Using Multiple Sensors for Discriminating Fire Detection

James A. Milke
Department of Fire Protection Engineering
University of Maryland, College Park, MD

Abstract

Numerous organizations are investigating the capabilities of multi-sensor fire detectors in the pursuit of an improved fire detector. Interest in such an advance is motivated by the potential of multi-sensor fire detectors to provide faster detection with fewer unnecessary alarms. Some multi-sensor detectors have already been developed and marketed which utilize existing sensor technology with an algorithm applied for the decision process. Discrimination between fire and nuisance sources can be achieved without sacrificing the time to detection by monitoring several aspects of the signature of an environment, including gas concentrations,. Increasing the number of sensors included in a detector to create an "artificial nose" can increase the sensitivity and level of discrimination. In the short term, such a detector is likely to be more expensive, have an uncertain reliability and have additional power and intelligence requirements. However, in the long term, with continued advances in sensor technology, such a multi-sensor fire detector may become feasible and practical. With the increasing interest in "smart buildings", such a detector may even become preferred, especially where a multi-sensor detector may be capable of monitoring the environment for multiple purposes, e.g. fire detection, carbon monoxide concentration, concentration of flammable gases and indoor air quality.

This paper describes research to demonstrate the performance of a multi-sensor fire detector. Experimental data of the signatures from a wide variety of fires and nuisance sources represented by CO, CO_2 and oxidizable gas concentrations is analyzed to develop rules for discrimination. Fire sources include flaming and non-flaming fires, while nuisance sources included aerosols and heated objects. In addition, engineering principles are applied to provide guidance on appropriate detector spacing to detect fires of a particular threshold fire size. Some discrimination between flaming fires, non-flaming fires and nuisance sources can be achieved using either a threshold concentration or rate of rise of CO_2 to identify flaming fires and a rate of rise of CO for non-flaming fires. A more sophisticated approach using threshold values and rates of rise of concentrations of CO, CO_2 and oxidizable gas sensors is also presented. The reduction in the time to detection and increased discrimination ability with this approach is compared to that from commercial, single-sensor smoke detectors.

Introduction

Two primary objectives of fire detection are:

1. to provide prompt indication of the presence of a fire
2. avoid "false positive" indications due to a response to deceptive signatures from nuisance sources.

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Unfortunately, contemporary single-station smoke detectors cannot easily discriminate between fire and non-fire sources of smoke, aerosols and odors. The substantial proportions of unnecessary alarms reported by smoke detectors may be indicative of this limitation. An estimated 95% of all alarms reported by smoke detectors during the 1980's in the U.S. were unnecessary [1]. In Switzerland, Pfister recently reported that between 1990 and 1995 the number of real alarms reported by smoke detectors increased from 7 to 9% with improved maintenance and increased fees for excessive unnecessary alarms [2]. In addition, limited experience in Switzerland with multi-sensor detectors in 1995 and 1996 indicated that real alarms were 40% of all alarms.

Grosshandler outlined advances in sensor technology along with intelligence that could be implemented to improve detection time while limiting the frequency of unnecessary alarms [3]. In the 1980's, Scheidweiler noted that intelligence was moving from the detector to the control unit [4]. In contrast, approximately 10 years later Thuillard proposed incorporating intelligence at the detector along with combinations of current sensor technology to minimize unnecessary alarms without sacrificing prompt activation [5].

Numerous researchers are exploring multi-sensor detection as the principal means of discriminating between fire and nuisance sources [5-7]. Multi-sensor detectors are used in a wide variety of industrial applications and in fire investigations [8]. Currently, many of these detectors are relatively expensive or slow.

At a recent international conference on fire detection, nine papers were presented on multi-sensor fire detection [7]. Using multi-sensor detectors, a vector can be assembled to describe the gas composition of the atmosphere and identify the signature produced from flaming fires, non-flaming fires and nuisance sources. Signature vectors may include gas concentrations, rates of rise, or both. The multi-dimensional map represented by the signature vectors may be assessed directly to determine the nature of the source, as is accomplished by mammals in analyzing the responses from thousands of olfactory receptors in the nose. Alternatively, the number of elements included in the pattern recognition process can be reduced by a variety of methods (neural network, principal component analysis, etc.) [9-14].

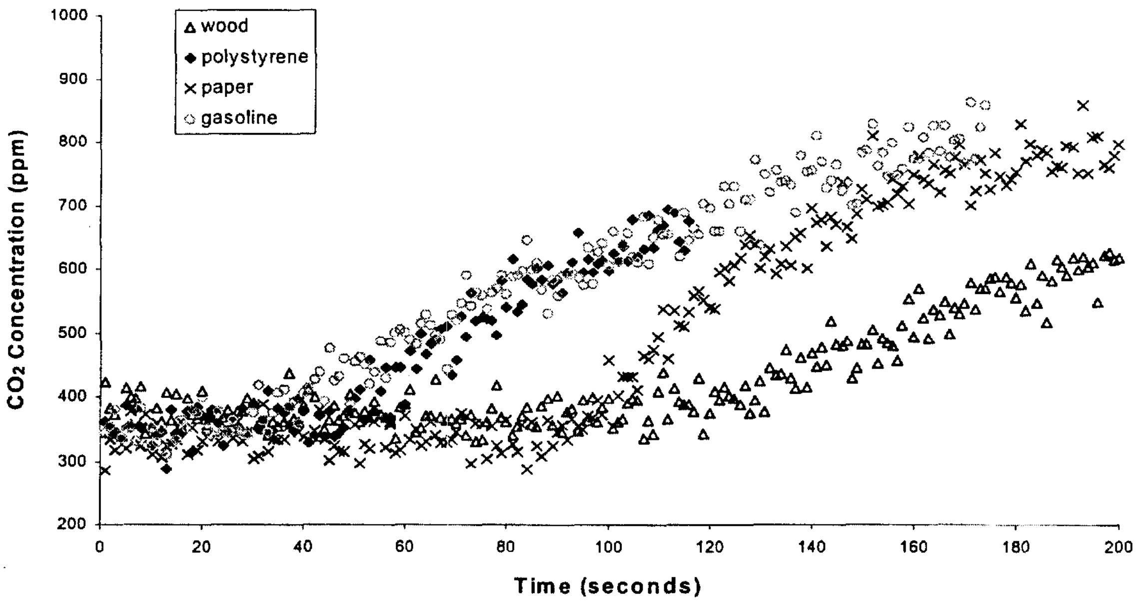
This paper describes the application of fire dynamics principles to support the development of a prototype advanced fire detector using multiple sensors. The performance of such a prototype advanced fire detector is demonstrated based on concentration magnitudes and rates of rise measured from experiments, along with pattern recognition methods.

Background

The ability to detect a fire is a function of the strength of the signature and the sensitivity of the sensor(s) to that signature. For example, a highly sensitive detector may provide a high frequency of unnecessary alarms if the magnitude of the threshold level of the signature for detection is only slightly different from ambient conditions. "Spikes" due to nuisance sources and electronic noise can give signals that exceed those from fires.

The generation of combustion products comprising the signature is a function of the fuel and combustion process. As an example, transient data of the CO_2 concentration from a set of tests involving the four flaming fire sources conducted in accordance with UL 268 are provided in Figure 1 [15]. The CO_2 profiles for polystyrene and gasoline are relatively similar, while those for paper and wood are appreciably different, both in terms of the time after ignition required to observe an appreciable increase in the CO_2 concentration to be recorded and the slope of the curve. The slopes of the curves during the initial growth period ranged from 2.5 to 6.5 ppm/sec.

Figure 1. CO_2 Accumulation Rate from UL 268 Flaming Fires



Rates of CO_2 accumulation in the upper portions of the UL test room are affected by the yield, heat of combustion and heat release rate of the fire source and the room geometry. The concentration of CO_2 in the upper layer can be determined by normalizing the amount of CO_2 produced by the volume of the upper layer. The volume of the upper layer can be estimated by a zone model approach. For a steady fire in a room with a constant horizontal cross-section area and flat ceiling, the height of the smoke layer from the top of the burning fuel package is [16]:

$$z = H\left[1 + \frac{2k_v t Q^{1/3} H^{2/3}}{(n+1)A}\right]^{-3/2} \tag{1}$$

The concentration of CO_2 in the upper layer can be determined for steady fires with a constant CO_2 yield by [16]:

$$Y_{CO2} = \frac{f_{CO2}Qt}{\rho\chi_a \Delta H_c A(H - z)} \tag{2}$$

Substituting the expression for the smoke layer height, z, from equation (1) into equation (2) provides a single equation relating the mass fraction of CO_2 and time.

$$Y_{CO2} = \frac{f_{CO2}Qt}{\rho\chi_a \Delta H_c AH\left(1 - \left[1 + \frac{2k_v t Q^{1/3} H^{2/3}}{A}\right]^{-3/2}\right)} \tag{3}$$

The mass fraction of CO_2 can be expressed as a volume fraction by applying equation (4):

$$ppm = 10^6 \frac{MW_{CO2}}{MW_{air}} Y_{CO2} = 1.53x10^6 Y_{CO2} \tag{4}$$

Differentiating equation (3) with respect to time for a steady fire provides an equation for the rate of rise of the mass fraction of CO_2 expected as a function of time, fuel properties and room geometry. The differentiation is performed using a mathematical software routine. For a steady fire, such as provided by the gasoline sample in UL 268, with an estimated heat release rate of 6.2 to 10 kW, the predicted rates of rise of CO_2 concentration compare favorably to those measured in two UL 268 tests, as presented in Figure 2. An estimate of the rate of rise of CO_2 is presented in Figure 3 for other heat release rates and room sizes. Variations in fuel composition of steady fires can also be investigated, as summarized in Figure 4. The influence of the fuel, while maintaining the same heat release rate is given by the ratio of $f_{CO2}/(\chi_a\Delta H_c)$. The value of the ratio for a variety of common fuels is given in Table 1 for flaming fires, based on values of the three parameters given by Tewarson for well-ventilated fires [17]. These estimates of CO_2 rate of rise for various fuels and room sizes are useful to provide guidance on appropriate detector spacing to detect fires of a particular threshold fire size, *i.e.* heat release rate.

Figure 2. Estimated Rate of Rise of CO_2

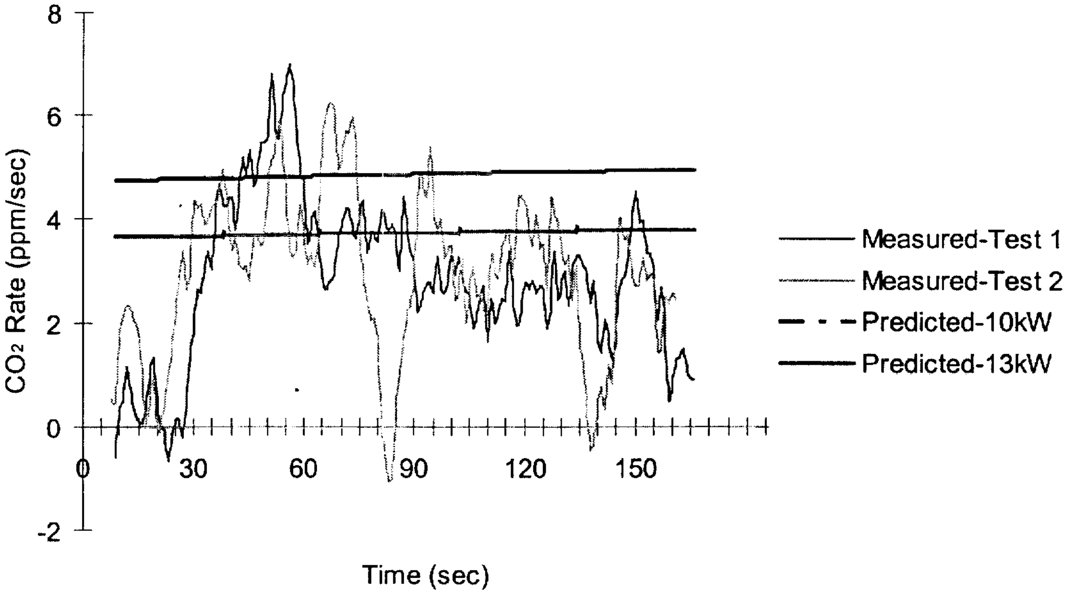


Figure 3. Rate of Rise of CO_2 for Gasoline Fires

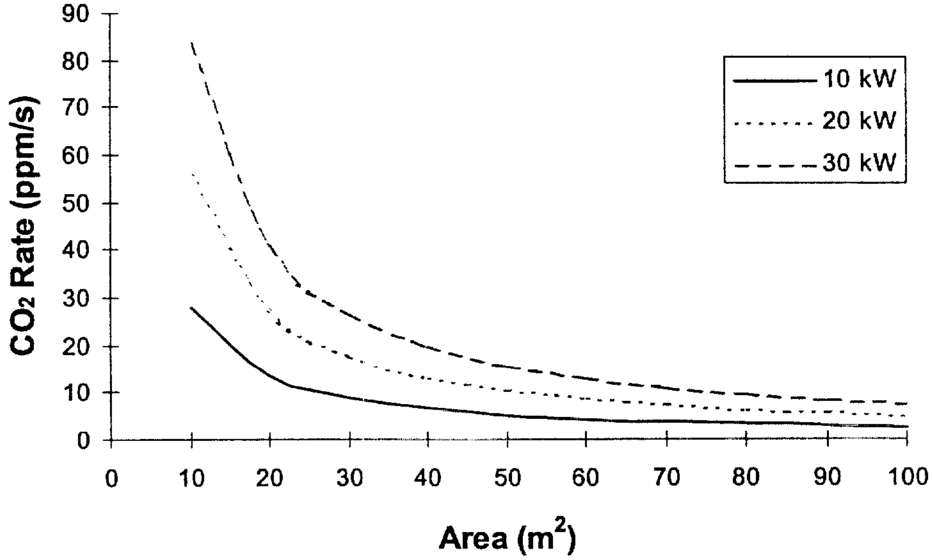


Figure 4. Effect of Fuel on Rate of Rise of CO_2

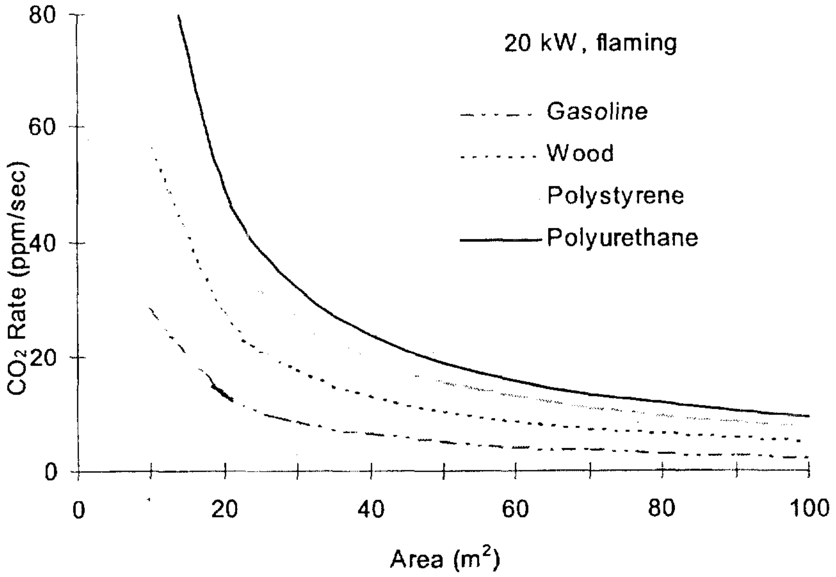


Table 1. Fuel Parameter for Yield of Carbon Dioxide

Fuel	**$f_{CO_2}/(\chi_a \Delta H_c)$ (g/kJ)**
methane	.055
heptane	.069
wood	.10-.11
polystyrene foam	.089-.095
polyurethane flexible foam	.079-.096
polyurethane rigid foam	.075-.097
polyvinyl chloride	.081

A similar analysis of the magnitude of the signature from non-flaming fires was conducted by Shaner [18]. One principal difference between flaming and non-flaming fires is the ratio of the CO_2 to CO generated. For flaming fires, the CO_2/CO ratio is on the order of 10 to 1,000. However, for non-flaming fires, the ratio may be on the order of 1. Yields for CO and CO_2 for smoldering fires are available in a limited number of references [18, 19]. The yield for CO in non-flaming fires reported by Quintiere, etal.., and Shaner is presented in Table 2. As with flaming fires, yield, heat of combustion and heat release rate of the fire source and the room geometry are the primary factors affecting the magnitude of the signature produced.

Table 2 CO Yield for Non-Flaming Fires

Fuel	f_{CO} (g CO/g fuel) [18]	f_{CO} (g CO/g fuel) [19]
Cotton	0.08-0.39	0.11
Paper	0.16-0.42	
cardboard	0.20	
wood	0.18	
polyurethane flexible foam	0.43	0.06-0.11

Experimental Program

The experimental program conducted by an interdisciplinary team from the Departments of Fire Protection Engineering and Chemical Engineering at the University of Maryland sought to compare the signatures of flaming fires, non-flaming fires and nuisance sources. Initially this was done through a set of small-scale experiments [20] similar to those by Okayama [21]. Subsequently, large-scale tests were conducted, described in more detail here.

Hagen conducted the large-scale experiments in a 3.6 x 3.6 m room with a height of 2.4 m [22]. The room was unconditioned, with the temperature and humidity dictated by exterior atmospheric conditions. Measurements included temperature, mass loss (fire source only), CO, CO_2 and O_2 concentrations, light obscuration and the voltage output from two metal oxide sensors (Taguchi models 822 and 880). In addition, two commercial smoke detectors (one photoelectric and one ionization) were located on the ceiling, at the center of the room. A diagram of the room, including the relative locations of the sensors, is provided as Figure 5. Data was collected for two minutes prior to introducing any source in order to document variations in ambient conditions in the unconditioned test room, such that the measured signatures could be properly related to a change in the ambient conditions.

The variety of sources used to generate conditions within the room are summarized in Table 3 [22]. The sources were intended to be representative of a wide variety of fire and nuisance sources in residential environments. The 87 tests included 34 flaming sources, 16 non-flaming fire sources and 37 nuisance sources, as described by Hagen [22].

A principal component analysis (PCA), a multivariate statistical analysis, was applied to analyze the maximum values recorded for each sensor during each test to identify the nature of the source. Measurements from the following six sensors were applied to develop the PCA model: CO, CO_2, two Taguchi sensors (T880 and T822), temperature and light obscuration. The PCA consisted of an examination of the maximum values of the measurements [11]. PCA determines the linear combinations of the raw data to form scores. The details of the PCA were reviewed by McAvoy, *etal.* [11].

Figure 5. Diagram of Test Room

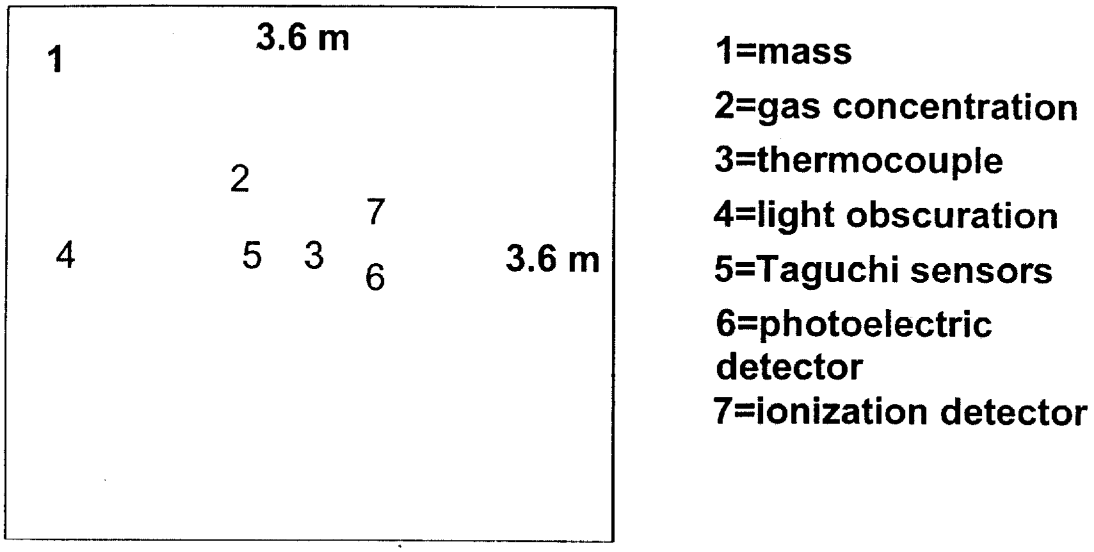


Table 3 Test Sources

Heated Fuels			Environmental Sources
Liquid	Solid	Gas	
heptane, 1-propanol, methanol, toluene, vegetable oil[1]	paper, cotton, polystyrene, pine, cardboard, cheesecloth, toast[2]	propane	propane, aerosols (disinfectant, furniture polish, cooking spray, hair spray), nail polish remover, ammonia-based window cleaner, bleach, water mist, boiling water, toast, cigarette smoke, coffee

[1] Boiling only
[2] Pyrolyzing only

The number of principal components that may be selected for an analysis of data ranges from one to the number of sensors used to collect the raw data. Increasing the number of principal components increases the ability of the system to accurately classify the source, but also increases the complexity of the algorithm. Thus, in selecting the appropriate number of principal components for a system, a balance is sought which adopts the least number of principal components, while providing sufficient accuracy of classifications.

Three principal components were used in the analysis by McAvoy, etal., to determine if variations in the environment were attributable to variations in ambient conditions or were outside the range of normal variations, thereby deserving further attention. The second step in the continuing analysis was to identify the type of source producing the abnormal signature [11]. Two of the scores (t_2 and t_3) were used to identify the type of source using the following rules:

- if $t_3 > 5$, then the source is a flaming fire
- if $-8 < t_2 < 0$, then the source is a non-flaming fire
- otherwise the source is a nuisance source.

The t_3 score was dominated by CO_2, while CO, temperature and the Taguchi sensors were most important in determining t_2.

The results of classifying the sources according to the noted rules are summarized in Table 4. All of the flaming sources were properly classified, with non-flaming fire sources classified properly in 88% of the tests. Nuisance and ambient sources were classified properly in 73% of the tests by the sensors and PCA approach. In contrast, the performance of commercial detectors noted in Table 5 indicates a response to 97% of the flaming fires (one was missed) and 25% of the non-flaming fires. 27% of the nuisance source cases were misclassified as non-flaming fire sources and hence represent false alarms.

Table 4 Classification of Test Sources

	Classification			Summary	
	Flaming Fire	Non-flaming Fire	Nuisance/ Ambient	Total	% Correct
Flaming Fire	34			34	100
Non-flaming Fire		14	2	16	88
Nuisance/ Ambient		10	27	37	73
Total				87	86

In addition to the improved classification rate, the time for detection by the sensors and PCA-based intelligence of the fire sources was significantly less than that for the commercial detectors, as indicated in Table 5. The time required for detection of flaming fires was reduced by an average of 45 s (representing a decrease of 57%), with the detection time for the prototype detector being 6 to 244 s less than that for the first responding commercial detector. The decrease in detection time was greater for the non-flaming fires, having an average reduction of 245 s and a range of 182 to 332 s.

Table 5 Comparison of Prototype PCA Detector and Commercial Detectors

	Flaming Fires	Non-flaming Fires
Total	34	16
# Undetected - commercial	1	12
# Undetected - PCA	0	2
Reduction in Detection Time (s)	45 (57%)	245 (30%)
Range of Reduction in Detection Time (s)	6-244 (41-94%)	182-332 (20-40%)

Use of a CO_2 threshold via t_3 is able to identify all flaming fires. Discrimination between non-flaming fire and nuisance sources is relatively good, especially considering the possible ambiguity between the two types of sources, *e.g.*, when is "burning toast" a fire hazard or merely an inconvenience?

Transient Analysis

A limitation of adopting threshold limits to define detection criteria is evident when a deceptive signature from a nuisance source is suddenly introduced, yielding an unnecessary alarm. To alleviate this problem and seek improvements in the discrimination ability between non-flaming fires and nuisance sources., transient data can be used. In particular, the sustained rates of rise of CO and CO_2 concentrations accumulating in the test room in Hagen's tests were reviewed to determine if improved discrimination can be obtained [18].

Using a least squares analysis of the CO_2 and CO concentration measured by Hagen over a 300 s time period, patterns on the rate of rise of CO and CO_2 concentration can be recognized to distinguish between non-flaming fire and nuisance sources, as summarized in Figures 6 and 7. Only two of the nuisance sources produced CO_2 rates in excess of 0.10 ppm/s. However, the concentration of CO_2 is also known to increase in closed rooms due to the exhalation of people. The rate of rise of the concentration of CO_2 due to the presence of people is also on the order of 0.10 ppm/s, with a short-term rate of rise up to 0.50 ppm/s noted in the EPA/BASE study [23, 24]. Such increases are experienced when many people enter an empty room, e.g. at the beginning of a work day or meeting.

Because of the potential nuisance alarm problems associated with using CO_2 rate of rise for non-flaming fires, CO was identified as a more viable measure. Only one of the nuisance sources produced a CO rate in excess of 0.025 ppm/s. In contrast to CO_2, exhalation by people will not include appreciable quantities of CO. Consequently, even though the rate of accumulation of CO for non-flaming fires is much less than that for CO_2 for flaming fires, the potential for unnecessary alarms is greatly reduced using the rate of rise of CO concentration.

Figure 6. CO_2 Rates for Non-flaming and Nuisance Sources

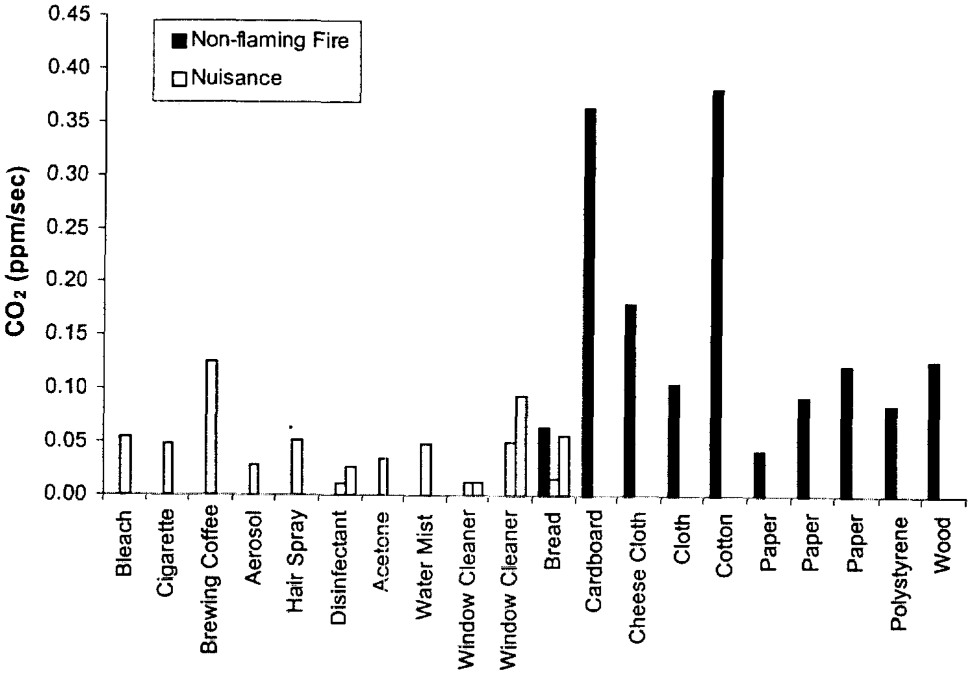
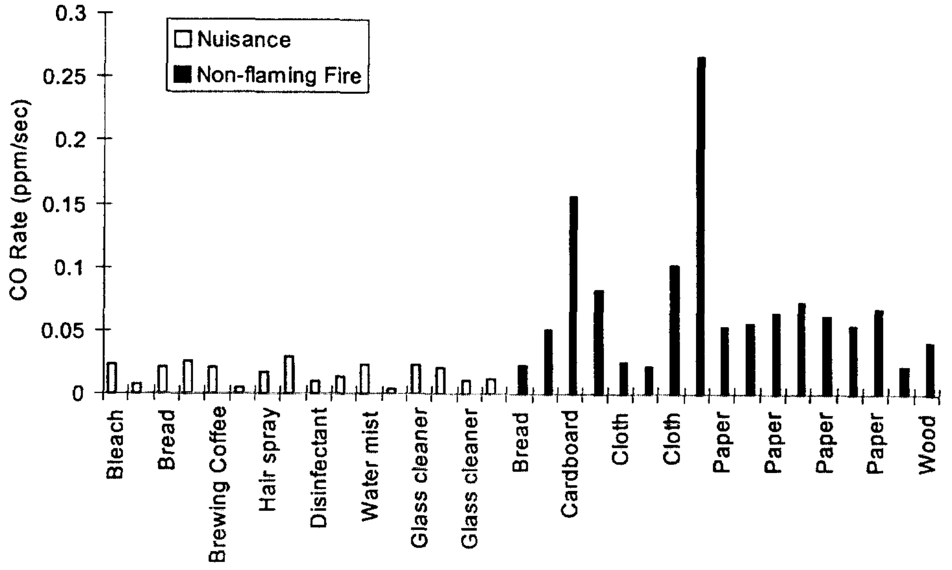


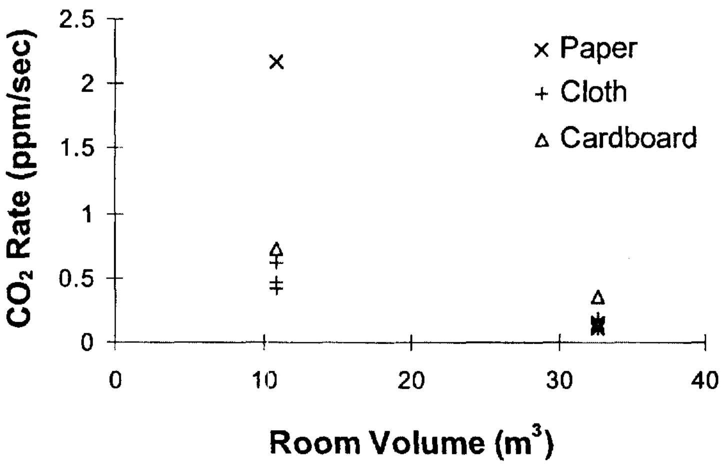
Figure 7. CO Rates for Non-flaming and Nuisance Sources



Room Effects

Predicting the gas species rates to account for different room sizes can be done analytically, as described previously. Shaner conducted experiments to introduce three of the same sources used by Hagen in a smaller room and investigate the effects of room size considered analytically. The size of the room used by Shaner was 3.6 x 1.2 x 2.4 m (height). A comparison of the maximum sustained rates of CO_2 for the tests in the two rooms is provided in Figure 8. Based on equation (1), the ratio of the CO_2 rates measured for each fuel should be inversely proportional to the ratio of the room volumes, *i.e.* on the order of 3:1. This is approximately true for the tests involving cotton cloth and cardboard, while the ratio for the paper tests is somewhat greater. Even so, the proper trend in the CO_2 rate is indicated, despite the significant challenge in replicating non-flaming fires given the simplistic test procedure used. Consequently, adopting a specific rate of rise of CO and CO_2 for fire detection based on room size and threshold fire size appears feasible.

Figure 8. CO_2 Rates in Two Test Rooms



Summary

A multi-sensor fire detector coupled with intelligence provides improved performance in detection time and discrimination of the signatures of fire and nuisance sources as compared to currently available detectors. One possible pair of sensors that could be used is a CO and CO_2 sensor. A CO_2 threshold concentration or rate of rise can be used to identify flaming fires. The rate of rise of CO concentration can identify non-flaming fires. The rates of CO and CO_2 accumulation in the smoke layer are well-predicted based on elementary algebraic equations. Such equations can be applied to investigate the threshold rates necessary for detection given a range of fuels, room sizes and heat release rates.

Acknowledgments

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Nomenclature

A: floor area of room (m^2)
f_i: yield fraction (kg CO_2/kg fuel consumed)
H: height of ceiling above floor (m)
ΔH_c: heat of combustion (kJ/kg)
k_v: entrainment constant (0.053 $m^{4/3} kW^{-1/3} s^{-1}$)
n: exponent of heat release profile, i.e. $Q = C(t)^n$
Q: heat release rate (kW)
t: time (sec)
Y_{CO2}: yield of CO_2 (kg CO_2/kg air)
z: height of smoke layer above floor (m)
χ_a: combustion efficiency
ρ: density of ambient air (kg/m^3)