

Home Smoke Alarms

A Technology Roadmap

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EXECUTIVE SUMMARY

The introduction of residential smoke alarms and their widespread adoption over the past four decades has been tremendously successful in saving countless lives and assuring home occupants of their safety in residential fires. Smoke alarms have been developed to be reliable in general, and economical to employ, requiring occasional maintenance of testing and battery replacement. Nevertheless, there remain some shortfalls in operation. Nuisance or false alarms, which are triggered by nonfire related sources, account for the majority of smoke alarm activations. These constitute a serious concern, as occupants sometimes disable the offending alarms, rendering them useless for alarming in genuine fires. Construction methods and room furnishing materials have changed, dramatically increasing the fire growth rate and reducing the time for safe egress. Arousing occupants in a timely manner can be challenging. Given these concerns, improvements in residential smoke alarms could have a huge impact upon residential fire safety, reducing the number of injuries and deaths.

Most residential smoke alarms are based solely upon the detection of smoke aerosol particles emitting from nearly all fires. Ionization and photoelectric aerosol sensors provide sensitivity to various types of smoke aerosols but also, unfortunately, to other aerosols, including cooking fumes, dust and fog. Other principal combustion products, including heat, carbon monoxide, and carbon dioxide, largely have been ignored as means for fire detection. The purpose of this report is to provide an overview of technologies that could prove helpful in designing improved home fire alarms. Recognition of fire and nuisance events, reliability, lifetime, power, and alerting issues are considered, as well as accessibility of the technology and cost. Based upon these criteria, comparisons between the technologies are provided, and recommendations are given for next-generation smoke alarms.

Key Findings

- Inexpensive microcontrollers can allow advanced signal processing from single or multiple sensors, to discriminate between fire and nuisance sources, and to provide earlier detection.
- Carbon monoxide sensors can serve a dual role of serving as a sensor for fire detection and acting as a sensor for conventional toxic-gas alerting.
- Temperature sensors can act in concert with other sensors to authenticate flaming fires.
- Photoelectric sensors can be improved by using blue light sources and by using dual-angle scattering.
- Material-based sensors, such as heated-metal-oxide or Taguchi sensors, can be very sensitive to fire effluents, but they suffer from interference of other sources and degradation that cannot be easily checked.
- Physical-based sensors, such as nondispersive infrared (NDIR) sensors, can be designed to detect principal combustion products and to be self-checking, but inexpensive versions are not presently available.
- Linear discriminant analysis, a mathematical technique based upon data from fire studies, can be implemented for optimizing signal processing to distinguish between conditions that warrant alarm and those that do not.

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MOTIVATION

The majority of smoke alarms in current use are based on sensor technologies that were developed more than 40 years ago. Since the introduction of residential smoke alarms in the 1970s, numerous incremental improvements have been made to the implementation of these technologies, but the underlying sensor technology has remained relatively static. There are two basic sensor types: ionization and photoelectric. Most smoke alarm activations are from nuisance sources,¹ sometimes leading to intentional disabling of the sounding alarms.² Controversies have arisen over the response of ionization and photoelectric smoke alarms to different modes of combustion. Some residential construction methods have changed so that engineered structural members may be more susceptible to collapse during a fire. Automatic fire sprinklers have not been widely adopted in residential occupancies. The fire growth rate from furnishings has increased dramatically in the past 20 years, which has decreased the available safe egress time from an average in 1975 of about 17 minutes for flaming fires, to an average of about three minutes in 2008.³ Finally, alerting occupants sometimes can be problematic. Thus, there is a strong need to improve the performance of home smoke alarms, especially to decrease the time to alarm for all modes of fire detection and at the same time improve the immunity from nuisance sources.

APPROACH

Home smoke alarms rely almost exclusively on the detection of smoke or aerosols. These alarms have been convenient, inexpensive, and fairly reliable. However, they suffer some shortfalls, because false alarms can be produced from nuisance sources that generate aerosols, such as fogging, dust, and cooking. Early detection of fires and discrimination of nuisance sources require improvements with the possibility of incorporating additional sensors into alarms. Besides aerosols, other primary products of combustion, including carbon dioxide (CO₂), carbon monoxide (CO), water, and heat, have not yet been widely incorporated into home-smoke-alarm technology. Still other combustion products include a wide range of hydrocarbons, various oxygenated organics, aromatic compounds, HCN, HCl, and numerous other compounds.

Developments in inexpensive electronic microprocessors and advancements in sensor technology offer opportunities to create smoke alarms that recognize fires more quickly while rejecting nonfire sources that have plagued existing smoke alarms. Sensors for potential use in home smoke alarms can be evaluated according to several factors, including sensitivity to fire effluents, chemical selectivity to aid in discrimination and nuisance rejection, response time, power consumption, longevity, and cost. The outputs of judiciously chosen sets of sensors can be combined intelligently by an economical microprocessor to yield fire-alarm performance that is far beyond what is

¹ "Nuisance sources" are defined as sources of alarming that are not predictive of pending destructive fire conditions and include aerosols produced in cooking, especially broiling, toasting and frying, as well as dust and fogging.

² Ahrens, M. 2004. "False Alarms and Unwanted Activations." National Fire Protection Association Fire Analysis and Research, Quincy, MA. November 2004. p. 58.

³ Bukowski RW, et al., 2008. "Performance of Home Smoke Alarms." Washington: National Institute of Standards and Technology Technical Note 1455-1. p. xxv.

possible with individual sensors. This technology roadmap is an attempt to survey possible sensor technologies for incorporation into next-generation home smoke alarms.

SENSOR TECHNOLOGIES

Residential smoke alarms have been based largely upon detection of smoke aerosols; the most commonly available commercial smoke detectors are ionization detectors, photoelectric detectors, or a combination of both. Although the patent literature indicates that other technologies have been—and still are—being evaluated seriously for fire detection (including solid state chemical sensors and spectroscopic sensors), there has not been much successful market penetration of residential smoke alarms based on other technologies. This is due most likely to the high cost of developing, implementing, testing, and validating new technologies when weighed against the uncertainties of robustness, reliability, and overall performance and when compared to inexpensive and established ionization and photoelectric smoke alarms.

Gas detection is generally based upon physical or material interactions with an analyte. Physical-based sensors use phenomena such as light absorption, light emission, light scattering, ion motion, or temperature. Material-based sensors depend upon absorption or chemical reaction of an analyte with a suitable material. The choice of technology primarily depends upon the ease with which a particular analyte can be sensed and differentiated from other compounds. Chemical sensing technology continues to be developed and is reported in scores of scientific and commercial periodicals. Technologies selected for their possible applicability to fire detection are described below.

AEROSOL DETECTORS

Ionization-type residential smoke alarms have evolved into a basic configuration that is used widely and implemented with various proprietary modifications, depending upon the manufacturer. Virtually all ionization detectors for residential smoke alarms use approximately 0.9 microcuries of americium-241 (^{241}Am), to create a source of ions. This radioactive isotope decays

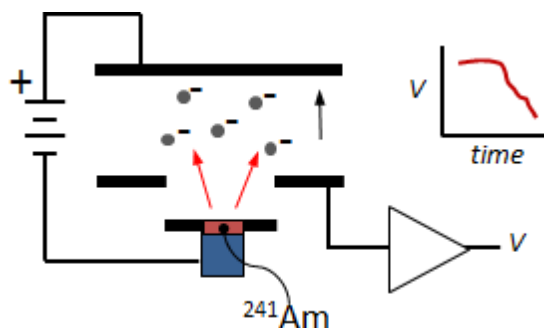


Figure 1. Schematic of ionization smoke sensor. The ^{241}Am source creates ions that drift under the influence of an applied electric field. The ions attach to smoke particles entering the chamber and drift much more slowly. The accumulated charge in the upper region changes the voltage on the floated plate that is monitored by an amplifier.

by emitting alpha particles (high-energy helium nuclei), which collide with air molecules to produce ions. The ions drift between electrodes and establish an equilibrium charge or current that is monitored continuously by an electronic circuit. A schematic is shown in Figure 1. Smoke or other particles entering the smoke alarm's ionization chamber attach to the ions and reduce their mobility, which is sensed by the circuit. If the ion current or charge changes beyond a certain threshold, the alarm is triggered, and an alert is sounded. Although this type of smoke detector is quite sensitive to small smoke aerosols, it is also sensitive to other particles that enter the ionization chamber, such as water droplets, dust, and other aerosols that unfortunately create nuisance alarms. Ionization smoke alarms have evolved from a very simple single-ion chamber design, into dual chamber designs that are more robust and less likely to produce nuisance alarms as a result of air currents and slowly changing environmental backgrounds. Microprocessors are also beginning to be used to improve sensitivity and discrimination by dynamically adjusting alarm thresholds according to signal levels and trends.⁴

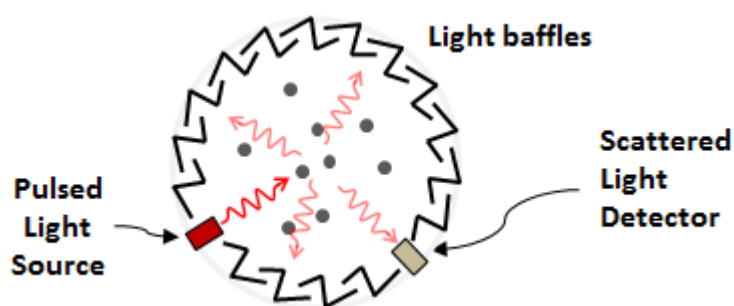


Figure 2. Schematic of a photoelectric smoke alarm. Smoke or other aerosol particles scatter light from a pulsed light source that is sensed by a photodiode light detector.

Optical or photoelectric smoke alarms detect smoke using a light source rather than a radioactive source. A schematic is shown in Figure 2. Most optical smoke alarms use a solid-state light source, such as a light-emitting diode (LED) and a photodiode, to detect the presence of smoke. These smoke alarms can be configured in a direct line-of-sight for measuring the amount of light obscured by smoke or in an orthogonal configuration, in which the light detector is placed off-axis to the light beam and is used to measure the amount of scattered light due to the presence of smoke. The off-axis configuration is far more common because of its higher sensitivity to fire aerosols. While obscuration responds proportionally to the aerosol-particle radius to the third power, scattering from larger aerosols is roughly proportional to the particle radius squared. Although optical smoke alarms are more immune to certain nuisance activations than ionization-type smoke alarms because of their insensitivity to very small aerosols, they are generally slower than ionization detectors to respond to fires that do not produce larger-particle smoke, such as flaming fires. Nuisance alarms also can be caused by backscattered light from dust or other aerosol particles that enter the detector chamber.

Major innovations in photoelectric smoke alarms have been focused on reducing their power consumption, size, and cost, as well as improving fire recognition with minimal false alarms. With mass manufacturing and low-cost, solid-state electronics, photoelectric smoke alarms are now cost

⁴ Gonzales, Eric V. "Dynamic Alarm Sensitivity Adjustment and Auto-Calibrating Smoke Detection." U.S. Patent Application 201110018726. 27 January 2011.

competitive and size competitive with ionization-type smoke alarms. It is generally recognized and well documented that smoke alarms using ionization sensors respond faster to the smoke produced by flaming fires, and smoke alarms using photoelectric sensors respond faster to the smoke produced by smoldering fires. The patent literature indicates that optical smoke alarms are continuing to evolve with regard to optimal arrangement of the light source and detector, as well as with the use of alternate wavelengths of light and scattering angles for better nuisance alarm discrimination. Inexpensive LEDs in near infrared (880–940nm) generally have been used, but some advanced smoke alarms use shorter wavelength LEDs to increase sensitivity to smaller-particle aerosols. Additional information on light scattering is found in Appendix A. Continued innovation in low-power light sources, light detectors, and inexpensive optics can result in further improvements in the performance of photoelectric smoke alarms.

MATERIAL-BASED SENSORS

Material-based sensors rely upon detecting a measurable change of some property of a sensing material as it interacts with an analyte or group of analytes. A simplified schematic is shown in Figure 3. The interaction can be classified as passive, in which the vapor is absorbed into the material, or active, in which a chemical reaction is involved. Passive interactions often can occur at room temperature so that heating is unnecessary. For example, frequently, humidity monitors are made using polyimide or another polymer that absorbs water from the atmosphere. Frequently,

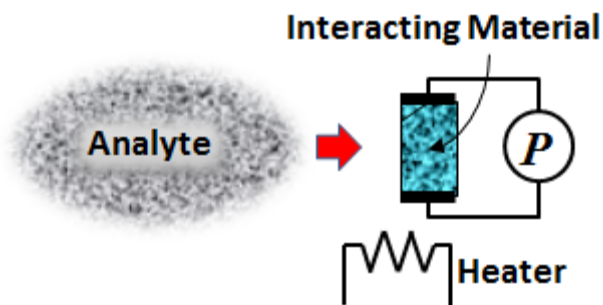


Figure 3. Generic schematic of a material-based sensor with electronic readout. As a selected material interacts with chemicals in its environment, some property, P , is monitored. Properties include: voltage, current, resistance, capacitance and resonant frequency. Some interactions need elevated temperatures and require a heater.

active interactions possess activation energies that must be overcome by application of heat. Taguchi or heated metal oxide sensors are examples that involve catalytic reactions, such as the oxidation of reducible species. In passive or active sensors, the interaction should be reversible, repeatable, and selective to make a sensor with desirable characteristics. Furthermore, material characteristics must be stable over time and resist changes caused by environmental conditions.

SORBENT SENSORS

A wide variety of sorbent and functionalized polymers or other materials have been used for chemical sensors, although sensitivity for some compounds and selectivity for single sensors can be very limited. Volatile and semi-volatile analyte vapors act as solutes that partition between vapor and solid phases with the absorbing material. The ratio of the concentrations of solid and vapor

phases is called the partition coefficient, which typically ranges from 10–1,000 for light organic materials, such as methanol and acetic acid, to greater than 10^6 for heavier organic materials. Both the volatility of the analyte and functional group interactions between the analyte and absorbing material affect the partitioning, and thus, the sensitivity and selectivity. Very volatile or noninteracting chemicals, such as methane, are very difficult to detect using absorption methods.

Materials can be found that interact chemically with an analyte to form a detection platform. Reversible sensing of CO_2 can be accomplished using an amino-containing polymer,⁵ for example. Unfortunately, chemically active polymers can also interact with contaminants occasionally present in the environment and become poisoned over time. The amino-group of chemically active polymers can react irreversibly with NO_2 , for example and limit the useful life of the sensor. Another disadvantage of this material is that the reaction has an activation energy that slows sensor response unless it is heated.

Partitioning of vapors into the absorbing material can be sensed by several means. Changes in the dielectric function or permittivity caused by the presence of the analyte can be measured capacitively, and such devices can be termed chemicapacitors. In the case of water, the permittivity of an absorbing polymer is increased dramatically by the polar nature of water, so that the capacitance can be calibrated to read relative humidity. Generally, polar analytes increase the permittivity, and non-polar analytes decrease the apparent capacitance due to polymer expansion. Sensing materials loaded with carbon or other conducting particles change resistivity primarily due to swelling, which alters the density of the conducting material. Such devices are termed chemiresistors. Swelling is also employed in cantilever stress sensors, where differential stress causes cantilever strain. An advantage of chemicapacitors, chemiresistors, and cantilevers is their ability to be manufactured using microelectromechanical-systems (MEMS) techniques and arrayed to expand chemical sensing and improve selectivity. Additional means to readout sensor-material absorption include: acoustic-resonance shifts in coated quartz-crystal microbalance (QCM), surface-acoustic-wave (SAW), flexural plate wave (FPW), or cantilever devices as the sensing transducers, which respond to mass and modulus changes in the material. Lower limits-of-detection are typically in the 1–100 parts-per-million (ppm) range for industrial solvents to parts-per-billion for very low vapor-pressure materials.

Sorbent sensors have proven successful in a number of applications for detecting volatile organic vapors, toxic industrial chemicals, and chemical warfare agents; however, various difficulties have prevented the development of low-cost, low-maintenance sensors. Degradation caused by chemical interactions of materials with the environment result in drift of the zero and calibration of the sensor.⁶ Calibration can be checked by exposure to known concentrations of analytes, but such costly and troublesome procedures cannot be tolerated by the consumer market.

The sole exception for a low-cost and reasonably stable sorbent sensor is the polymer relative-humidity hygrometer, which has been produced at low cost for at least 20 years. As a material-based sensor, it also experiences some zero drift and decalibration. Calibration is affected by exposure to high concentrations of certain solvents, like methanol; but it is more likely to occur

⁵ Zhou, R., D. Schmeisser, and W. Gopel. (1996). "Mass sensitive detection of carbon dioxide by amino group-functionalized polymers." *Sensors and Actuators B-Chemical* **33**(1-3): 188–193.

⁶ The output of a sensor in the absence of analytes or in clean environmental conditions (including background oxygen and CO_2) is termed the "zero," "baseline" or "offset" of the sensor. "Calibration" refers to the output of a sensor to known concentrations of an analyte and may be nonlinear.

with condensation of water, which dissolves salts and other materials from environmental deposits to alter the material properties. By coating the polymer with a material that is permeable to water vapor, but impermeable to liquid water, the calibration drift is reduced substantially. Response time is also important for fire and smoke detection and is unfavorably affected by coating, which can extend the rise time. Certainly, a judicious selection and testing of a humidity sensor is warranted if it is to be used for smoke alarm applications.

HEATED METAL OXIDE (TAGUCHI) SENSORS

Heated metal oxide sensors were first developed and marketed by Naoyoshi Taguchi in 1968. These sensors are based upon electrical conduction through a polycrystalline metal-oxide semiconductor material. Conduction through such materials is controlled primarily by the potential barriers at grain boundaries. An illustration of the sensing action is shown in Figure 4. A favorite material is conducting tin oxide, which is slightly oxygen deficient (SnO_{2-x}) on the interior of grains. When exposed to ambient oxygen, an enriched-oxide-surface forms and becomes negatively charged,

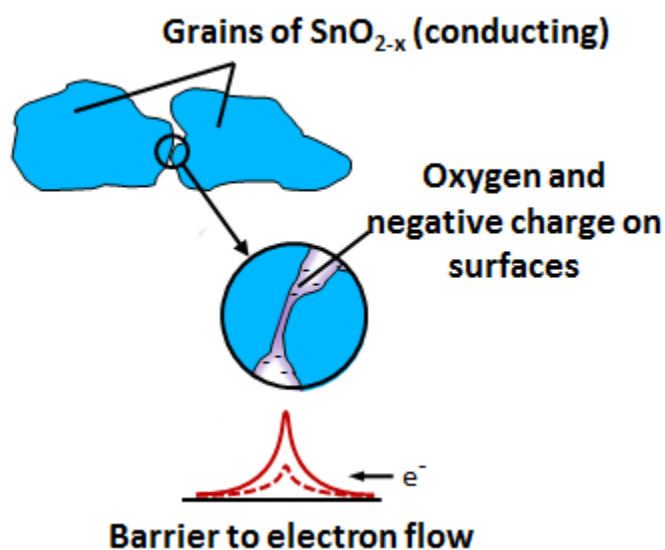


Figure 4. Illustration of the sensing mechanism in the Taguchi or heated-metal-oxide sensor. The typical sensing material is oxygen-deficient tin oxide, which is a good electrical conductor. Conduction between grains is impeded electrostatically by the accumulation of negative charge on the surfaces. Hydrocarbon and other vapor analytes lower the conduction barrier and reduce the resistance of the sensor.

creating a potential barrier to electron conduction between the grains. Reducing vapors (gases that can be oxidized, such as carbon monoxide, and methane) react on the surface to lower the potential barrier and promote conduction in the sensor. Heat must be applied to activate the reaction for reasonable rates. Selectivity to various chemicals can be modified by choosing the operating temperature and the sensing material. Taguchi sensors have a very nonlinear response, which is typically characterized as a power of the gas concentration. Figure 5 shows responses from two example Taguchi sensors. Sensitivity to a number of fire-related effluents is readily demonstrated, although the relative response differs between two sensor types. Although the Taguchi sensors

have very high sensitivity to low concentrations of chemicals, their sensitivity to humidity under ordinary conditions may dominate and limit their practical usefulness at very low levels.

Advantages of the sensor include small size, simple readout, high sensitivity, and relatively low cost. Its disadvantages include lack of chemical selectivity, as well as sensitivity to temperature and humidity conditions, and long-term drift. Power consumption prevents battery operation for extended periods, although MEMS devices can consume as little as 1mW in pulsed operation. One manufacturer cautions that silicone vapors from adhesives and hair grooming materials can inhibit sensitivity irreversibly. Nevertheless, successful operation of 10 years or more for carbon monoxide warning has been reported. Using pattern-recognition algorithms, Taguchi-sensor arrays also have been used to detect odors and various chemical analytes.

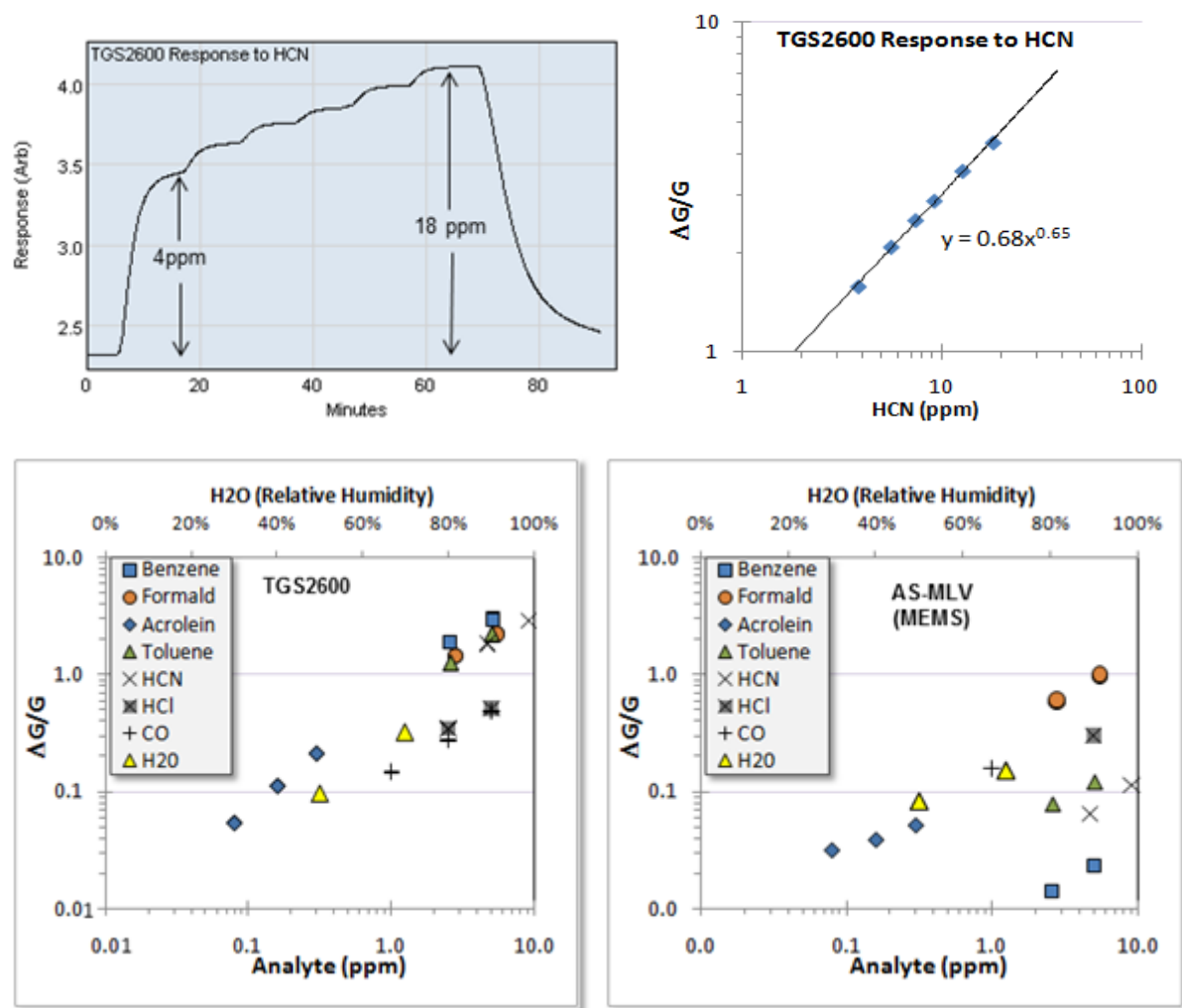


Figure 5. Example responses of Taguchi sensors. (*upper left*) Figaro TGS2600 sensor responding to concentrations of HCN. (*upper right*) Same data plotting the relative change in conductance as a power-law dependence. (*lower left*) Response of the TGS2600 to several compounds. (*lower right*) Response of an Applied Sensor AS-MLV MEMS detector.

CATALYTIC SENSORS

Catalytic or catalytic bead sensors use heated catalyst material to oxidize any combustible vapors that may be present. The heat released from gas oxidation on the material increases the temperature of the device and changes its resistance. There are a number of drawbacks of these sensors for fire and smoke detection. They are not sensitive to combusted vapors, are easily poisoned, and have a limited life expectancy (3–5 years).

ELECTROCHEMICAL SENSORS

Electrochemical gas sensors measure a chemical reaction involving the loss of electrons (oxidation) on one electrode and the gain of electrons (reduction) on another electrode. The process also involves the movement of ions between the electrodes through an electrolyte or ionic conductor that bridges between the electrodes. Some analytic electrochemical sensors add one or two additional electrodes for more precise control. By connecting the two electrodes to an external circuit, a measurement of either the current produced (amperometric) or the voltage generated (potentiometric) can be related to the gas concentration.

Following cost reductions and technology improvements to extend lifetimes to seven years or more, electrochemical cells are now widely used to detect carbon monoxide (CO). Figure 6 shows a diagram of an electrochemical sensor that consumes CO and oxygen to generate a current proportional to the CO concentration. In the process, protons are generated at the anode and are conducted to the cathode through a proton-conducting electrolyte. An orifice and a diffusion barrier control the rate of gas exchange and water evaporation.

Advantages of the sensor include small size, simple low-power operation, high sensitivity and relatively low cost. It is generally reliable with good selectivity for CO and little sensitivity to other

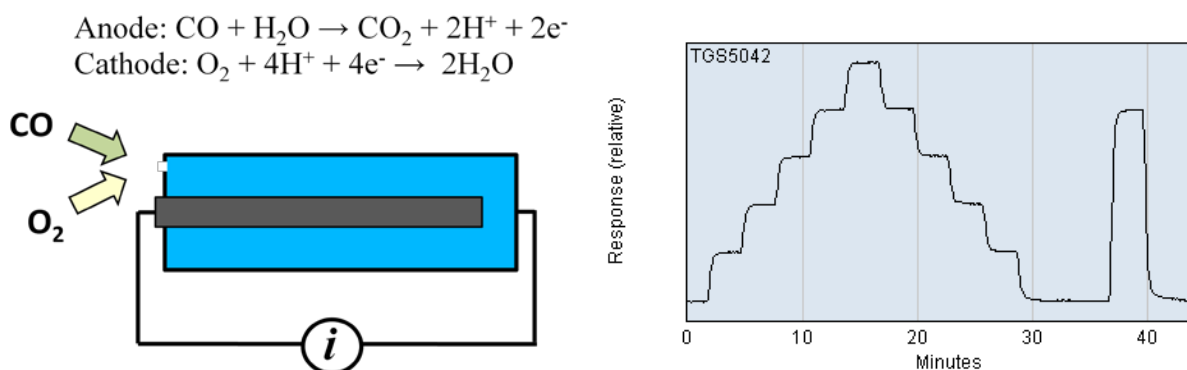


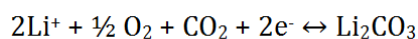
Figure 6. (left) Diagram of carbon monoxide (CO) electrochemical sensor. (right) Response of a commercial sensor (Taguchi TGS5042) to steps of 5ppm CO and to a single pulse at 20 ppm.

materials commonly found in home environments. However, acetylene and MAPP gas can stimulate a response that could be confused with CO.⁷ The principle disadvantage is that calibration and proper operation cannot be validated without applying a test gas. For consumer applications, the

⁷ Gases other than CO that have been tested with the Figaro TGS5042 in the authors' laboratory include: CO₂, benzene, toluene, formaldehyde, acrolein, HCl, HCN, MAPP gas, and water (humidity).

sensor must be replaced according to the manufacturer's recommendation. Often the unit is designed to generate a warning after a specified period of operation to indicate that replacement is required.

Electrochemical sensing of carbon dioxide requires a radically different chemistry and activation at elevated temperatures. Typically, a sodium or lithium ion reacts with oxygen and CO₂ to form a carbonate in equilibrium. The electrolyte in this case must conduct Na⁺ or Li⁺ ions—known as an ion-selective membrane. An example overall reaction is



The reaction is usually monitored by the voltage produced, which is proportional to the logarithm of the ionic activity or CO₂ pressure, according to the Nernst equation.

Other forms of heated solid-state electrochemical sensors are ion-conducting ceramics with metallic electrodes. These ceramic-metallic or cermet sensors have been used for decades in certain applications like oxygen sensing in automotive exhausts. By altering the materials and the operating temperature, these sensors also can be made to detect numerous chemical species, and typically, they have a very broad response, like Taguchi sensors, and can be assembled in arrays for electronic-nose applications.⁸

Advantages of the solid-state electrochemical sensor include small size, high sensitivity, and relatively low cost. Like Taguchi sensors, heater power requirements prevent battery operation for extended periods, although some MEMS devices have been shown to consume 50mW or less. Cross sensitivity to formaldehyde, CO, and HCN has been seen in a commercial CO₂ sensor.⁹ Because these compounds are also found in fire effluents, cross sensitivity is not necessarily a shortcoming for fire detection. The principle disadvantage is that calibration and proper operation cannot be validated without applying a test gas.

PHYSICAL-BASED SENSORS

Physical-based sensors rely upon detecting a measurable change of some physical interaction of the analyte with the sensor (Figure 7). Aerosol detectors are good examples of physical-based sensing, even though the means of detection in each is very dissimilar. Most high-quality analytical instruments rely upon physical interactions. Examples include spectrometers for ion mass, ion mobility, and optical absorption and fluorescence. Even though materials used to construct these instruments must remain relatively stable over time, they do not participate directly in the property that is sensed, so that one or more means for validating instrument operation can be designed into the system. The possibility for self-checking is generally not possible with material-based sensors.

⁸ See, for example, Hammond, M.H., et al. (2008) "Cermet microsensors for fire detection." *Sensors and Actuators B* **130**: 240–8.

⁹ The Figaro TGS4161 has been tested with CO₂, CO, benzene, toluene, formaldehyde, acrolein, HCl, HCN, and water (humidity) in the authors' laboratory.

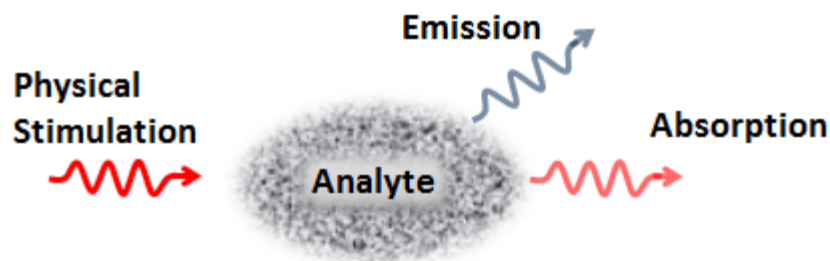


Figure 7. Generic illustration for the principle of physical sensing. Some sort of physical stimulation, including electromagnetism, light sound, charge directly interacts with the analyte. The absorption or modulation of the stimulation is monitored. Alternatively, an emission of some sort is monitored (*e.g.*, scattered light, ions, charges, fluorescence, acoustic energy).

NONDISPERSIVE INFRARED (NDIR) SENSORS

Infrared spectroscopy is a highly preferred method for analyzing gases. The vibrations of asymmetric and polyatomic molecules can be directly stimulated by incident infrared (IR) radiation at frequencies or wavelengths that are very specific to the molecule. Spectrometers are generally equipped with a means for selecting wavelengths of interest, either by interferometry (*e.g.*, Fourier-transform infrared or FTIR) or by dispersion, using a prism or diffraction grating. Nondispersive infrared (NDIR) sensors are simple spectrometers in which one or more wavelength-selective filters have replaced the dispersive element. Fortunately for fire and smoke detection, the primary combustion products— H_2O , hydrocarbons (as a group), CO_2 and CO —have absorption bands in the mid-IR that make possible detection and quantification of each.

The basic NDIR concept is shown schematically in Figure 8. An infrared light source illuminates a region that is ventilated with air to be tested. Typically, the IR source is an incandescent solid that produces a broad spectrum of light in the mid-IR region of $2\mu\text{m}$ – $6\mu\text{m}$ and may approximate black-body radiation. The broadband IR source is partially absorbed by the gas at characteristic wavelengths and detected by a suitably filtered detector. The absorption follows the familiar Beer-Lambert law, where I_0 and I are the intensity of the incident light and the transmitted light, respectively, and the transmission exponentially decays with the absorption coefficient, α , for the analyte at bandpass of the filter; the partial pressure of the analyte, p , and the path length, L , taken by the light.

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The light source is pulsed to lower power consumption and to improve signal-to-noise. Because its intensity can change over time, a parallel reference channel at a nonabsorbing wavelength is often

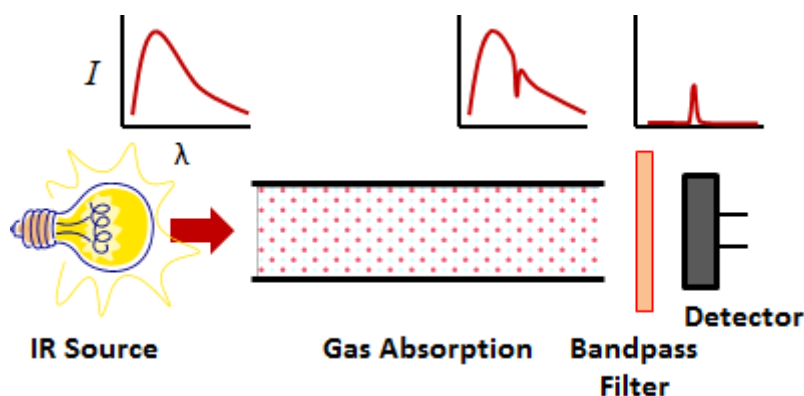


Figure 8. Schematic of an NDIR sensor. Part of the light at an analyte-specific wavelength, λ , is absorbed and detected.

added to increase the accuracy and reliability. Unfortunately, shifts in the spectral content of the source may not be properly compensated by the reference channel; so drifts in the zero and calibration can be seen over time. Slow changes in the sensor zero can be compensated for¹⁰ but should not be an important issue for fire detection. Only increases in combustion-product concentrations over a short period are significant.

The advantages of the NDIR sensing include its exquisite selectivity for each of the primary combustion products and lifetime of more than 10 years. NDIR sensors can also automatically check basic functionality by observing the difference in signal with the light on and off. The disadvantages include high cost and power consumption (1–3 watts) of present commercial designs. Also, accuracy is not assured unless the sensor is periodically calibrated by applying a test gas. Innovative designs can address these concerns and are discussed later in this report.

PHOTOACOUSTIC SENSORS

Photoacoustic sensors are a variant of NDIR sensors, in which the light detection is accomplished by a microphone or pressure transducer. Absorption of IR energy by a gas is converted into heat energy, which translates into a transient pressure rise. If the source is modulated, pressure waves are generated and can be detected mechanically, rather than by conventional thermoelectric, pyroelectric, or photodiode detectors. A schematic is shown in Figure 9. Because a microphone is capable of response at acoustic frequencies, the signal-to-noise can be enhanced dramatically over low-frequency detection. The limits-of-detection are improved commensurately. Unfortunately, inexpensive mid-IR sources modulated at high frequencies are not readily available. Mechanical choppers (motorized shutters) are generally used, which increases the complexity and cost of the

¹⁰ Very slow drift of the sensor zero can be corrected automatically by using the assumption that the sensor mostly experiences clean environmental conditions. The zero is reset by subtracting an offset equal to the minimum reading over a period of several days, for example. In the case of CO₂, its concentration increases with human occupancy and activity but has a minimum of about 400 ppm. This method is used in some commercial products and is called the automatic-background-correction (ABC) method.

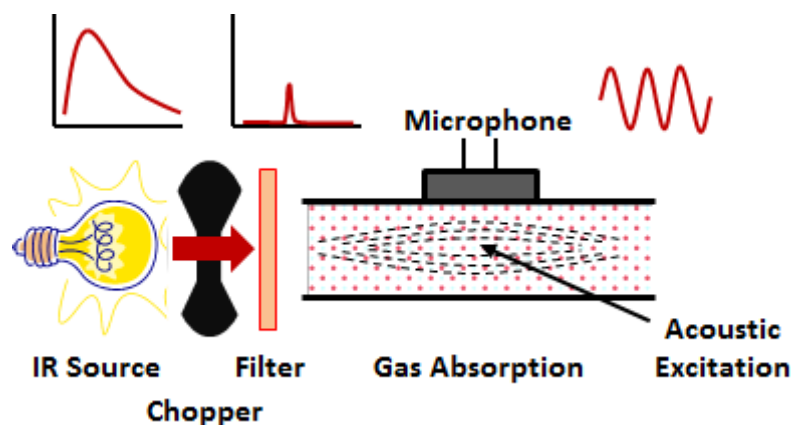


Figure 9. Schematic of a photoacoustic detector.

system. A lower cost compromise is to use MEMS emitters, which can be modulated at frequencies up to 50Hz or more, which is in a favorable range of the microphone to allow good sensitivity.

Photoacoustic detection can be performed directly on the absorption column, as is shown in Figure 9, or using a cell containing a large concentration of the analyte. In this case, the gas cell only absorbs wavelengths specific to the analyte, detected by a built-in microphone or pressure sensor.

PROSPECTS FOR APPLICATION IN SMOKE ALARMS

DESIGN REQUIREMENTS

Cost is one of the most important consumer qualifications for smoke alarms. Residential smoke alarms range in price from less than \$10, to more than \$50. Suggested retail prices are sometimes higher, but products are often heavily discounted. A goal of \$20–\$30 for next-generation home smoke alarms is desired and may not be unreasonable, if designs are carefully considered and high-volume manufacturing methods are employed.

Maintenance and replacement should be considered in the overall cost of ownership. Frequent replacement of batteries is not only costly and inconvenient, but it also risks leaving the smoke alarm inoperative if batteries are dead or not installed in a timely fashion. Because most smoke alarm failures (to warn occupants of a fire adequately) are attributable to missing, disconnected, or dead batteries,¹¹ battery life is an important factor. Battery life of up to 10 years is available in some commercial models, and such longevity should be a goal for next-generation smoke alarms. Current aerosol-detector alarms have lifetimes of 10 or more years, which should also be attained by future smoke alarm units, if possible.

Convenient and continuous power for a smoke alarm is vital to providing full protection to home occupants. Installation in new homes may allow wired connections to supply power and provide interconnection with other alarms. Nevertheless, battery backup is required during intervals when the main power is interrupted. A rechargeable NiMH (nickel metal hydride) or a primary AA

¹¹ Ahrens, Marty. (2008) "Home Smoke Alarms: The Data as Context for Decision." *Fire Technology* **44**: 313–27.

battery, for example, has an energy content of roughly 3 watt-hours in low-drain operation. Three batteries could power a 50mW average load for more than a week. For retrofit and wireless operation, a conventional 9V battery has an energy content of almost 5 watt-hours and can power a 0.5mW load for one year or a 0.1mW load for 5 years. Ideally, a battery-powered alarm should require no more than 0.1mW for 5-year operation and no more than about 50mW for a wired alarm in battery-backup mode.

If new sensors are employed, they must be able to sense fire-signature components quickly at low concentrations to allow the earliest possible alarm. Thresholds for current smoke alarms with aerosol sensors are set near the ultimate limit for early fire detection with reasonable nuisance rejection. Thresholds for other combustion products have yet to be determined, and in fact, are not always applicable for some advanced discrimination algorithms that incorporate multiple channels of data. Hagen and Milke investigated a number of smoldering, flaming, and nuisance sources and determined thresholds for changes in CO, CO₂, temperature, and Taguchi sensors.¹² Using only these sensors, they found useable thresholds for detecting flaming fires of 210ppm for CO₂ and 40°C for temperature. For smoldering fires, the thresholds were 17ppm for CO and 22ppm for CO₂, plus particular responses from two Taguchi sensors. Although not definitive, such levels can be of help preliminarily in scaling detection limits for CO and CO₂ sensors. Consequently, signal-to-noise levels equivalent to about 5ppm or less for CO and CO₂ seem to be consistent and reasonable goals for evaluating potential sensors for these compounds. The required level at which hydrocarbons should be detected is yet to be determined, but high sensitivity is desirable for early detection. In any case, multiple sensors providing different information about various components associated with fires should improve smoke-alarm performance.

Although water is produced as a combustion product, calculations show that ordinary humidity levels would dominate sensor response. Assuming a –CH₂– backbone for cellulose, as an example, equal amounts of water and CO or CO₂ would be formed during combustion. Thus, if the order of 20 ppm of CO or CO₂ is significant for fire detection, then water could be expected at the same level. For ordinary room temperature, a change of 20 ppm of water in the air corresponds only to about 0.06 percent relative humidity change. This level of precision cannot be expected by a sensor that is also responsive to ambient levels of humidity. On the other hand, humidity sensing could be useful to recognize and reject nuisances related to water fogging or condensation. For example, a combination of relative humidity and temperature sensors can be used to suppress false alarms caused by humidity conditions in ionization and photoelectric smoke alarms.¹³

CARBON DIOXIDE DETECTION

SOLID STATE SENSORS

Numerous studies have been performed over the past few decades that illustrate various ways to detect CO₂. Chromophores, pH indicators, semiconductors, metal oxides, photoconductors, polymers, sol-gels, and other materials have been demonstrated as sensing materials for CO₂. The most successful material-based methods have used Na⁺ or Li⁺ ionic conductors in a heated

¹² Hagen, B.C. and J. A. Milke. (2000) "The use of gaseous signatures as a mean to detect fires." *Fire Safety Journal* **34**: 55–67.

¹³ Chabanis, G., P. Mangon, and S. Rivet. (2009) "Fire or smoke detector with high false alarm rejection performance." U.S. Patent App. 2009/0051552.

electrochemical cell. These may be employed in commercial products, such as the Figaro TGS4161 sensor, which has been shown in our laboratory tests to have a remarkably low noise, equivalent to 2 ppm CO₂ (see Figure 10). These are reported to have a long life (perhaps several years) but can be degraded by high humidity. Power consumption in the TGS4161 is 250mW, which exceeds the power budget even for battery backup of a wired sensor. Experimental microfabricated versions have also been demonstrated that could reduce power consumption to acceptable levels for wired systems. Nevertheless, until material-based CO₂ sensors have demonstrated reliable performance approaching 10 years in ordinary home environments, they should be removed from consideration.

NDIR SENSORS

Although more bulky and costly, NDIR systems have long been preferred for CO₂ sensing. A very strong infrared (IR) absorption band at 4.26 μ m dominates over interference from water and most other species. At this wavelength, the transmittance of certain glasses is still high enough to allow an encapsulated filament to be used as a light source. The average power consumption ranges from less than 50mW to 1W or more, depending upon the manufacturer and mode of operation.

Figure 10 shows data taken with two commercial NDIR CO₂ sensors that are near their limits in their ability to distinguish changes in CO₂ concentration. These sensors actually were designed for building ventilation control, where changes of 50 ppm or more are significant. Nevertheless, changes of 10 ppm or less are apparent.

Some simplifications and refinements are needed for application of NDIR CO₂ sensing for smoke alarm applications. Other than the wavelength and band pass filter, the basic components are

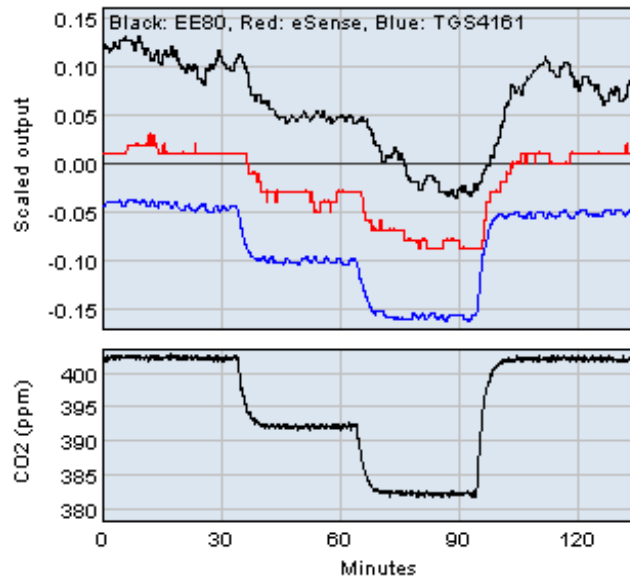


Figure 10. (*upper*) Response to steps of 10ppm CO₂ for two commercial NDIR CO₂ sensors, an E+E Electronik EE80 and a SenseAir Duo, and an electrochemical sensor, the Figaro TGS4161. Outputs have been scaled for comparison. (*lower*) Reading from a high-quality reference sensor, the Licor 820.

similar to those in a near-IR photoelectric smoke alarm. However, because low-cost LEDs have not been developed yet for the mid-IR region, incandescent lamps continue to be employed as the light source. Likewise, photo detection is more difficult in the mid-IR, requiring special materials for photodiodes, which are expensive, as are bolometers. Pyroelectric and thermopile detectors are relatively inexpensive and generally are used.

INFRARED SOURCES

Incandescent lamps offer an inexpensive mid-IR source but are very inefficient and suffer from long-term drift. Much of the IR radiation at 4.26 μ m is absorbed by the envelope, which reradiates but at a much lower temperature. The resulting spectrum is not representative of a predictable black-body source. Additionally, changes in the filament and the envelope, over time, alter the spectrum and output intensity. For NDIR systems that use a separate wavelength for reference, spectral shifts will cause decalibration. At least one manufacturer uses two lamps, one pulsed regularly for sensing and one reserved as a reference for occasional auto-calibration. Typical power required is roughly 10 watts for 0.1 seconds, resulting in an average power consumption of 100mW, if the sampling is done on 10-second intervals (1 percent duty factor).

MEMS emitters are being explored as much more efficient and stable alternatives. Membranes or tiny suspended hotplates can be micro-manufactured to provide low thermal mass and low thermal conductivity to the supporting structure. These can be operated at 10–50Hz or more, depending upon the design, to allow ac noise-reduction techniques or to modulate photoacoustic detectors. Devices are available commercially that operate at 400°C to 700°C providing adequate light in the mid-IR. The structures are claimed to have lifetimes of as much as 10⁵ hours (11 years) or more. The emitting surface can also be fabricated as a photonic structure and tuned to enhance emission at 4.26 μ m or other wavelengths. The power required depends upon the heated area and the design; but typically, several hundred mW of continuous power is required, or less than 10mW average power for a 1 percent duty factor.

Mid-IR sources are also possible with LEDs, which may eventually join their shorter-wavelength versions as a low-cost option. When they become available, mid-IR LEDs will allow modulation at higher frequency for improved signal-to-noise performance. Also, they would be ideal for photoacoustic sensors to allow operation at frequencies that are better matched to the high-Q region of microphones. Unfortunately, despite many years of effort, mid-IR LEDs still have broad emission and generally emit at lower intensities than thermal emitters. Military applications will continue to drive their development; so this technology bears watching for NDIR applications. Semiconductor and quantum-cascade lasers are much more remote possibilities for tuned mid-IR sources.

INFRARED DETECTION

Mid-IR photodetection is generally accomplished with a photodiode, bolometer, thermopile, or pyroelectric detector. Photodiodes in this wavelength region require special materials (HgCdTe¹⁴) and cooling to achieve optimum performance. Bolometers (thermoresistive) are somewhat less sensitive and still restricted to applications that can support their higher costs. Thermopiles and pyroelectric detectors are applicable for consumer applications. In fact, inexpensive home occupancy alarms to sense the presence of a person use a pyroelectric detector and a compound lens. Pyroelectric devices have a higher frequency response than thermopiles but also have

¹⁴ Mercury cadmium telluride

significant noise and are best applied for detection of modulated sources. Thermopiles probably represent the best general choice for NDIR, due to their low cost and very flat response over the mid- and long-wavelength IR.

Photoacoustic detection can be a viable option if the IR source can be modulated. Studies have shown very high signal-to-noise characteristics when using narrow, high-frequency bands. Even at frequencies accessible to MEMS thermal emitters, enhanced signal-to-noise has been seen. Beer and coworkers compared photoacoustic and thermopile detectors for NDIR detection of CO₂, CO and CH₄, using a modulated thermal source, and reported gains of well over an order of magnitude.¹⁵ The detection limit for CO₂ was only 20 ppm, and results have yet to be verified; but such studies suggest the possibility of making small, highly sensitive NDIR systems. Photoacoustic cells of various designs have been made using anodic bonding of transparent windows to silicon. Building in a microphone that is micromachined in silicon would make a highly integrated device; however, development of MEMS requires a large investment to achieve low manufacturing costs. To date, low-cost photoacoustic cells have not been commercially manufactured.

NDIR DESIGNS

Implementing technology like NDIR gas sensing for a low-cost consumer product is challenging because the technology is still maturing even for building ventilation applications. The basic design of an NDIR system shown in Figure 8 is simple and may be adequate for CO₂ sensing. Without a reference, stability of the system, especially the IR source, can be a concern. Any drift in the source will be seen as an equivalent change in CO₂ concentration; however only short-term increases in gas concentration are important for fire discrimination. Drifts in calibration can be corrected automatically, assuming that the light source is relatively stable in the short term (hours), the light path is unaltered, and the filter bandpass remains stable. Long-term drifts in source intensity will be seen as a gradual change of the detector signal, which can be used to adjust the calibration or sensitivity in a proportional manner. Such corrections may not be fully satisfactory for building-ventilation requirements but may be adequate for detection of a fire. Alternatively, other innovative methods could be used.

Hollow-tube light pipes are sometimes used as absorption cells and have also been used for NDIR sensing. Although gold coatings have a slightly higher reflectivity in some IR regions, aluminum is extremely good and it is also inexpensive. Folded-path absorption cells are often used for very small systems, but the stability of the reflective surface is more critical and is affected by absorbed dust particles. Thus, a filtration membrane to keep dust out of the optical region is essential. Mayrwöger and his colleagues modeled a light-pipe NDIR system and determined the number and angles of reflections and the path lengths, among other characteristics. They found a significant portion of rays that alter the filter bandpass due to their angular distribution.¹⁶ This could affect calibration if the reflectivity of the light pipe changes with surface contamination over time. However, the effects should be modest due to the predominance of low-angle scattering.

A more stable system can be designed by adding a reference channel, which can ensure that short-term drifts in the IR source do not cause sensor inaccuracies. Rather than use a bandpass filter

¹⁵ Beer, S., A. Helwig, et al. (2009) "Infrared-based Fire Gas Detection Systems." 14th International Conference On Automatic Fire Detection (AUBE-09), September 8–10, 2009, Duisburg, Germany. Proceedings, Vol.1, p. 197.

¹⁶ Mayrwöger, J., P. Hauer, et al. (2010) "Modeling of Infrared Gas Sensors Using a Ray Tracing Approach." IEEE Sensors Journal **10**(11): 1691-8.

centered in a nonabsorbing part of the IR spectrum, this sensor uses a bandpass filter identical to that at the end of the absorption column with the reference detector close to the IR source.¹⁷ A schematic is shown in Figure 11. The ratio of the signal from the two channels can be related to the concentration of CO₂ and is independent of the IR source intensity or even the spectral content of the light. Common-mode noise between the two channels is compensated to first order. Thus, noise is reduced and long-term stability is greatly improved. Tests of a prototype NDIR system with a path length of only 2.5 inches has shown resolution of better than 10 ppm CO₂ in the authors' laboratory.

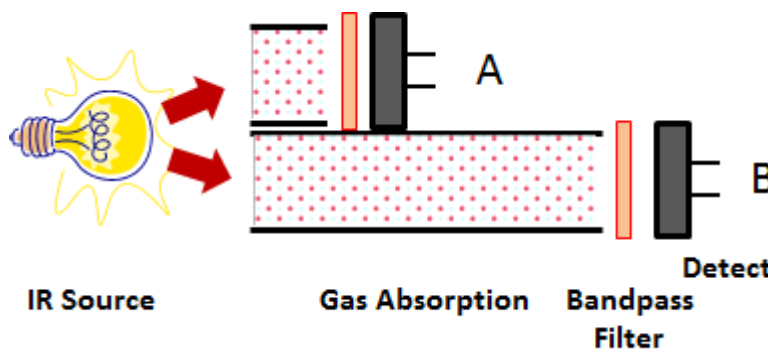


Figure 11. Schematic of an absorption-biased (AB) NDIR using two channels with identical detectors and bandpass filters but with unequal paths.

Regardless of whether incandescent or MEMS emitters are used, only wired systems with battery backup are possible with currently available IR sources. Even at 10mW consumption for MEMS, batteries would not last much more than a month, but battery backup could easily be handled. Powering is more of a concern if conventional incandescent emitters are used. The sampling rate might need to be extended to 30 seconds or more during line-power outages to stay within the backup power budget.

CARBON MONOXIDE DETECTION

Carbon monoxide alarms have been available for home monitoring since the 1990s. Biomimetic, Taguchi, and electrochemical technologies have been used, but the latter has generally displaced the other technologies, due to low power and superior performance. Alarm thresholds are a function of concentration and time and are designed to mimic the uptake of carbon monoxide in the body. For such home-monitoring units, UL2034¹⁸ specifies, in part, that a unit must alarm in 60 to 240 minutes at 70 ppm, which is much too slow and insensitive for early fire detection. Therefore, CO sensors must operate quite differently than CO alarms in current use.

ELECTROCHEMICAL

Fortunately, electrochemical CO sensors are well developed and capable of rapidly sensing CO concentrations commensurate with early fire detection, as shown in Figure 6. To the authors' knowledge, extensive testing has not been performed to ensure stability at the low ppm levels

¹⁷ Wong, Jacob Y. (2011) "Absorption Biased NDIR Gas Sensing Methodology." U.S. Patent App. 20110042570.

¹⁸ Single and Multiple Station Carbon Monoxide Alarms.

ultimately required by fire detection. However, some fire alarms are beginning to appear that intelligently combine aerosol and CO sensors to improve sensitivity and reduce nuisance alarms. Lifetimes have been extended to seven years or more by tight design and by increasing the water-reservoir volume. In general, electrochemical sensors do not have self-checking methods and must be replaced when their expected life expires.¹⁹

NONDISPERSIVE INFRARED (NDIR)

The IR absorption of CO is roughly an order of magnitude weaker than that of CO₂, making detection proportionally more difficult at similar concentrations. Also, at 4.65 μ m, the IR absorption is excessive for incandescent-lamp envelopes commonly used for CO₂ sensing, requiring MEMS emitters to be used at this wavelength. With the modifications of a MEMS emitter, an extended absorption path length, and a bandpass filter centered at 4.65 μ m, an NDIR CO sensor is identical to the NDIR sensor for CO₂. Again, because NDIR sensors can be self-checking, proper operation can be assured over the sensor lifetime, which can be in excess of 10 years.

DETECTION OF HYDROCARBONS AND OTHER SPECIES

Numerous hydrocarbons and other compounds are produced in greatly varying amounts as combustion proceeds. Heavier hydrocarbons tend to condense on surfaces and aerosols, while lighter hydrocarbons often persist as vapors that can be detected. Concentrations associated with incipient fire conditions are difficult to assign, but sensitivity to concentrations in the low ppm range would be desirable for an acceptable sensor technology. Sorbent sensors and electrochemical sensors sometimes can have limits in the low-ppm range. For example, MEMS chemicapacitors have typical detection limits of roughly 10–100 ppm, including benzene, toluene and methanol.²⁰ Species like methane and formaldehyde cannot be sensed easily by reversible absorption. Electrochemical technology has similar limitations in sensitivity but has different gaps in detection chemistries. Only Taguchi and NDIR sensors appear to cover a wide range of hydrocarbons and combustion products.

Taguchi sensors, as has been noted, can respond to a wide range of hydrocarbons and other species associated with combustion, like CO, HCl, and HCN. They generally have sensitivity to humidity as well, which could act as a nuisance, unless formulations are chosen to be less sensitive to humidity. If humidity sensors are also available in the fire detector, compensation could be applied. Because Taguchi sensors generally have a broad range of sensitivities, other nuisances like cigarette smoke, hair spray, and fingernail polish could be problematic. Nevertheless, if properly integrated, Taguchi sensors could add valuable sensing of compounds to corroborate information from other sensors in fire recognition.

Ordinary Taguchi sensors require too much power for battery backup systems, but MEMS versions are beginning to appear. For example, one manufacturer makes a volatile-organic-compound sensor that is being used in a commercial bathroom air freshener (about \$12 retail). In high

¹⁹ The internal basic functionality can be checked by reversing the current to generate hydrogen, which reacts subsequently on the catalytic electrodes, releasing a current that is characteristic of a functioning electrochemical cell. See Shen, Y. and F. Consadori (2001). "Gas Sensor with Diagnostic Device." U.S. Patent 6,200,443.

²⁰ Patel, S. V., T. E. Mlsna, et al. (2003). "Chemicapacitive microsensors for volatile organic compound detection." *Sensors and Actuators B-Chemical* **96(3)**: 541–53.

volumes, the sensor chip could sell for \$2 each, or possibly less. The manufacturer claims a lifetime of about 10 years or more, if operated in pulsed mode, which consumes the order of 1mW.

NDIR sensors can be set to 3.2 μ m–3.5 μ m bandpass, which is primarily associated with C-H stretch common to all hydrocarbons. Although commercial hydrocarbon NDIR sensors are generally adjusted to read 0–100 percent lower explosive limit (LEL), an NDIR sensor could be designed to sense hydrocarbon increases of a few ppm relevant to early fire detection. Absorption strength is roughly similar to that of CO, but the entire repertoire of combustion hydrocarbons would be detected. As with NDIR sensors for CO₂ and CO, a high-efficiency MEMS emitter would be required to allow battery-backup operation.

TRENDS & RECOMMENDATIONS

Fire detection technology must continue to evolve with advances in sensors, microcontrollers, and alerting methods. Indeed, some integration is already beginning to be seen. Combination ionization and photoelectric smoke alarms have been available for a few years. If integrated well with a microcontroller, such combination alarms address the weaknesses of each type of alarm with a single sensor. Nuisance rejection is more difficult with aerosol sensors; however, the use of an intelligently programmed microcontroller can help recognize conditions and trends for sensitivity adjustment. Microcontrollers allow even more advanced discrimination techniques to be exploited and are particularly applicable for multiple channels of data which must be classified as “fire,” “nuisance,” or “normal” conditions. For systems that include a CO sensor, a fourth class could be added to indicate the presence of that toxic gas, according to UL-2034 specifications. Approaches based upon rules involving set concentration thresholds become cumbersome for the design engineer and possibly inaccurate when in service. Appendix B discusses some advanced statistical techniques that allow data from multiple channels to be classified for alarming. Linear discriminant analysis (LDA), for example, involves a set of linear equations that can be readily evaluated on an inexpensive microcontroller. The linear coefficients would be determined beforehand, using training data from fire scenarios. Fortunately, considerable data already exists in prior tests undertaken by Underwriters Laboratory²¹ (UL) and the National Institute of Standards and Technology²² (NIST). Such techniques also allow each sensor output and its rate of change to be included in the analysis.

Advances in photoelectric smoke alarms have been implemented in an attempt to improve fire detection and discrimination of smoke particles. For example, some models intended for commercial applications employ dual-angle scattering to allow better characterization of the size of aerosol particles. Other models add blue-wavelength scattering to detect smaller aerosols typically associated with flaming fires or use dual wavelengths (near-IR and blue) to determine the size of the aerosols and to reduce false alarms. Although these refined photoelectric sensors are designed for commercial use and currently are available only in Europe, they may signal what future aerosol detectors may contain. There is a strong desire in some communities to replace ionization sensors and their associated radioactive sources with photoelectric sensors.

²¹ Fabian TZ, Gandhi PD. 2007. “Smoke Characterization Project.” Northbrook, IL: Underwriters Laboratory Inc.

²² Bukowski RW, et al., 2008. “Performance of Home Smoke Alarms.” Washington: National Institute of Standards and Technology Technical Note 1455-1. <www.nist.gov/el/fire_protection/buildings/home-smoke-alarm-tests.cfm>.

Other multisensor systems are making inroads for commercial applications. Data from temperature and CO sensors are often combined with aerosol and other sensors in a fire control panel with pattern-recognition algorithms for fire recognition and alarming. One detector adjusts the sensitivity of the photoelectric aerosol detector based upon increases in temperature. Another manufacturer adds CO sensing and IR sensing of ambient light levels. One manufacturer even uses an “electronic nose” of six metal-oxide (Taguchi) sensors along with humidity and temperature to signal early stages of fire. The existence of these and other advanced systems demonstrate the need of, and market for, improved fire detection.

Residential smoke alarms can benefit and have benefitted from the adoption of some of the advancements seen in the commercial market. Microcontrollers allow better discrimination, diagnostics, and more intelligent integration of multiple sensors. Environmental factors and sensor drift can be compensated in part through baseline adjustment provided by analysis of sensor output over time and by correlation with temperature and humidity sensors. Adding a temperature sensor is probably the simplest option that will at least signal the rapid heat rise accompanying open fires. Thermistors are very inexpensive (~\$0.03) and are readily coupled to microcontrollers, which can calculate the rate of temperature change (ΔT) and use the information (both T and ΔT) to adjust thresholds for alarm. The combination of a conventional photoelectric smoke alarm with a temperature sensor should improve response time for both flaming and smoldering fires, while reducing false alarms due to certain nuisances (*e.g.*, cooking emanations detected by ionization alarms). Humidity sensors could help discriminate problems due to condensation and fogging, but their worth needs to be balanced against their cost (currently \$1–\$5). Chemical sensors for other fire components would be the next step to provide early warning and better discrimination.

Carbon monoxide sensing adds two important dimensions for protecting the home occupant. Not only is CO primarily associated with oxygen-deficient and smoldering conditions in fires, but it is also linked to faulty heaters and other sources of combustion that can lead to incapacitation of exposed occupants. Partial incapacitation caused by CO ingestion from fire conditions can also hinder an occupant’s ability to respond to an alarm signal. Gottuk and coworkers demonstrated that combination aerosol and CO detectors using simple algorithms significantly improved fire detection and nuisance rejection.²³ Cestari and coworkers also found that CO sensing could respond to smoldering fires faster than photoelectric sensors and with better nuisance rejection.²⁴ In fact, they found that three combinations of CO, temperature, and ionization signals provided the “best fire sensitivity and nuisance immunity.” The essential element in these three combinations was the CO sensor.

Electrochemical sensing provides the easiest path for incorporating a CO sensor into a smoke alarm and is already available for the residential market in standalone CO alarms and combination smoke/CO alarms. It requires low power and is compatible with extended battery operation, but currently, it has a lifetime of about seven years. Taguchi sensors also can detect CO, as well as numerous other species, and they have been used extensively in Japan in CO monitors. These are said to have lifetimes of 5–10 years. MEMS versions are capable of being used with a wired system with battery backup. A key feature of the Taguchi devices is their high sensitivity to other chemical compounds accompanying fires but also, unfortunately, to other common environmental

²³ Gottuk, D.T. et al. (2002) “Advanced fire detection using multi-signature alarm algorithms.” *Fire Safety Journal* **37**: 381–94.

²⁴ Cestari, L. A., C. Worrell, and J.A. Milke (2005). “Advanced fire detection algorithms using data from the home smoke detector project.” *Fire Safety Journal* **40**(1): 1–28.

compounds. Because electrochemical sensing is well developed for toxic-gas detection and is relatively inexpensive, it is likely to be employed as an auxiliary sensor for fire detection in the near term.

The development of an NDIR CO detector would offer extended lifetimes well beyond 10 years and also provide for self-checking to ensure full protection from both fires and CO poisoning. To date, the limited market and the current high cost for NDIR has thwarted interest and has resulted in very few available CO detectors. Innovative design and high-volume manufacture should be able to bring the assembled cost to \$5–\$10.²⁵ A low-cost, reliable CO monitor would represent a major advance for both fire and CO protection.

Carbon dioxide production is primarily associated with flaming fires, which also produce aerosols and temperature increases. Thus, CO₂ data should correlate with ionization and temperature data and may prove partially redundant, if these sensors are also present. On the other hand, a CO₂ monitor may prove just as effective, if not more so, than an ionization sensor. If so, an inexpensive CO₂ sensor could replace the ionization sensor to eliminate concerns about radioactivity. An electrochemical CO₂ sensor is possible, but this would require development of a lower-powered MEMS version for battery backup. Concerns of lifetime and validation that accompany material-based sensors discourage this approach. The reliability advantages of an NDIR CO₂ sensor are offset by its present expense; although very high volume manufacturing methods could reduce production costs to well under \$5, commensurate with cost reductions seen in the manufacture of compact-disk heads. An NDIR CO₂ sensor could be combined with an NDIR CO sensor with very modest incremental cost, by adding another bandpass filter and detector. The fact that CO₂ is also produced by human respiration should also be factored into fire detection algorithms. For example, sudden increases in CO₂, accompanied by commensurate increases in temperature, are characteristic of flaming fires; while slower, modest increases in CO₂, unaccompanied by high temperatures, are more characteristic of room occupancy.

Sensing of hydrocarbons and other compounds is probably accomplished most easily with Taguchi sensors with inexpensive MEMS versions that are already available. Alternatively, NDIR sensing of hydrocarbons is also possible. The absorption intensity for individual species is roughly similar to that of CO; but the additive absorption from a combination of fire effluents should make detection easier. Working designs of NDIR CO sensors should be preliminary to consideration of NDIR sensing of hydrocarbons. Devices combining hydrocarbon sensing with NDIR CO₂ and CO sensing could eventually lower costs.

Another important consideration for residential smoke alarms is the means for alerting occupants. The temporal-three (T-3) pattern, as defined by the ISO standard 8201, "Acoustics - Audible Emergency Evacuation Signal," may become the standardized alarm signal. However, a mixed frequency T-3 alert has been found to be more effective than a high-frequency T-3 signal used in current U.S. smoke alarms. Other studies have shown that voice alarms and a lower pitch T-3 signal were better than high-pitched sounds.²⁶ Ian Thomas and Dorothy Bruck have found that a 520-Hz square-wave auditory signal is much more effective than the current 3100-Hz T-3 alarm signal.²⁷ The widely spaced overtones produced by the square-wave excitation of the voice-coil speakers

²⁵ J.A. Wong, Airware, Inc., private communication.

²⁶ Ahrens, M. (2008). "Home Smoke Alarms: The Data as Context for Decision." *Fire Technology* **44**: 313–27.

²⁷ Thomas, I. and D. Bruck. "Awakening of Sleeping People: A Decade of Research." *Fire Technology* **46**(3): 743–61.

also appear to be important in the alerting action. Resonant sounders are unlikely to be able to effectively produce such frequencies, so a speaker would be required.²⁸ A speaker could also provide voice alerting, as well as identification of the nature of the problem and a clear message to evacuate.

CONCLUSIONS

Home smoke alarms have matured over the past four decades to the point that many consumers consider them a low-cost commodity. However, early and accurate recognition of real fire events continues to be a challenge for most of the home smoke alarms in use today. Studies have shown that only about half of smoke alarms operated properly in reported home fires. Nuisance alarms are the leading cause for disabling of home fire alarms, which is associated with the majority of home fire deaths.²⁶

Technically, there are a number of viable technologies that can greatly improve the performance of home smoke alarms. In fact, manufacturers are already taking steps to implement improvements. Microcontrollers are being incorporated that allow more sophisticated tracking of sensor data and better integration of multiple technologies. Discrimination algorithms, as described in Appendix B, could take advantage of inherent computing power to provide more sensitive detection of fires with improved nuisance rejection. As a component of fire sensing, CO sensors are beginning to be coupled with smoke alarms. Advances in photoelectric aerosol detectors, such as blue-light and multiple-angle scattering, appear mostly in restricted commercial applications. However, with the advent of inexpensive blue LEDs, replacement of near-IR LEDs should be considered to extend sensitivity of photoelectric detectors for smaller aerosols associated with flaming fires.

Temperature sensing is available in a few smoke alarms and is very powerful for recognizing heat released from flaming fires. It should be very resistant to most nuisances when intelligently programmed to recognize persistent increases in temperature. The incremental cost of incorporation of temperature sensing is extremely low when added to microcontroller systems.

Carbon monoxide monitoring is potentially one of the most effective ways to sense smoldering fires while also alerting home occupants to toxic levels of CO from other sources. Electrochemical sensors are available and are already being implemented. These can be totally battery powered for replacement of units in existing homes. Disadvantages include limited life and inability for full self-checking. NDIR sensors, on the other hand, can be made self-checking and have lifetimes greater than 10 years, commensurate with photoelectric smoke alarms. Innovations are required to reduce manufacturing costs to be competitive with electrochemical sensing.

Beyond these basic technical refinements in the home smoke alarm arsenal, detection of CO₂, hydrocarbons, and other compounds can also be used to provide even better discrimination. While CO₂ evolution is expected from smoldering fires, CO₂ grows unmistakably in flaming fires. Clever extension of existing hardware will be required to keep costs affordable. Each added channel of

²⁸ A prototype battery-powered ceiling fire alarm containing a ~3.6-inch-diameter speaker has been demonstrated capable of producing greater than 85dBA at 520Hz in UL tests. Tests in the authors' laboratory indicate that the power consumption when the sounder is operated continuously is about 4 watts, equivalent to operating three AA alkaline batteries for roughly 2.5 hours or roughly 6–7 hours in the standard T-3 pattern.

fire-related sensor data should improve the ability of the home fire alarm to provide early and reliable warning of impending danger.

Consideration should also be given to the adoption of a more effective means of alerting home occupants. Studies²⁷ show a 520-Hz T-3 alarm signal produced by a speaker is much more effective than the current 3100-Hz T-3 signal usually produced by an efficient sounder. Interconnection of all the household alarms would also be much more effective at alerting occupants throughout households.

For the immediate future, the most effective technical strategy for designing improved smoke alarms is to employ discrimination algorithms in the microcontroller code. Appendix B provides some initial guidance to implement linear discriminant analysis for any number of sensors. Additional details will be provided in a future publication.²⁹ Even a single aerosol sensor could benefit from code that would perform baselining to correct for slow changes in sensor output. The code could calculate rate of change, as well and provide a second stream of data to be incorporated into the discrimination algorithm. Obviously, additional sensors giving data on temperature and CO, for example, would aid recognition and reliability in a substantial manner.

Additional development of testing under realistic conditions would benefit smoke-alarm development. Tests at NIST²² and UL²¹ have provided a very valuable means for developing and evaluating recognition algorithms with various sensor combinations. As sensors are refined and as new sensors are developed, testing under authentic conditions would ensure they become implemented in optimal ways. For example, photoelectric sensors that use wavelengths and scattering angles not previously tested should be included in future testing.

Beyond technical issues, other challenges that may hinder immediate implementation are certification, building codes, and engineering costs for manufacturers. Validation testing of sensors may need to be adjusted to ensure realistic fire conditions. A detailed study comparing the merits and costs for employing different technologies would be desirable. The availability of affordable home smoke alarms, coupled with strong recommendations from federal agencies, will help state and local agencies reform building codes to protect homes in their communities.

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²⁹ Warmack, R.J., and Wolf, D.A. (2012). unpublished.

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APPENDIX A

LIGHT SCATTERING FROM AEROSOL PARTICLES

Aerosol particles can be approximated as dielectric spheres that scatter incident light in patterns that can be predicted according to wavelength, polarization, particle diameter, and complex index of refraction. Observed scattering patterns, therefore, can be used to characterize aerosol sizes and optical properties. Such information could prove useful in discriminating aerosols produced from fire and nuisance sources. The following material highlights light scattering theory related to aerosols of interest in photoelectric smoke detection.

Light scattering scales according to the ratio of particle diameter to incident wavelength, λ . The scattering efficiency, defined as the scattering cross section divided by cross-sectional area, is shown in Figure A1. For small diameters (d less than $\sim\lambda/3$), the scattering becomes very weak, making particles difficult to detect. For diameters of the order of the wavelength, the scattering efficiency approaches the geometric cross section. In 1908, Gustov Mie calculated the scattering of light for any size particle as a series of Legendre functions. Earlier, Lord Rayleigh found an approximation for small particles ($d < \lambda/3$), in which the scattering efficiency is proportional to $(d/\lambda)^4$. Thus, larger aerosols in a distribution of particle sizes tend to dominate the scattered light intensity.

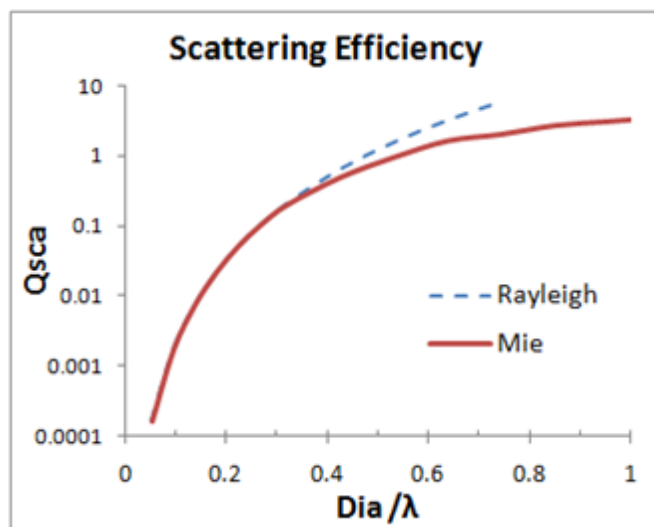


Figure A1. Scattering efficiency, defined as the scattering cross section, divided by cross-sectional area, as a function of scaled particle diameter. The index of refraction is 1.5. The Rayleigh approximation matches the Mie theory for small d / λ ratios.

Calculations of scattering efficiency for specific wavelengths are shown in Figure A2. Typically, inexpensive near-infrared LEDs with wavelengths of 880nm–940nm are used in modern photoelectric detectors. In recent years, blue LEDs with wavelengths near 470nm have become available and may allow improved detection of smaller aerosols. Smoke particles of interest for

early fire detection³⁰ range from roughly 0.05 μm to 0.3 μm , shaded in Figure A2. The increase in scattering efficiency for blue light over that for near-infrared is very clear. Nevertheless, for practical systems, the radiant intensity of the LED, after collimation and the sensitivity of the scattering detector, must be evaluated.

To gain information about particle size, data from different wavelengths or scattering angles can be

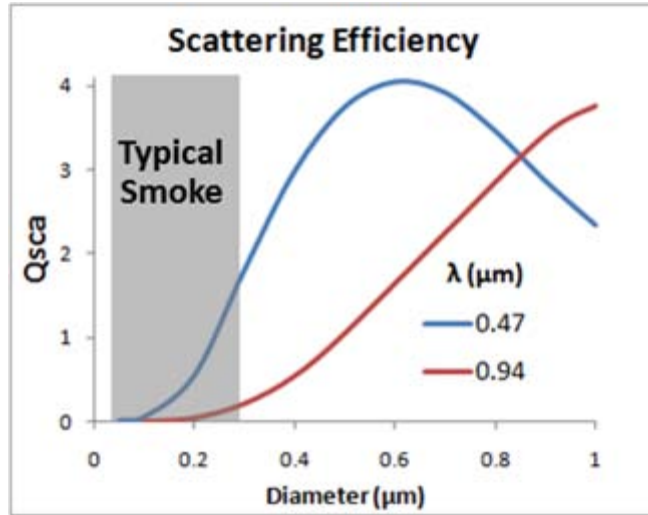


Figure A2. Scattering efficiency as a function of particle size for two selected wavelengths ($n = 1.5$). The typical mean diameter of smoke particles is shaded.

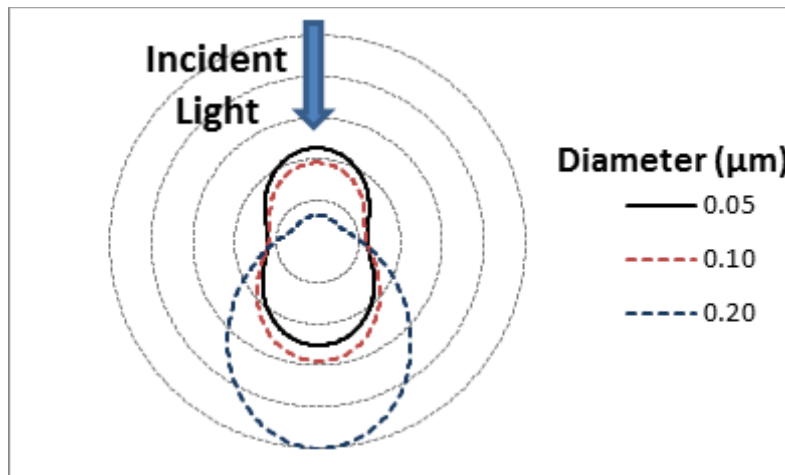


Figure A3. Normalized scattering of unpolarized 470nm light for three particle diameters ($n = 1.5$).

useful. Figure A3 shows how light that is scattered equally in the forward and backward directions

³⁰ Fabian TZ, Gandhi PD. 2007. Smoke Characterization Project. Northbrook, IL: Underwriters Laboratory Inc. p. 77ff.

for small particles becomes markedly forward-scattered for larger particles. Figure A4 shows the calculated ratio of scattered light in the largely backward and forward directions. This ratio can be used to gain information about particle size and can be combined with other sensor data to aid in authenticating fire conditions.

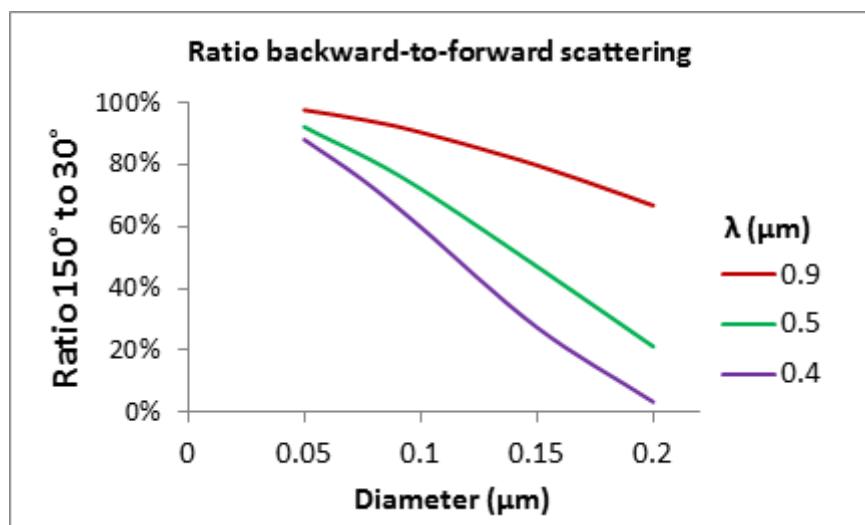


Figure A4. Calculated ratio of the scattered light at 150° and 30° as a function of aerosol diameter ($n = 1.5$) for three wavelengths.

APPENDIX B

CLASSIFICATION TECHNIQUES AND DISCRIMINANT ANALYSIS

The critical function of a fire alarm is to determine whether observed conditions indicate that an alarm is warranted. For most existing alarms with a single aerosol detector, classification is simply to alarm for aerosol concentrations beyond a fixed threshold. Unfortunately, nuisances can also sometimes trigger the alarm. For systems with more than one sensor data channel, the classification can be extended to “fire,” “nuisance,” or “normal” classes. For systems that include a CO sensor, a fourth class could be added to indicate the presence of that toxic gas, according to UL-2034 specifications. Designing an alarm based upon whether any one of several channels exceeds a certain threshold can lead to excessive nuisance alarms, if the thresholds are set too low, or insensitivity to fire conditions, if the thresholds are set too high. Pattern recognition or statistical classification couples the data channels, so that the analysis provides the best discrimination for classification based upon sensor response to historic data.

Classification methodologies are types of mathematical techniques that determine class or group membership of an object of unknown membership, according to rules derived from training data collected from all classes. These include discriminant analysis, tree-based modeling, neural networks, and nearest-neighbor classification. Principal components analysis is a useful technique for understanding the main characteristics of multi-attribute data and how those characteristics may relate to class differences. Below, we discuss principal components analysis and then focus upon linear discriminant analysis as a recommended technique to control alarms in residential smoke alarms.

PRINCIPAL-COMPONENTS ANALYSIS

One of the goals of principal-components analysis (PCA) is to identify main characteristics of a data set containing a number of interrelated variables³¹ (*e.g.*, sensor data channels in a fire alarm). PCA transforms the original variables into a new set of uncorrelated variables called principal components (PCs). The PCs are weighted sums of the original variables, where the weights are optimally chosen. The first PC is constructed so that it explains the most variation in the data, with the caveat that the source of the variation may or may not be due to differences among the classes. The second PC explains the next greatest amount of the variation and is uncorrelated with the first. Similarly other PCs are constructed. PCA is not a classification technique *per se*, but if the major sources of variation in the data are related to the class differences, then the PCs can be useful in a discriminant analysis.

LINEAR DISCRIMINANT ANALYSIS

Discriminant analysis is supervised pattern recognition.³² A set of discrimination rules are constructed from training data and used to classify new observations into predefined groups. Linear discriminant analysis (LDA) is one approach that classifies an observation according to its (multivariate) similarity or closeness to a group. In LDA, the observed data variables, or their PCs,

³¹ Jolliffe, I. T. *Principal Component Analysis*. Springer-Verlag: New York, 1986.

³² K. V. Mardia, J. T. K.; Bibby, J. M. *Multivariate Analysis*. Academic Press, Inc.: New York, 1976.

are transformed by a linear transformation into new, uncorrelated variables, called discriminant coordinates, in such a way to maximize the differences among the predefined groups, as measured on these variables.

There is a hierarchy of the discriminant coordinates. The first discriminant coordinate, LD_1 , accounts for the greatest separation among the groups; the second discriminant coordinate, LD_2 , accounts for the next greatest separation, and so forth. The maximum number of discriminant coordinates that can be extracted is one fewer than the number of groups.

Plots of combinations of the various discriminant coordinates are often used to visualize group separations. Clear group separations seen in two-dimensional plots will indicate success for those groups. Groups that appear to overlap in one plot (*e.g.*, in the LD_1 vs. LD_2 plot), may appear separated in another two-dimensional view (*e.g.*, LD_2 vs. LD_3). A discrimination rule can still be effective, even though there is no clear separation of groups in certain two-dimensional plots.

To illustrate a specific example, assume that the fire-alarm system consists of three sensors: an ionization chamber, a thermistor, and a CO sensor. Training data from room-sized fires and nuisance sources for these three sensors are used to determine the linear transformation to discriminant coordinates, so that the best separation is made. The data from those sensors might include their scalar values (preprocessed if desired, *e.g.*, averaged and baselined) and their time derivatives for a total of six data channels. Suppose there are four groups of interest: “normal,” “nuisance,” “CO,” and “fire,” and we have training data from each group on all six channels. A maximum of three discriminant coordinates can be derived in this example, but suppose for simplicity, that good classification is possible with the first two coordinates. Let \mathbf{x} represent the six data channels and \mathbf{w}_1 and \mathbf{w}_2 represent the corresponding coefficients for the first and second linear discriminants derived from the training set. Suppose \mathbf{c}_1 and \mathbf{c}_2 represent the four group centroids calculated from the training data and expressed in linear discriminant coordinates. The coefficients \mathbf{w}_1 and \mathbf{w}_2 for transforming the data channels into discriminant coordinates and the centroids of the four groups are stored in the microcontroller.

During operation of the fire alarm, the three sensors are sampled, the data are preprocessed, and the time derivatives are taken. The preprocessed data channels \mathbf{x} are then converted to discriminant coordinates \mathbf{y} by the linear transform:

The squared Euclidean distances to each of the centroids are calculated:

The nearest group is then determined from the smallest d_i^2 . This corresponds to the discriminant classification, which can be used directly for alarm, or further checks and rules can be applied before sounding the alarm. Such an algorithm can be readily employed by inexpensive (<\$1) microcontrollers.