Designing a Low-Power Toxic Gas Detector

By Luis Orozco

Safety first! Many industrial processes involve toxic compounds, including chlorine for manufacturing plastics, agrochemical, and pharmaceutical products; phosphine and arsine for producing semiconductors; and hydrogen cyanide, released when burning consumer-packaging materials. It is important to know when dangerous concentrations exist.

In the United States, the National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Government Industrial Hygienists (ACGIH) have established short- and long-term exposure limits for many toxic industrial gases. The Threshold Limit Value-Time Weighted Average (TLV-TWA) is the TWA concentration to which most workers can be exposed repeatedly in an 8-hour day without adverse effect; the Threshold Limit Value-Short Term Exposure Limit (TLV-STEL) is the concentration to which most workers can be exposed continuously for a short period of time without irritation, damage, or impairment; and the Immediately Dangerous to Life or Health Concentration (IDLHC) is a limiting concentration that poses an immediate or delayed threat to life, that would cause irreversible adverse health effects, or that would interfere with an individual's ability to escape unaided. Table 1 shows limits for a few common gases.

Electrochemical sensors offer several advantages for instruments that detect or measure the concentration of toxic gases. Most sensors are gas-specific, have usable resolutions under one part per million of gas concentration, and operate with very small amounts of current, making them well suited for portable, battery powered instruments. One important characteristic of electrochemical sensors is their slow response: when first powered up, the sensor may take several minutes to settle to its final output value; and when exposed to a mid-scale step in gas concentration, the sensor may take 25 to 40 seconds to reach 90% of its final output value.

This article describes a portable carbon monoxide (CO) detector using an electrochemical sensor. The IDLH concentration for CO is much higher than for most other toxic gases, making it relatively safe to handle. Nevertheless, CO is still lethal, so use extreme care and appropriate ventilation when testing the circuit described here.

Figure 1. CO-AX carbon monoxide sensor.

Figure 1 shows a CO-AX sensor from Alphasense. Table 2 shows a summary of the CO-AX sensor's specifications.

Table 2. CO-AX Sensor Specifications

Sensitivity	55 nA/ppm to 90 nA/ppm (65 typ)
Response Time (T_{90} from 0 ppm to 400 ppm CO)	< 30 s
Range (Guaranteed Performance)	0 ppm to 2,000 ppm
Overgas Limit	4,000 ppm

Achieving the longest possible battery life is the most important goal for portable instruments in this application, so keeping power consumption to a minimum is crucial. In typical low-power systems, the measurement circuitry powers up to make a measurement, then shuts down for a long standby period. In this application, however, the measurement circuit must remain continuously powered due to the electrochemical sensor's long time constants. Fortunately, the slow response allows the use of micropower amplifiers, high value resistors, and low-frequency filters that minimize Johnson noise and 1/f noise. In addition, single-supply operation avoids the wasted power of a bipolar supply.

Figure 2 shows the circuit of the portable gas detector. An ADA4505-2 dual micropower amplifier is used in a potentiostat configuration (U2-A), and a transimpedance configuration (U2-B). The amplifier is a good choice for both potentiostat and transimpedance sections because its power dissipation and input bias current are extremely low. Consuming only 10 μA per amplifier, it will permit a very long battery life.

Table 1. Exposure Limits for Some Common Industrial Toxic Gases

Toxic Gas	Long-Term Exposure Limit (TLV-TWA) (ppm)	Short-Term Exposure Limit (TLV-STEL) (ppm)	Immediate Danger to Life and Health Concentration (IDLHC) (ppm)
Carbon Monoxide	50	200	1,200
Carbon Dioxide	5,000	30,000	40,000
Chlorine	0.5	1	10
Phosphine	0.3	1	50
Hydrogen Sulfide	10	20	100

In 3-electrode electrochemical sensors, the target gas diffuses into the sensor through a membrane before interacting with the working electrode (WE). The potentiostat circuit senses the voltage at the reference electrode (RE) and supplies the counter electrode (CE) with the current required to maintain a constant voltage between the RE and WE terminals. No current flows in or out of the RE terminal, so the current flowing out of the CE terminal flows into the WE terminal. This current is directly proportional to the target gas concentration. The current through the WE terminal can be positive or negative, depending on whether reduction or oxidation takes place in the sensor. For carbon monoxide, oxidation occurs, causing the CE terminal current to be negative (current flows into the output of the potentiostat op amp). Resistor R4 is typically very small, so the voltage at the WE terminal is approximately equal to V_{REF}.

The current that flows into the WE terminal results in a negative voltage at the output of U2-A with respect to the WE terminal. This voltage is typically a few hundred millivolts for a carbon monoxide sensor, but can be as high as 1 V for other sensor types. To run from a single supply, an ADR291 micropower reference, U1, raises the entire circuit 2.5 V above ground. The ADR291 consumes only 12 µA; it can also provide the reference voltage for an analog-to-digital converter to digitize the output of this circuit.

The output voltage of the transimpedance amplifier is simply:

$$V_O = 2.5 \text{ V} + I_{WE} \times R_f \qquad (1)$$

where:

I_{WE} is the current into the WE terminal.

R_f is the transimpedance resistor (shown as U4 in Figure 2).

The maximum response of the sensor is 90 nA/ppm, as shown in Table 2, and its maximum input range is 2,000 ppm. This results in a maximum output current of 180 µA, and a maximum output voltage determined by the transimpedance resistor, as shown in Equation 2.

$$V_O = 2.5 \text{ V} + 2{,}000 \text{ ppm} \times 90 \text{ nA/ppm} \times R_f = 2.5 \text{ V} + 180 \text{ µA} \times R_f \qquad (2)$$

Sensors for different gases or from different manufacturers will have different current output ranges. Using an AD5271 programmable rheostat for U4 instead of a fixed resistor makes it possible to maintain a single assembly and bill of materials for different gas sensors. In addition, it allows the product to have interchangeable sensors, since a microcontroller can set the AD5271 to the appropriate resistance value for each different gas sensor. The AD5271's 5-ppm/°C temperature coefficient is better than most discrete resistors, and its 1-µA supply current is a very small contributor to the system power consumption.
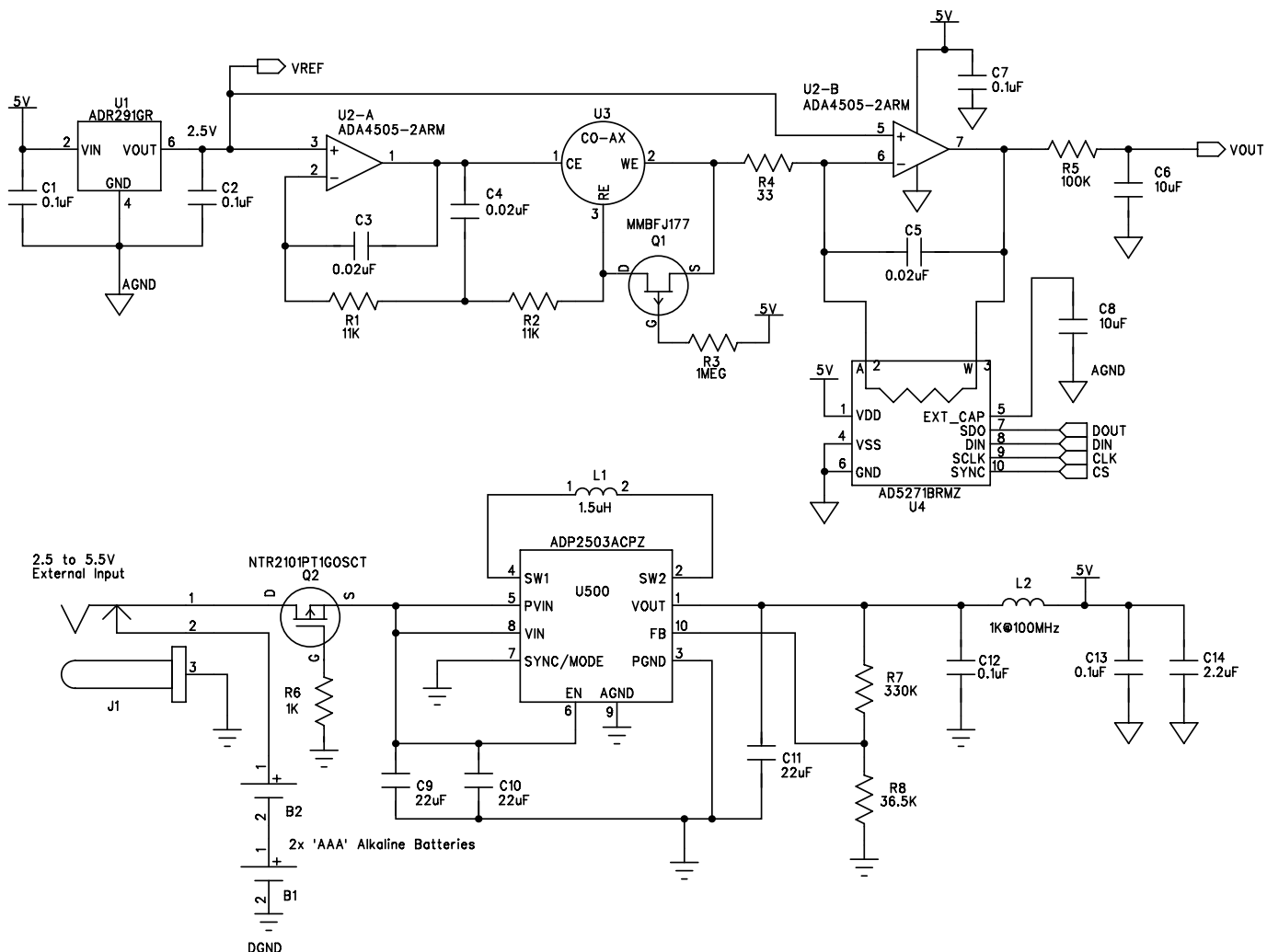

Figure 2. Portable gas detector using an electrochemical sensor.

When operating from a single 5-V supply, a 2.5-V range is available at the output of transimpedance amplifier U2-B, according to Equation 1. Setting the AD5271 to 12.5 kΩ takes advantage of the available range for worst-case sensor sensitivity, and allows for approximately 10% overrange capability.

Using the typical 65-nA/ppm sensor response, the output voltage can be translated to ppm of carbon monoxide as follows:

$$V_O = 2.5 \text{ V} + 813 \text{ μV/ppm} \qquad (3)$$

With a differential input ADC, simply connect the 2.5-V reference output to the ADC's A_{IN-} terminal, eliminating the 2.5 V term in Equation 3.

Resistor R4 keeps the transimpedance amplifier's noise gain at reasonable level. The value of R4 is a compromise between the magnitude of the noise gain and the sensor's settling time error when exposed to high concentrations of gas. For this circuit, R4 = 33 Ω, which results in a noise gain of 380, as shown in Equation 4.

$$NG = 1 + \frac{12.5 \text{ kΩ}}{33 \text{ Ω}} = 380 \qquad (4)$$

The input noise of the transimpedance amplifier is multiplied by this gain. The ADA4505-2's 0.1 Hz to 10 Hz input voltage noise is 2.95 μV p-p, so the noise seen at the output will be

$$V_{output\_noise} = 2.95 \text{ μV} \times NG = 1.1 \text{ mV p-p} \qquad (5)$$

The output noise is equivalent to over 1.3 ppm p-p of gas concentration. This low-frequency noise is difficult to filter out. Fortunately, the sensor response is very slow, so the low-pass filter formed by R5 and C6 can have a cutoff frequency of 0.16 Hz. This filter has a time constant of one second, which is negligible compared to the sensor's 30-second response time.

Q1 is a P-channel JFET. When the circuit turns on, the gate is at V_{CC}, and the transistor is off. When the system powers off, the gate drops to 0 V, and the JFET turns on to maintain the RE and WE terminals at the same potential. This greatly improves the turn-on settling time of the sensor when the circuit turns on again.

Two AAA batteries power the circuit. Using a diode for reverse-voltage protection would waste precious energy, so this circuit uses a P-channel MOSFET (Q2) instead. The MOSFET protects the circuit by blocking reverse voltages, and turns on when a positive voltage is applied. The MOSFET's on-resistance is less than 100 mΩ, causing a much smaller voltage drop than a diode. The ADP2503 buck-boost regulator allows the use of an external supply of up to 5.5 V as well as the AAA batteries. When operating in power-save mode, the ADP2503 consumes only 38 μA. The filter formed by L2, C12, and C13 removes any switching noise from the analog power rail. Rather than using a circuit to disconnect the batteries when an external power supply is connected, a jack that mechanically disconnects the batteries when plugging in the external power connector avoids waste of power.

The total current drawn from the AAA batteries is approximately 100 μA under normal conditions (no gas detected), and 428 μA under worst-case conditions (2,000 ppm CO detected). When the instrument is connected to a microcontroller that can enter a low-power standby mode while not making measurements, battery life can extend to over one year.

References
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