 1983.	N. Tsoulfanidis, Measurement and Detection of Radiation, McGraw-Hill Book Company, New York, ISBN 0-07-065397-6, 1983, chapter 5.
Vincoli, 1995.	J. W. Vincoli, Basic Guide to Industrial Hygiene, Van Nostrand Reinhold, New York, ISBN 0-442-01960-2, chapter 7.

White, 1993. J. R. White, "Detecting pulverizer fires before they start," Power Engineering, 97, February 1993, pages 42-43.

Wiederhold, 1996. P. R. Wiederhold, "The Cycling Chilled Mirror Dew Point Hygrometer," Sensors, 13, July 1996, pages 25-27.