

10 Carbon Monoxide Sensors and Systems

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10.1 INTRODUCTION

Carbon Monoxide (CO) is one of the most important gases in the field of sensor technology. This is because its toxicity combined with its properties of being odorless, colorless, tasteless, and nonirritating to the respiratory tract. Attempts at detection of CO date back to the famous French physiologist, Claude Bernard, circa 1846,¹ who performed experiments with CO poisoning dogs. Small birds and mammals were used for decades in mines as living CO detectors. CO has been called the “silent killer,” the “stealthy-poison,” and even the “smart poison” because it enters the body without notice and leaves so quickly with little trace. See an earlier discussion of CO detectors by Kwor in *Carbon Monoxide Toxicity*, 2000.

Today’s CO detectors/alarms are small electronic devices. Such devices are installed in homes near heating devices or in garages where sources of CO such as combustion burners and/or motor vehicles may potentially pollute the breathing space. If a sufficient level of CO is detected, the device audibly alarms, giving occupants a chance to ventilate the area or safely vacate. Unlike smoke, CO is undetectable by the unaided human senses, and hence, people often find themselves in environments polluted with CO without knowing it.

During the mid 1990s, the installation of residential, wall-mounted CO alarms grew rapidly in the United States. This was a result of the availability of low cost CO alarms, marketing campaigns, education campaigns by the American Lung Association and advocacy by the US Consumer Products Safety Commission (CPSC). In 1995, Chicago was the first municipality in the United States to mandate CO alarms in all single and multiple family housing, and in some special use buildings such as schools, churches, theaters, museums. By 1998, approximately 20 million units had been shipped and an estimated 8–15% of homes had at least one CO alarm installed.⁷

CO alarms today retail for \$20–\$80 (U.S.), are widely available, and can either be battery-operated or AC (mains) powered. Other locales such as Massachusetts have followed Chicago in acknowledging CO poisoning as a priority and have enacted state legislation which requires CO detectors in homes. Such domestic detectors are required to meet performance standards such as BS EN 50291 (UK and Europe), UL 2034 (USA), and CSA 6-19-01 (Canada). The Canadian standard has been argued to be superior as it requires “time of manufacture” and test for “lifetime reliability.” As an example, the British–European standard requires domestic CO alarms to behave in the following way:

- No alarm within 60 min at 45 ppm CO
- Alarm within 30 min, but not less than 10 min, at 150 ppm CO
- Alarm within 6 min at 350 ppm CO
- Recovery from the alarm state within 6 min in clean air

Although these design standards help set a benchmark for performance, they do not specify the degree to which alarms must maintain their performance, and hence has contributed to CO detectors known to becoming notoriously unreliable with age. Poor sensitivity at low humidity was a major problem in one field experiment, showing as much as 79% of alarms failed when tested at 5% RH and that 3 of the 10 brands tested worked well.⁸

Other than the domestic need for CO alarms, another important CO sensing application that has recently gained considerable interest is vehicle cabins. Exhaust pollutants find their way into the cabin through the ventilation system, also known as the heating, ventilation, and air conditioning (HVAC) system. Independent studies^{9,10} have shown that vehicle cabins commonly show concentrations of toxic gases such as CO, hydrocarbons (HC), volatile organic compounds (VOC), and oxides of nitrogen (NO_x) higher than safety limits set by Occupational Safety and Health Administration (OSHA) and World Health Organization (WHO). Among the array of toxins found in vehicle exhaust gases, CO is the most deadly poison. It is a major subject of overlooked issues concerning motor-vehicle cabin air quality and suicides involving CO.^{9,11} Of the 2,320 suicides registered for the year 2002 in Australia, 416 persons (18%) died from use of motor-vehicle exhaust gases.¹⁰ By understanding the problem of CO pollution within vehicle cabins, CO sensor technology can be employed to circumvent the danger. See Chapter 9 of Carbon Monoxide Toxicity, 2000, and Appendix 1 for additional discussion of this issue.

10.2 SENSOR TECHNOLOGIES FOR CARBON MONOXIDE GAS DETECTION

At the heart of any gas alarm and detecting system are the sensors. The sensor detects target gases, and then converts the information into an electrical signal for processing. There are numerous ways to sense gas. However, as cost, size, and simplicity are critical sensor attributes, three main sensing technologies have dominated domestic CO alarms. These are

1. Semiconducting metal oxide (SMO) technology
2. Electrochemical (EC) technology
3. Infra-red/optical technology (IR)

SMO gas sensors are currently the smallest CO sensors available. These sensors have a small heated element, causing reducing/oxidizing gases to react with the surface of a metal oxide film, changing the semiconductor's conductivity proportionally to the gas concentration. Electrochemical gas sensors have electrodes placed in contact with a liquid electrolyte to form an Electrochemical sensor. As the gas diffuses, it reacts with the working electrode, changing its electrical potential proportional to the gas concentration. And third are IR sensors, where the optical sensing element undergoes light transmission changes when exposed to the target gas.

Table 10.1 compares the technologies against seven key sensor device criteria. Domestic CO alarms predominantly employ either the semiconductor Electrochemical sensor. Semiconductor based CO sensors have penetrated the market with companies such as Figaro (Japan), Microchemical (MICS) (Switzerland), or FIS (Japan). Some Electrochemical sensor manufacturers include City Technology (U.K.), Monox (UK), and Kidde (USA). Optical CO sensors have been pioneered by Quantum (USA). For vehicle cabin air quality monitoring installed within the HVAC systems of vehicles, metal oxide sensors have dominated as they are small, have long lifetime and the technology allows for the sensor element to be conveniently

TABLE 10.1
Comparison of Three Gas-Sensing Technologies with Respect to Desirable Carbon Monoxide Domestic and Vehicle Air Quality Monitoring Criteria

Criteria	Infra Red—Optical	Electrochemical	Metal Oxide
Cost	<US\$15	<US\$10	<US\$5
Life time	>6 years	2–3 years	>6 years
Sensitivity	Very good	Very good	Very good
Selectivity	Excellent	Very good	Poor
Response time	Seconds	Seconds	Seconds
Size	Medium	Medium	Small
Ease of use	Good	Excellent	Excellent

optimized for various toxic gases. However, for aftermarket vehicle CO detectors, optical sensors from Quantum have dominated.

10.2.1 SEMICONDUCTING METAL OXIDE (SMO) GAS SENSORS

SMO gas sensors are relatively small, reliable, durable, and have low cost. Traditionally, the major disadvantages of SMO as gas sensitive devices has been their poor gas selectivity, and the influences of humidity and temperature.^{11,12} The introduction of noble metal catalysts (such as platinum and palladium), filters (activated carbon), and modification to the SMO microstructure and nanostructure has enabled SMO sensor manufacturers to improve selectivity and stability performance.¹³ For reducing gases such as CO, molecules react with adsorbed oxygen ions (from ambient air) on the surface of the oxide. The adsorbed oxygen loses its electron by reacting with the reducing gas molecule, thereby increasing the films conductivity. A simple model consisting of three possible reactions is shown below^{14,15}:



From this reaction it is obvious that a change in ambient oxygen concentration will also change the rate of this redox process and influence the output signal of the sensor. The relationship between film conductivity (σ) and gas concentration (c) follows a power law that can be described by¹⁶:

$$\sigma = kc^n$$

where k is a measured proportionality constant unique to the film/sensor and the exponent n can range from 0.3 to 0.8. Owing to this intrinsic nonlinear semiconducting nature, linearization circuitry within hardware/software is usually required. In addition, for the SMO material to react with a gas, the material is elevated to temperatures between 90°C and 250°C enabling the reduction/oxidization process to occur. Elevating the sensor to high temperature requires an integrated heater circuit to be fabricated below or adjacent to the sensing element. Owing to this high temperature requirement, SMO gas sensors require relatively high power consumption. Traditional SMO sensors fabricated on alumina substrates typically consume above 350 mW. One way of reducing power consumption is by fabricating gas sensors using a thin Si membrane as done by MiCS in Switzerland. Power consumption of the MiCS sensor is about 30–50 mW. Typically for detecting CO gas, the sensitive film material used in SMO sensors is tin oxide (SnO_2). Other transitional metal oxides such as tungsten oxide (WO_3), indium oxide (In_2O_3), chromium titanium oxide (Cr_2TiO_4) fabricated at a thickness between 200 nm and 10 μm have also been shown to be effective CO sensing materials.^{17–24}

For automobile air quality monitor (AQM) applications, MiCS manufactures dual element sensors for detecting both reducing gases such as CO and HC's and oxidizing

gases such as NO_2 and O_3 . This allows for detection of gasoline pollution from cars and motorbikes, and diesel pollution from diesel-powered cars as well as trucks and buses. The Si based sensor chips (Figure 10.1a) are bonded to either transistor outline (TO) packages or SMD (surface mount device) packages. Figure 10.1b shows two sensor chips on the same housing developed for the automobile industry, capable of detecting both CO and NO_x . Typically, the sensor is integrated on a printed circuit board with peripheral electronics and packaged as a CO alarm for domestic or automobile use.

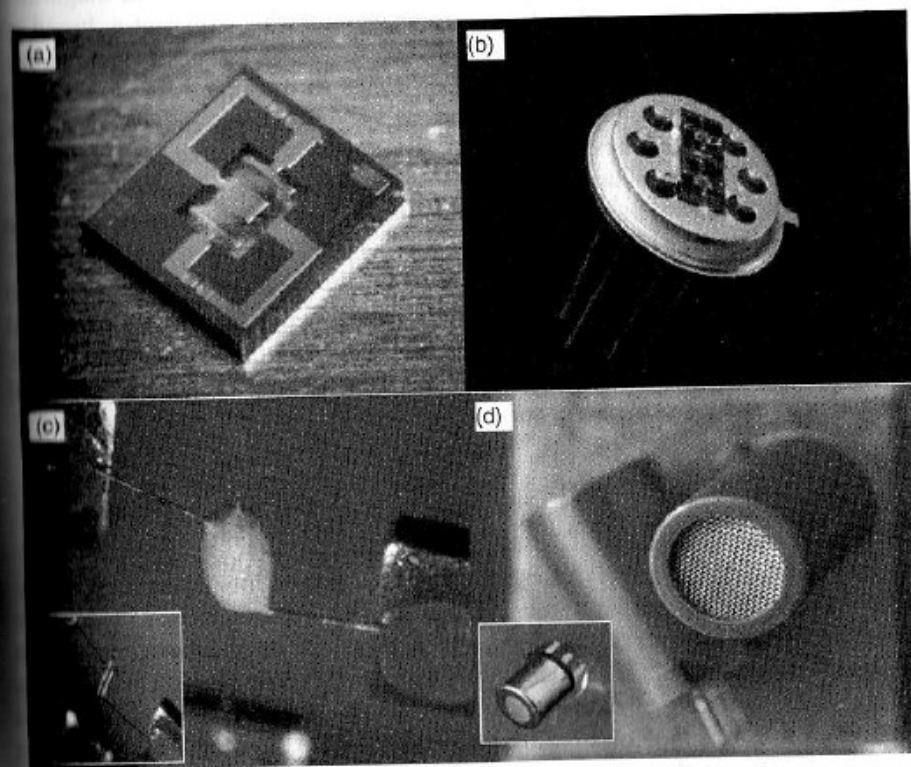


FIGURE 10.1 Photographs of commercial CO gas sensors. (a) The MiCS Micro-Electro-Mechanical Systems (MEMS) chip 2.1×2.3 mm. This chip is made up of a thin Si membrane, which is a micromachined silicon platform that includes an integrated heater and interdigital electrodes. The sensitive layer is a thin (about 200 nm in. thickness) metal oxide polycrystalline film; (b) Dual MiCS MEMS chips mounted and bonded onto a TO5 package. These sensors are used in automobile applications to control the HVAC system; (c) The FIS SB series sensing element made up of a platinum coil heater (as shown in the inset) with a sensing platinum electrode in the middle of the coil. The structure is coated and covered with sensitive semi-conducting metal oxide, tin dioxide (SnO_2). The SnO_2 material is made up of many small particles in the size range of submicron to several tens of microns. (d) The FIS SB series sensor structures are encapsulated in nickel plated brass (as shown in the inset) with an attached active charcoal filter and then enclosed in an outer plastic housing. These sensors are typically employed within domestic CO detectors. (Courtesy of MicroChemical of Switzerland and FIS of Japan).

Figure 10.1c and d shows the sensor design of the FIS (Japan) sensor employed in domestic CO detectors. Compared to MICS, the FIS design is based on a tin dioxide coated over a platinum coil and a sensing electrode. The coil heats the structure at an elevated temperature while the working electrode senses the conductance changes. Figure 10.2a shows the FIS sensor responding to CO gas. Some important characteristics to note are: (1) The sensor signal returns to its original baseline. This characteristic ensures that the sensor remains calibrated, free of drift that will result in signal errors. (2) The response time and decay time of the sensor is a few minutes which is adequate for either domestic or automobile applications. (3) The magnitude of sensor signal changes as a function of concentration (i.e., exponent n , based on Equation 10.1). This permits a greater signal to noise ratio and signal dynamic range. Figure 10.2b is a typical selectivity test performed to determine cross-sensitivity to other gases. As shown, the SMO sensor does not offer absolute CO selectivity. Improving selectivity requires optimizing catalyst concentration (such as platinum), optimizing material annealing temperature and optimizing crystal and grain properties. Figure 10.2c shows a stability test of the FIS CO sensor. The slight change in baseline is a result of the complicated nature of the crystallization process due to operation at elevated temperatures. The sensor is extremely stable over 1000 days—even after 1000 days a baseline change of only 10% occurs, which is usually mitigated by intelligent microprocessor algorithm programming. Improving this characteristic of SMO sensors is a great challenge that drives the active research disciplines of semiconductor metal oxide gas sensors.

10.2.2 OPTICAL GAS SENSORS

IR-based sensors are relatively physically small, consume low power, are selective, and are rapidly decreasing in cost. These sensors are considered as solid state and have a lifetime of over 6 years (depends on IR source degradation/failure) with good resolution, relatively high selectivity, and broad dynamic range. These sensors identify gases by taking advantage of a gas's unique IR absorption spectra. Most gases (more than one type of atom) can be detected by measuring their absorption at a particular IR wavelength, which corresponds to the resonance of the molecular bonding between dissimilar atoms. Figure 10.3a shows an IR absorption spectrum of some common gases. For example, to detect CO, the wavelength at which one carbon atom and one oxygen atom resonate in a carbon monoxide molecule is 4.7 μm . Therefore, the IR system will be filtered to detect radiation at a bandwidth centered at 4.7 μm .

There are certain basic components common to all IR gas sensors: an IR source (e.g., incandescent lamp), an IR detector (e.g., thermopiles, pyroelectric detectors, photodiode), a means to select appropriate wavelengths (e.g., band pass interference filter) and a sample cell. The simple sensing setup is shown in Figure 10.3b. The IR source is at one end and the IR sensor at the other. The band pass optical filter must correspond with the absorption wavelength of the gas being measured. As the concentration of the gas being measured increases, the output signal from the sensor reduces as the IR is absorbed by the target gas molecules. The relationship between

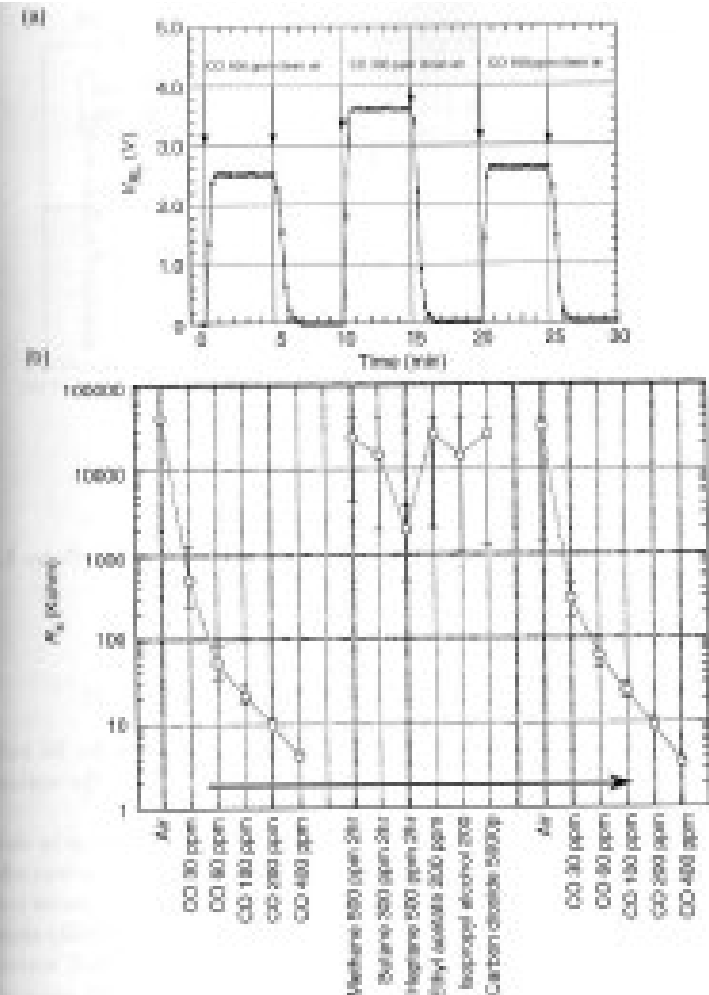


FIGURE 10.2 FIS SB series-CO sensor data showing, (a) exposure to 100, 300, and 1000 ppm (CO) with clean air cycles. The x-axis represents time (minutes) and the y-axis represents the proportional voltage response from the sensing element. The sensor is stable when responding to CO gas, returning to baseline within a few minutes. In addition, the repeatable response characteristic at 100 ppm also is another desirable sensing attribute. (b) selectivity to other gases following the UL2034 specification. The largest cross-sensitivity is with heptane (error bars overlap with an equivalent CO error signal of about 30 ppm). (c) long-term stability. The sensor's stability over 1000 days shows extremely stable characteristics, even after 1000 days a baseline change of only 10% occurs, which is usually mitigated by intelligent microprocessor algorithm programming. (Courtesy of FIS, Japan).

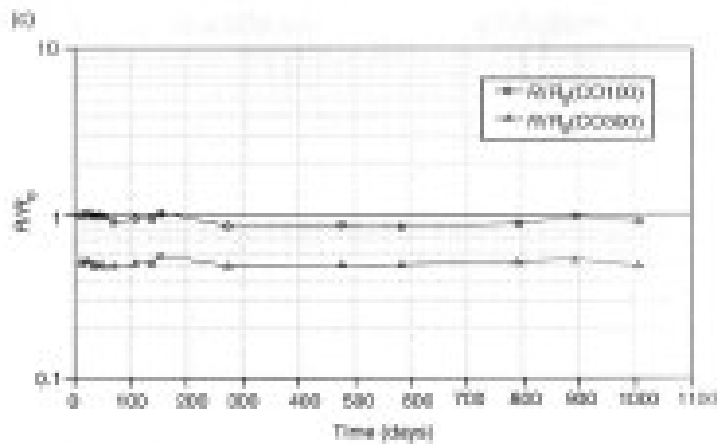


FIGURE 10.2 Continued.

IR transmission, T , and gas concentration, c , can be explained by Beer's Law of Absorption:

$$I = I_0 e^{-kcl}$$

where I is the intensity of IR radiation at the IR detector, I_0 is the IR radiation emitted from the IR source, k is the absorption coefficient, and l is the optical path length.

To improve the signal to noise ratio, an improved IR detection setup as shown in Figure 10.3c was developed. The difference is that a reference detector was added to compensate for humidity, vibration, source intensity deterioration, detector contamination, vibration, and aging. As a result, a dual beam topology is typically employed with most IR gas sensors. A reference detector senses IR at a neutral wavelength where almost no absorption takes place (i.e., 4 μm). By taking the ratio of both detector voltage U_1 and reference signal U_2 , the common I_0 coefficient is cancelled, and the target gas signal component remains which corresponds to the target gas concentration.

The Quantum Group (US) is the leading manufacturer of optical gas sensors for domestic CO alarms. They have developed a unique type of solid state IR gas sensor based on the "biomimetic" phenomena. The company has been successful in developing a broad range of domestic CO alarms and it is the first company to offer an aftermarket CO detector for vehicle safety applications. The IR-based "biomimetic" sensors are designed to replicate the CO uptake by hemoglobin in the blood, hence the name "biomimetic." In doing so, the sensing element can be set to alarm based on the replicated blood level of carboxyhemoglobin (COHb).

Figure 10.4a shows the elements of the biomimetic CO sensor. The porous sensing elements are made from a porous transparent disk coated with a monolayer

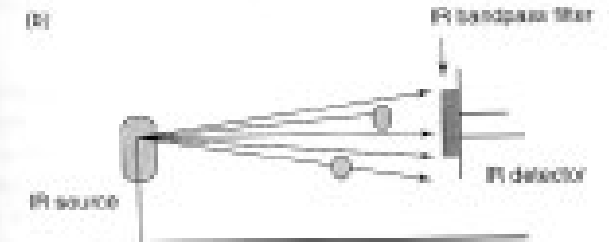
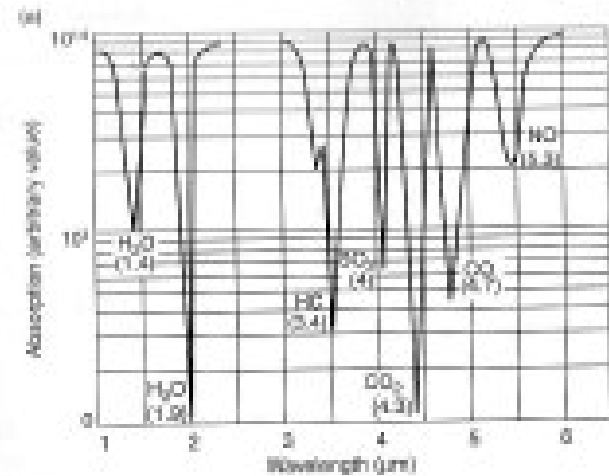


FIGURE 10.3 IR sensor design that is based on, (a) the absorption bands of various gases in the IR region, (b) A simplified diagram of a single beam IR absorption gas detector and, (c) an improved version of the dual beam arrangement makes the gas detector insensitive to source performance deterioration. (Courtesy of PerkinElmer Optoelectronics, Germany).

of supramolecular organometallic complex. This complex is formed through a self-assembly process to generate the sensing elements that mimic hemoglobin. Upon exposure to CO, one or both of the sensing elements changes its spectral character and absorbs photons of light at a rate dependent on the concentration of CO in the surrounding environment. The sensing elements reverse their spectral shift by a self-assembly process whose rate depends upon the decrease of CO in the environment.

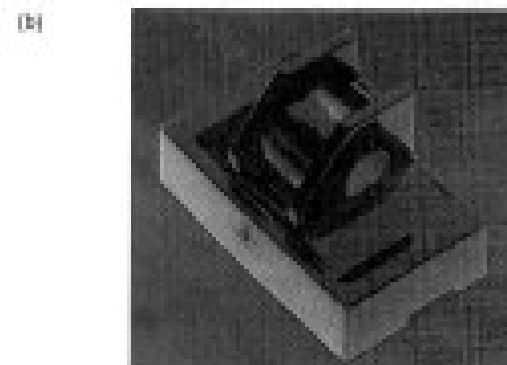
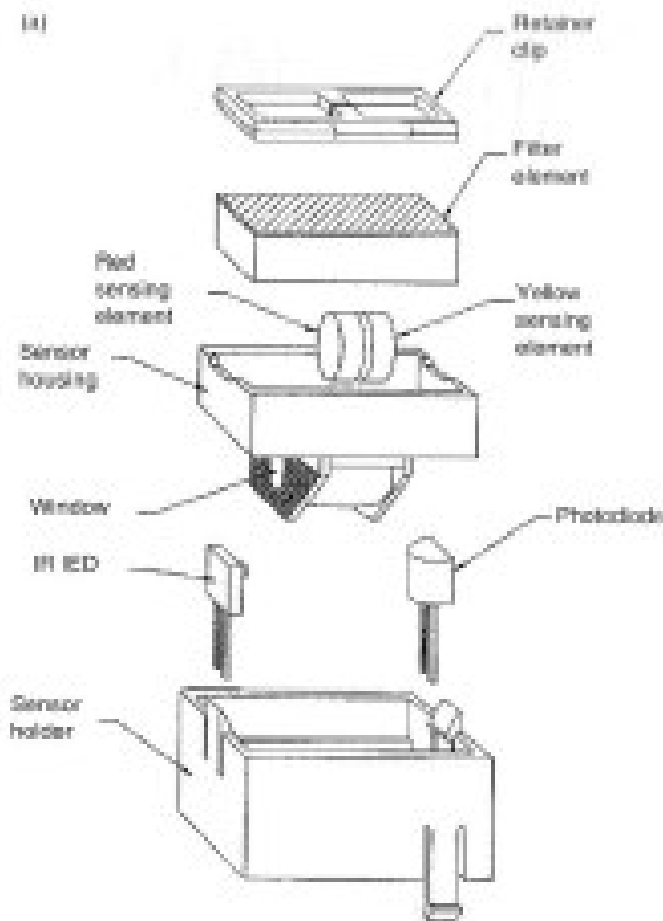


FIGURE 10.4 A commercialized optical CO gas sensor, (a) components and structure of Quantum's biomimetic CO gas sensor, and (b) a photograph of the CO sensor cell (incorporated within Quantum's line of domestic and automobile CO detectors). (Courtesy of the Quantum Group, USA).

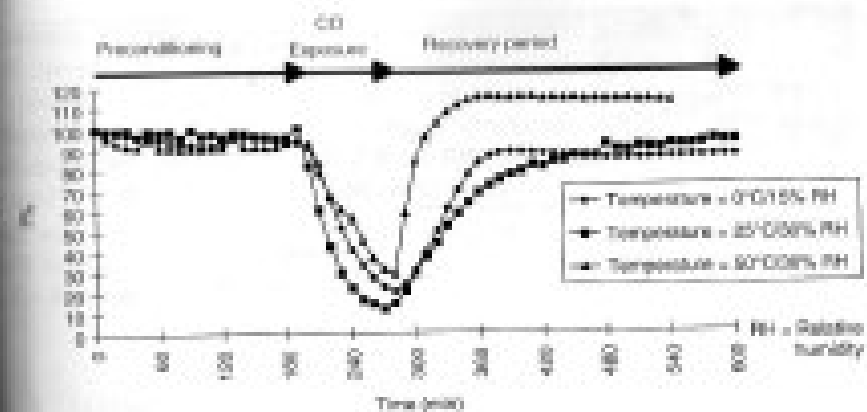


FIGURE 10.5 Response curves of a Quantum biomimetic sensor towards 100 ppm CO for 90 min with varying ambient temperatures from 0°C to 50°C and relative humidity from 15% to 80% RH. It can be seen that varying these parameters influences the response time and baseline of the optical sensor. (Courtesy of the Quantum Group, USA).

This mechanism acts as a variable IR bandpass filter. By monitoring the rate of change in the amount of light transmitted through the sensing elements, the concentration of the CO in the surrounding environment can be determined accurately. The sensing elements are held in optical alignment by the sensor-housing placed between an IR light emitting diode (LED) and a photodiode. Pulses of light emitted by the LED pass through the first sensor-housing window and are attenuated by the sensing elements. The attenuated light exits through the second sensor-housing window and is then detected by the photodiode. The light transmittance follows Beer's Law (Equation 10.2).

Figure 10.5 shows the response of the Quantum Group's biomimetic sensor over 90 min to a 100 ppm concentration of CO at varying temperatures and relative humidity. After the 90 min, the CO is removed and the sensor begins regenerating. When exposed to CO, the sensor rapidly absorbs photons at 940 nm. In a fixed alarm point detector, a value of 30% is typically set as the alarm point. Thus in such a detector, the alarm would be triggered within 40 min of exposure, which is well within the UL safety guidelines. When the sensor is again exposed to clean air (awaked or recovery time), the biomimetic component begins a self-regenerating process. As the sensor reverses its spectral shift, the signal increases and within hours the sensor has fully recovered. Although the response time is slower than the SMO sensor, incorporating sensing algorithms based on the rate of change of signal, improves response time.

10.2.3 ELECTROCHEMICAL GAS SENSORS

Electrochemical gas sensors are also small electronic devices. A City Technology CO sensor commonly found in CO-domestic alarms is shown in the inset of Figure 10.6. In their simplest form they are comprised of two electrodes: sensing and counter,

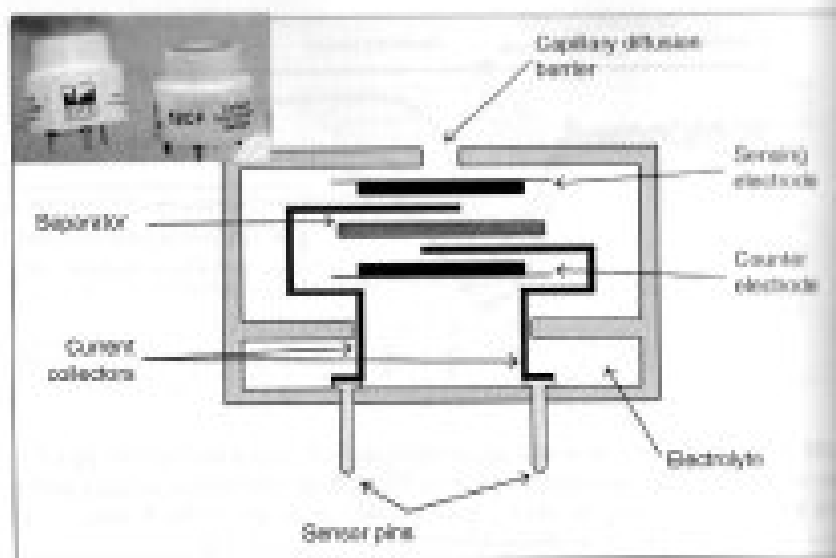


FIGURE 10.6 A simplified schematic of a two electrode electrochemical cell manufactured by City Technology. The inset show photographs of the complete sensor package. These sensors are employed within domestic CO detectors. (Courtesy of City Technology, U.K.)

separated by a thin layer of electrolyte. The structure is enclosed in a plastic housing that has a small capillary tube to allow gas entry to the sensing electrode and includes pins which are electrically attached to both electrodes and allow easy external interface. These pins may be connected to a simple resistor circuit that allows the voltage drop resulting from any current flow to be measured. Gas diffusing into the sensor is either oxidized or reduced at the sensing electrode and, coupled with a corresponding (but converse) counter reaction at the other electrode, a current is generated through the external circuit. Since the rate of gas entry into the sensor is controlled by the capillary diffusion barrier, the current generated is proportional to the concentration of gas present outside the sensor. Of great importance to any electrochemical gas sensor is the design of the diffusion barrier, which limits the flow of gas to the sensing electrode. The electrode is therefore able to react with all target gas as it reaches its surface, and still has electrochemical activity in reserve. The reactions that take place at the electrodes in a CO sensor are:



Similar reactions take place for all other toxic gases that are capable of being electrochemically oxidized or reduced. From the reaction at the counter electrode, it is evident that oxygen is required for the current generation process to take place. This is usually provided in the sample stream by air diffusing to the front of the sensor, or by diffusion through the sides of the sensor (a few thousand ppm is normally sufficient).

However, continuous exposure to an anaerobic sample of gas may result in signal drift, despite the oxygen access paths which may cause the sensor to be poisoned.

Similar to SMO gas sensors, electrochemical gas sensors are also affected by temperature variations. The baseline signal of most electrochemical sensors tends to increase exponentially with temperature, approximately doubling for every 10°C rise in temperature which proves problematic for domestic applications as the baseline shift with temperature could seriously affect the ability to measure these gases accurately and result in false alarming. Nevertheless, by compensating for this drift either in the hardware or software, such temperature influences can be reduced.

10.3 SENSOR SYSTEMS

The CO sensor is the main component within all domestic CO detectors. Support electronics are also required to provide the sensor with intelligence so that it will generate alarms according to compliant standards. Most detectors incorporate at least one microprocessor that allows them to be quickly reprogrammed and the behavior of the alarm to be altered to suit various applications or standards. For domestic applications, CO alarm design and alarm requirements are well defined by associated performance specifications. However, in emerging CO and air quality monitoring applications such as monitoring vehicle cabin air quality, specifications, and standards have yet to evolve. Vehicle cabin air quality concerns are usually generated by the following four scenarios: (1) Pollutant gases entering the vehicle through the ventilation system, (2) A lack of fresh airflow resulting in low oxygen and high carbon dioxide concentrations due to occupant respiration, (3) Pollutant gases entering from the external environment through window openings, imperfect seals, and door holes, and (4) Toxic gases entering the vehicle cabin by redirected exhaust gases for self-harm (i.e., suicide) purposes.

Currently, no system or aftermarket product addresses all four vehicle AQM concerns. Only two commercial AQM solutions currently exist for vehicles: (1) The most common are AQM systems controlling HVAC ventilation flaps, and (2) Less common are aftermarket toxic gas alarms for vehicle cabin applications, such as those commercialized by the Quantum Group (U.S.). Currently, the demand for AQM systems is driven by the increasing concern for passenger safety, health, comfort, and by automakers aiming for features and attributes that differentiate their vehicles. In turn, this growth has increased demand for reliable automotive air quality sensors. Figure 10.7 shows a simplified view of an AQM system controlling the HVAC ventilation flap. External gases enter the vehicle cabins through the ventilation system. Mounted in the air intake of the HVAC system, the AQM sensor sends a signal to the fresh air inlet flap to close when pollutant gases are detected and automatically reopen when the external air quality returns to an acceptable level. Although a driver could close the air inlet manually, forgetting to reopen it could cause the oxygen concentration in the cabin to decrease and carbon dioxide levels to increase. Therefore, a compromise must be reached. One way of tackling the problem to implement with the system an air quality factor. For instance, the absolute concentration of particular gas (C_a) in the vehicle cabin is dependent on the exhaust flow rate (F), time (T), cabin



FIGURE 10.7 An overview of a typical automobile air quality monitor (AQM) equipped within a heating, ventilation and air conditioning (HVAC) system. When the ventilation flap is open, dangerous pollutants such as CO and NO_x may enter the cabin. To mitigate this, electronics automatically close the ventilation flap. High carbon dioxide and low oxygen concentrations may result through occupant respiration. High carbon dioxide and low oxygen concentrations are dangerous because they induce fatigue and drowsiness, reducing driver attention and response times.

volume (V), and cabin seal (S). Therefore,

$$C_x = f(F, T, V, S)$$

Concentrations of carbon monoxide (C_{CO}), and oxygen (C_{O_2}) have been identified as important gas species contributing to poor cabin air quality. The summation of each absolute gas species concentration gives rise to an air quality factor (AQ_{cabin}) such as:

$$AQ_{cabin} = \alpha CO + \beta (CO_2)^{-1}$$

Where α , and β are proportionality coefficients. It should be noted that other gas species such as hydrocarbons and nitrogen oxides have been ignored. Absolute threshold limits could then be set for scenarios such as suicide ($AQ_{suicide}$) and driver fatigue ($AQ_{fatigue}$). For increased reliability and effective suicide attempt identification, the change of air quality with time (dAQ_{cabin}/dt) should also be incorporated into the driver fatigue and suicide detecting algorithms:

$$\frac{dAQ_{cabin}}{dt} = \alpha \frac{\partial C_{CO}}{\partial t} + \beta \frac{\partial (C_{O_2})^{-1}}{\partial t}$$

An alarm threshold, $dAQ_{suicide}/dt$, could also be incorporated as done so by Quantum Group. Therefore, the cabin gas-sensing system should include both absolute and changing air quality factors, to determine if alarms need to be activated.

Software solutions to improve CO detectors are commonplace. In addition, rate of change, humidity compensation (through humidity sensors) and temperature

compensation (through temperature sensors) are also common within sensor systems. However, compensation for environmental variables increases the cost of the CO detector. Data referenced above showing that 70% of alarms failed when tested at 5% RH³ is compelling evidence of performance standards not meeting real-life long-term requirements for adequate domestic CO monitoring.

10.4 CONCLUSIONS

Detection of CO has gone far beyond the primitive approach of Claude Bernard and others. CO sensors and detectors employ advanced materials, electronics, and software to ensure reliable and selective performance while maintaining economic sensitivity and feasible for the domestic market. This chapter has discussed the three basic sensing techniques employed in mainstream CO detectors/alarms. SMO sensors depend on chemi-absorption between the oxide and CO molecules for CO detection. Various methods are employed by industry to increase selectivity through the introduction of catalysts such as Pt and Pd, and films using activated carbon. Optical sensors depend on CO energy absorption by incident photons. Humidity, temperature, and pressure are environmental factors that may affect sensor components. Electrochemical sensors are also vulnerable to cross sensitivity, temperature, and humidity variations.

The intrinsic deficiencies of materials and electronic components that make up commercial CO sensors and systems have been documented and are well known. These issues have plagued manufacturers and the research community for many years and continue to be areas of active scientific interest. Nevertheless, economic forces, government legislation, competition, and customer demand drive CO detector products to be sold at the lowest possible prices, while high customer standards, product superiority, competitive advantage and market reputation drive product quality and innovation. Hence, these forces lead to the classic economic balance between price and performance.

10.5 ACKNOWLEDGMENTS

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10.6 APPENDIX 1 (D.G. PENNEY)

Suicide in Australia, especially that of young men, had attained an alarming rate in recent years, higher than that in the USA and most other countries. The use of motor-vehicle exhaust gas for this purpose was the most popular method. For this reason, in 1998 the Australian Medical Association in cooperation with other governmental and industrial groups as well as various individuals in Australia, invited me to provide conceptual solutions for reducing this tragic loss of young life.

Almost immediately, it was felt that by limiting the availability of the lethal component of motor-vehicle exhaust gas, carbon monoxide (CO), the use of the method of committing suicide would decline, possibly saving several hundred lives per year. The use of CO was often chosen because of its availability, ease of use, and supposed painless induction of unconsciousness. Making CO unavailable would defeat this approach.

Several solutions were considered: (1) Accelerate the rate of installation of effective catalytic converters on Australian motor vehicles, possibly by instigating a recall program. (2) Require the sale or retro-installation of CO detectors on all motor vehicles in Australia that would warn drivers/occupants of the danger, and/or, immediately shut-down the engine and prevent restarting. (3) Place a distinctive odorant in petrol/gasoline that would give motor-vehicle exhaust an unpleasant odor and thus discourage/warn potential suicide attempters. (4) Design ignition systems that would prevent motor vehicles from remaining in an "idle" mode for more than a short time.

Catalytic converters are expensive, eventually wear-out, are slow to come on-line in Australia owing to a long mean vehicle life, and retro-fitting would be difficult and place financial burdens on people least able to pay. Also, current catalytic converters still permit exhaust gases to contain lethal CO concentrations. Finally, the fact that catalytic converters only become effective in reducing CO at elevated temperatures means that exhaust gases would continue to contain supra-lethal concentrations of CO during the "warm-up" period. CO detectors that produce engine "shut-down" would have to be carefully designed so as not to exacerbate traffic problems due to elevated ambient CO concentration. This approach appeared to be the best overall solution, and could have provided some additional health benefits separate from the suicide issue. Solutions involving odorants in motor-vehicle fuel might cause public discomfort and complaints and undesirable environmental pollution. Most motor vehicles need the capability to idle, for example, waiting for traffic or stop lights, taxis, and vehicles being repaired.

Australia represented just 1% of the world motor-vehicle market. The average age of Australian motor vehicles (8×10^6) in 1987 was 12–14 years. It was my chance in visiting Australia in early April, 1998, to recommend to the Australian Medical Association (AMA) and the Working Group on Motor Vehicle Exhaust Suicide, a CO concentration that might be set as the threshold at which engine shut-down would occur. Mathematical modeling of motor vehicle exhaust gas revealed a "unique signature" that might be used to quickly and unequivocally identify a suicide attempt distinct from simple leakage of outside gases into the vehicle.

Motor vehicles would be equipped with a sensor array in the passenger compartment that was sensitive to carbon monoxide, carbon dioxide, and oxygen. Sensor output would be directed to a microchip with an embedded program such that (1) measured CO concentration was integrated over time in a manner modeling human CO uptake, and thus provides a low warning alarm at 35 ppm (7% COHb), and a high warning alarm at 100 ppm (14% COHb), and (2) A CO concentration at 100 ppm and above, as well as rapidly rising CO₂ concentration and rapidly falling O₂ concentration would immediately trigger engine shut-down.

There were several advantages to this scheme: Low and high alarms give warning of CO presence at levels shown to impair psychometric performance ("low alarm") and known to produce health damage in at-risk groups (congestive heart failure (CHF), coronary artery disease (CAD), fetus). These would give warning of elevated ambient CO and/or abnormal exhaust gas leaks into the motor-vehicle driver/passenger compartment.

With concentration \times time computer integration, neither heavy cigarette smoking, the tunnels, nor congested roads would be likely to trigger even the low CO alarm. Use of CO₂ concentration and O₂ concentration changes along with CO concentration would prevent "false positives," that is, inappropriate engine shut-down. Changes in the concentrations of these three gases would provide a unique "signature" of the suicide attempt.

A second sensor array might be placed outside the motor-vehicle, preferably near the rear tailpipe. This would cause engine shut-down in those instances where people attempt to commit suicide outside of the car, behind the tailpipe (in a garage, outside, etc.). If the cost of the three-sensor array proved too great, only one sensor responding to CO might instead be used. In this event, threshold CO concentration might be set somewhat higher in order to avoid inappropriate engine shut-downs.

CO detectors are standard equipment in households in the USA, warning of heater malfunction, etc. They are also required in motor homes, recreational powerboats, and other devices where people are fully or partially enclosed and in proximity to an internal combustion engine. Why shouldn't such devices now become standard equipment in motor vehicles, considering that cars are such prodigious generators of CO and in such close proximity to the driver and passengers, and the fact that cars already incorporate minimally several microcomputers in their normal operation. For the details of the proposed scheme, see www.cobheadquarters.com/CO1.htm.

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