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A Rugged LED-Based Sensor for Fire Detection

1. Introduction

An ideal instrument for early detection of aircraft cargo compartment fires would combine high sensitivity, rapid response time, automatic self-testing, and would have a zero false alarm rate. In addition, such systems could provide continuous data to the pilots, giving them the ability to monitor the growth and possible extinction of a fire after activation of the on board suppression system. Current aircraft cargo compartment fire detection systems, which are primarily smoke detectors, do not meet this ideal. These detectors have false alarm rates, defined as the percentage of alarms with no verified smoke in the cargo compartment, as high as 99%, resulting in over 150 unscheduled landings in the last four years [1]. Current gas detection systems also fall short of the ideal; tests of commercially available CO detectors showed various failures that included false alarms at low CO levels, and worse, no alarms at dangerous CO levels [2].

Southwest Sciences is developing a novel optical absorption spectroscopy technique for fire detection. Key gases produced by incipient fires are detected by optical absorbance measurements using inexpensive, rugged mid-infrared Light Emitting Diodes (LEDs). Fully engineered sensors will achieve rapid response with low false alarm rates, will be small, lightweight, fully automatic, self-checking, and use little power. The reduction in false alarms is accomplished by measuring the concentrations of multiple gases in order to detect incipient combustion. This multi-parameter detection approach has been examined by NIST [3].

Target gases for the Southwest Sciences' instrument include carbon monoxide (CO), carbon dioxide (CO₂), hydrogen cyanide (HCN) and acetylene (C₂H₂). Carbon dioxide is an important gas to monitor because its non-zero ambient concentration allows the detection system to automatically confirm correct performance. In addition, in flaming

combustion carbon dioxide concentrations are well in excess of ambient levels (350 ppm) and can reach concentrations in excess of 1500 ppm [4]. In contrast smoldering fires tend to produce large amounts of carbon monoxide [5, 6]. Monitoring both CO and CO₂ reduces false alarm rates because the ratio of these gases due to combustion is known [7] and should be significantly different from the ratio due to emissions from biological cargo. Acetylene has a zero ambient concentration and plays a critical role in the development of soot [8, 9]. Hydrogen cyanide, which also has a zero ambient concentration, is produced during the thermal degradation of nitrile containing plastics and foams [10, 11, 12]. Thus, the presence of either hydrogen cyanide or acetylene could indicate the occurrence of a fire.

This paper reports on absorbance measurements of CO and CO₂ using this innovative technique and examines the feasibility of detecting hydrogen cyanide and acetylene.

2. Experimental Hardware

2.1 Mid-IR LEDs & Detectors

A benchtop LED-based absorption spectroscopy gas detection system (*Patent Pending*) was built with off-the-shelf components. Compact mid-infrared LEDs that operate at a center wavelength of 4.6 μm were used as the light sources for this sensor (Fig. 1). They are inexpensive, rugged, and compact (~ 5 mm dia.). The LEDs have a spectral bandwidth of 0.85 μm (FWHM) and an output power of 11 μW . Each LED package includes a 1 cm diameter parabolic reflector used to direct the output. Because the emission bandwidth is much greater



Figure 1 - Mid-IR LEDs

than the target absorption bands ($\sim 0.2 - 0.3$ microns), bandpass filters were used to achieve selective detection of the target species. Three such filters were used in the tests reported in this paper: $3.91 - 4.09 \mu\text{m}$ (reference), $4.16 - 4.45 \mu\text{m}$ (CO_2), and $4.53 - 4.77 \mu\text{m}$ (CO).

Mid-infrared LED output was measured with an infrared detector. Initially a thermoelectrically cooled mercury cadmium telluride (HgCdTe) infrared detector, which is well suited for continuous monitoring applications, was used. After a failure with this detector, a liquid nitrogen cooled indium antimonide detector was used. Both detectors have good spectral response to $5\mu\text{m}$ and a 1.0 mm^2 active area.

2.2 Prototype Detection System

A schematic diagram of the gas detection system (*Patent Pending*) is shown in Fig. 2. This system uses two LEDs that are each pulsed at 10kHz with a 50% duty cycle. Light from the LEDs is bandpass filtered and combined using a cadmium telluride (CdTe) flat, and then focused onto the detector using two plano-convex, calcium fluoride

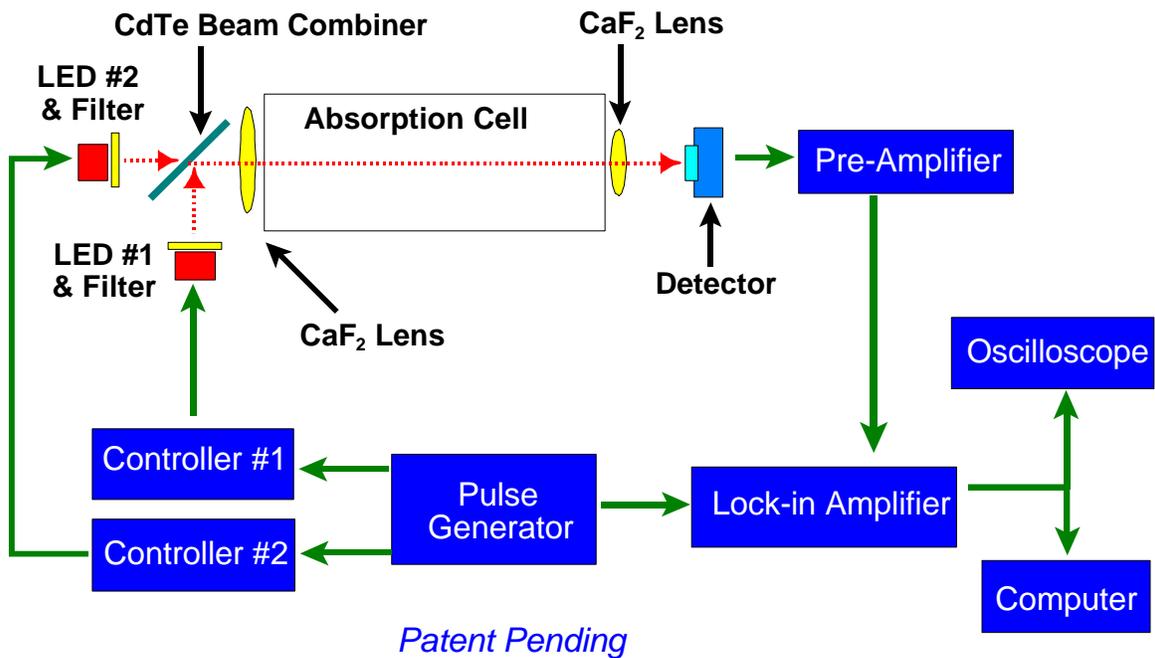


Figure 2 – Schematic of the prototype detection system

lenses. The light passes through an absorption cell that has a path length of 35.5 cm before reaching the detector. The pre-amplified signal from the detector is sent to a lock-in amplifier that provides phase-sensitive detection at the LED modulation frequency. The output from the lock-in can be viewed directly, or captured using an analog-to-digital data acquisition board in a personal computer.

3. Spectroscopic properties

Spectroscopic detection of CO and CO₂ is possible using commercially available LEDs having a 4.6 μm center wavelength. The ν₃ band of CO₂, centered around 4.27 μm, and the CO fundamental vibrational band, centered at 4.67 μm, are both strong absorption features, and are sufficiently well separated to allow selective detection of the two gases using bandpass filters in combination with the LEDs, Fig. 3.

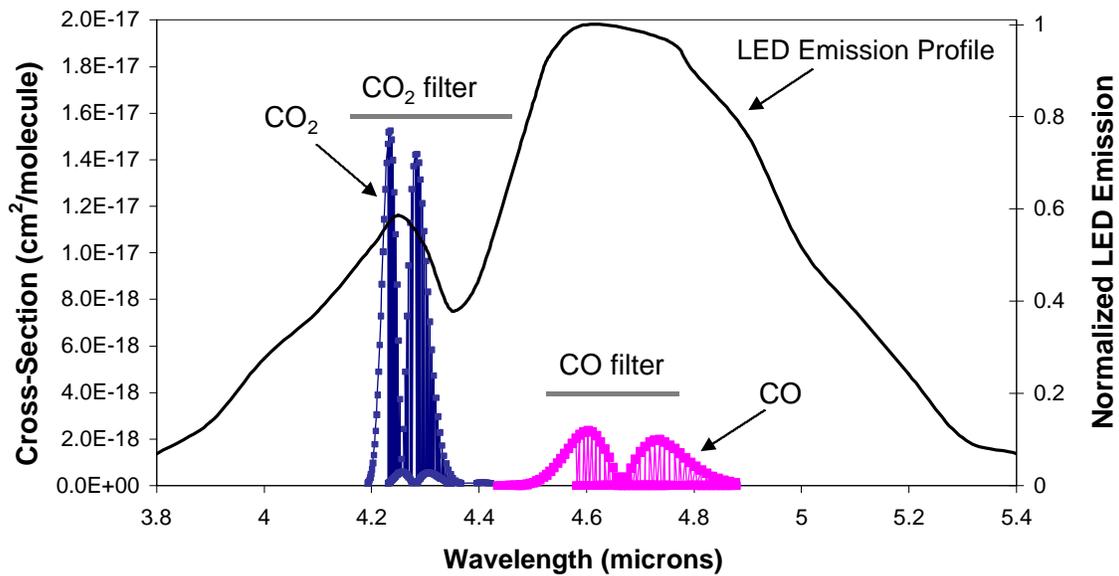


Figure 3 - LED emission profile, CO and CO₂ filter bandwidths, and absorption bands of CO and CO₂.

This technique utilizes a broad emission (from the LEDs), covering a large portion of an absorption band, instead of a single line feature that would be used for a high-resolution tuned diode-laser. Effective cross-sections can be calculated by integrating molecular

line strength data (from the HITRAN database [13]) across a bandpass filter transmission window:

$$\sigma_{\text{EFF}} = \Sigma S(T) / \Delta\nu_{\text{FILTER}} \quad (1)$$

Although individual molecular line strengths, $S(T)$, are functions of temperature, the resulting effective cross-section (σ_{EFF}) is invariant to temperature over the expected range (300-1000K). The effective cross-section is related to an effective absorbance (α_{EFF}) through the Beer-Lambert Law:

$$\alpha_{\text{EFF}} = \sigma_{\text{EFF}} N L \quad (2)$$

in which (L) is defined as the optical path length, and (N) is the number density of the absorbing gas. Measured cross-section and absorption values are compared against experimentally derived data in the next section.

4. Experimental Results

Two techniques were used to measure the concentrations of CO and CO₂: direct absorption measurements using a single LED and differential absorption measurements using two LEDs.

4.1 Direct Absorption Measurements

In these experiments, measurements were performed using a single LED modulated at 10 kHz, and with a lock-in amplifier set to a one second time constant. For carbon dioxide, data was obtained with the test cell evacuated (0 ppm CO₂) to provide a baseline (I_0), and then filled with air (~ 350 ppm CO₂ at 600 Torr). (The ambient pressure at Southwest Sciences, located in Santa Fe at 7000 feet above sea level, is 600 Torr.) The experimentally determined absorbance (0.17) was within 10% of the effective absorbance (0.16) computed using Eq. (1) and (2). The experimental absorption cross-section was $7.1 \times 10^{-19} \text{ cm}^2/\text{molecule}$ in comparison to the computed effective cross-section of $6.4 \times 10^{-19} \text{ cm}^2/\text{molecule}$.

For carbon monoxide, measurements were made with the cell filled with 100% nitrogen (0 ppm CO) to provide a baseline (I_0). Calibration data were obtained with varying concentrations of CO that ranged from 20 to 10,000 ppm. All measurements were made

at 296 K and at 600 Torr. Figure 4 shows the measured absorbance data plotted against CO concentration. A linear best fit of these data is then used to compute an experimental cross-section ($7.4 \times 10^{-20} \text{ cm}^2/\text{molecule}$), which is within 1.3% of the numerically predicted cross-section ($7.5 \times 10^{-20} \text{ cm}^2/\text{molecule}$). The excellent agreement between the experimental and theoretical values validates the numerically computed effective cross-section and absorbance. Figure 4 also shows the FAA's CO minimum performance standard, $200 \pm 50 \text{ ppm}$ [1,14,15].

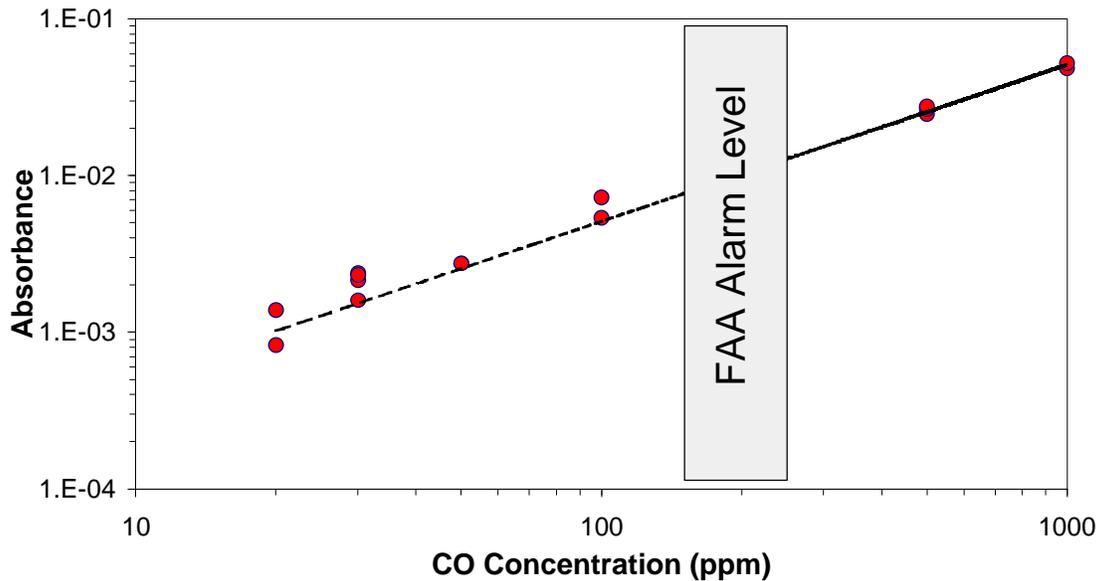


Figure 4 - Direct absorption measurements and the FAA's CO minimum performance standard for CO [1,14,15]

4.2 Differential Absorption Measurements

One approach to reducing the fire detector false alarm rates is to increase the detector sensitivity, making it possible to differentiate between ambient levels and fire generated concentrations of the key gases. Standard absorption spectroscopy techniques, such as direct absorption, measure small changes on a large baseline signal making detection of trace levels more difficult. Our approach uses a novel (*Patent Pending*) modulation method that improves detection sensitivity and helps to distinguish among the target gases and to reject signals due to background gases such as water vapor. This is to be accomplished by measuring small changes on a zero baseline. Specifically, the goal of

this technique is to discern small concentration changes, potentially as small as the limit set by the intrinsic detector noise.

This technique uses two LEDs (as shown in Fig. 2) pulsed 180 degrees out of phase, and uses the difference between the two LED intensities at the detector to measure absorbance by a gas. The LED emissions are filtered to provide a reference signal and an absorption signal. Initially, the LED input currents are adjusted such that the detection signal level (I_0) is the same for each LED/filter combination with no absorbing gas present in the cell, as shown in Fig. 5. When the lock-in amplifier processes these signals, the resulting output is zero because the signals cancel each other out. When there is an absorbing gas, such as CO or CO₂ present in the cell, the sample beam intensity decreases while the reference intensity is unchanged and the lock-in amplifier displays a non-zero output. The technique is effective because it allows measurements of small absorbances against zero baseline and minimizes the dynamic range requirements of the lock-in amplifier.

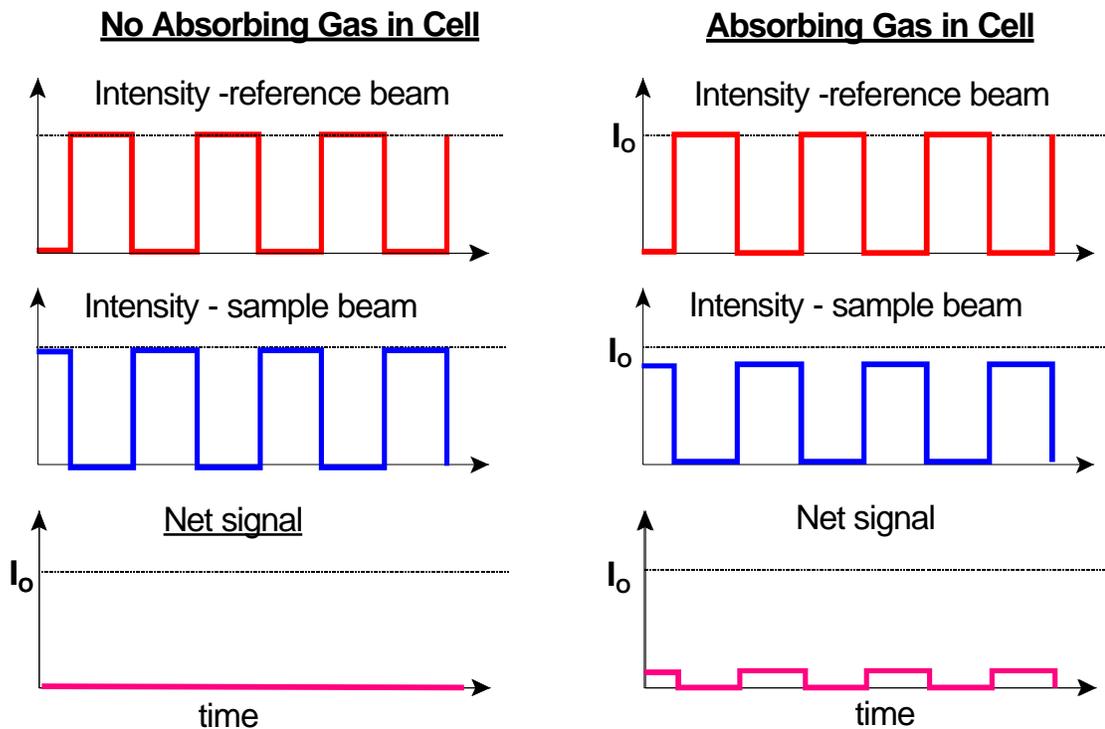


Figure 5 - Differential absorption measurement technique

Calibration measurements were made with concentrations of CO that ranged from 10 to 10,000 ppm. The differential technique was able to measure a CO concentration of 10 ppm, which is lower than the direct absorption measurements. Thus, the differential absorption technique has a higher sensitivity than the direct absorption technique! All measurements were made at 296K and at 600 Torr. Figure 6 shows the measured change in intensity plotted against CO concentration and the FAA's CO minimum performance standard, 200 ± 50 ppm [1,14,15]. The detection limit for the differential absorption technique is below the FAA's CO alarm level [14,15] and below the 8 hour weighted average exposure (40 ppm) established by National Institute for Occupational Safety and Health [16].

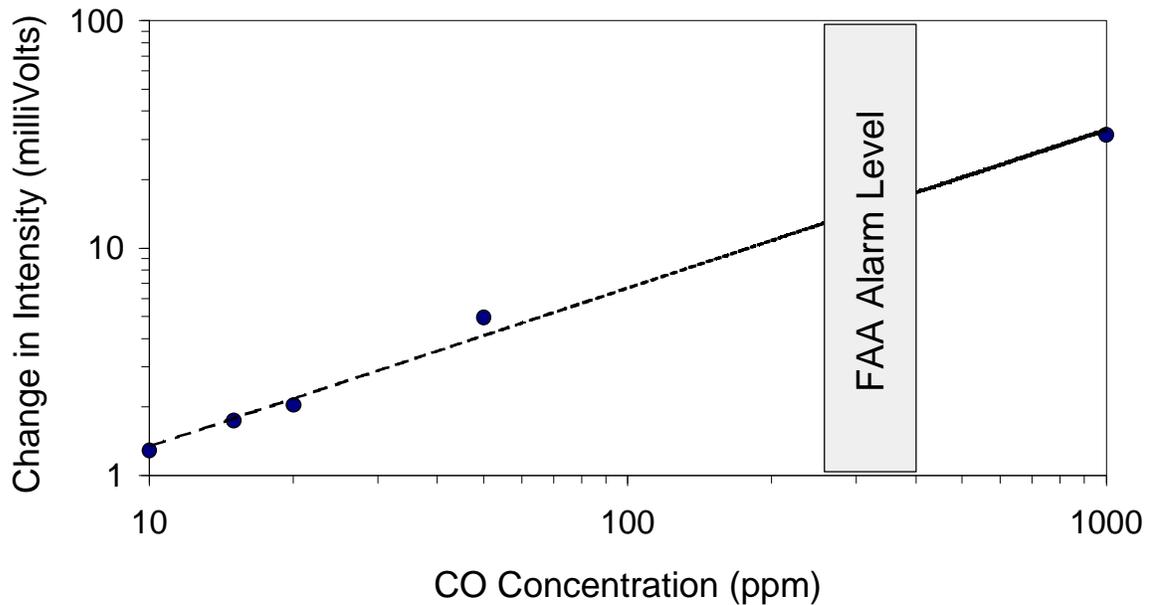


Figure 6 - Differential absorption measurements and the FAA's minimum performance standard for CO [1,14,15]

4.3 Cross Talk

Successful implementation of Southwest Sciences' fire detection method requires sensitive and *selective* detection of the target gases. Selectivity refers to measurement of one gas in the presence of the others. Our results show trivially small cross talk between CO and CO₂. Filling the sample cell with 0.8 atm of CO₂ shows a false

positive response equivalent to 50 ppm CO; that means selectivity for CO in the presence of CO₂ is 16,000:1. We expect no detectable false positive CO signals for all realistic CO₂ concentrations. In the other direction, filling the cell with 10,000 ppm CO gives a false CO₂ signal of 77 ppm. This corresponds to a selectivity of 130:1. The small false positive CO₂ signals are unimportant relative to the large CO₂ background: 430 ppm of CO – a substantial CO concentration that will certainly exceed alarm threshold – would introduce a false CO₂ signal equal to only 1% of the 350 ppm CO₂ background.

5. Spectroscopic Modeling

5.1 Feasibility of measuring HCN and C₂H₂

These gases have absorbance bands in the mid-IR that can be reached with commercially available LEDs and filters. There is strong overlap between HCN and C₂H₂ absorbances, which may prevent this technique from selectively measuring these gases. However, even if these gases cannot be detected separately, monitoring for HCN and C₂H₂ is useful because trace amounts of either gas, which have a zero ambient concentration, would clearly indicate the presence of combustion. Using the validated numerical simulation, the effective cross-sections for both gases are nearly identical to each other (6.1×10^{-20} cm²/molecule and 8.1×10^{-20} cm²/molecule for C₂H₂ and HCN, respectively) and to CO (7.3×10^{-20} cm²/molecule). This translates into a minimum detectable concentration of similar to that of CO – 10 ppm.

5.2 Interference by Water Vapor

Cross-section calculations, Eq. (1), also allow us to predict potential interference by background gases. Water vapor, because it is ubiquitous in air and has numerous infrared absorption bands is the most important background gas. Spectroscopic modeling computations show that there is no significant interference by water vapor for detection of carbon monoxide, carbon dioxide, hydrogen cyanide, or acetylene. These computations use the spectral line parameters in the HITRAN database [13], which are

known to be accurate for these low molecular weight gases (including water vapor) at temperatures near ambient. Under worst case conditions – 100% humidity at 310 K which might occur in an open cargo bay on the ground during the summer at a coastal location – the optical absorbance due to water vapor contributes a false positive signal of 15 ppm CO. This concentration is below the OSHA maximum workday exposure [16] and is well below FAA CO minimum performance levels (200 ± 50 ppm) [14,15]; moisture levels during flight will be at least a factor of three lower.

6. Conclusions

A new, innovative technique (*Patent Pending*) has been utilized for measuring trace gas concentration. The mid-IR LEDs used in this system are ideally suited for continuous monitoring in situations that require a small, low-cost alternative to conventional systems, such as in aircraft cargo compartments. Using multiple LEDs, the system has the ability to separately measure the instantaneous concentration of multiple gases, greatly reducing the likelihood of false alarms, and increasing the likelihood for detecting incipient fires. In addition, continuous monitoring of carbon dioxide, which has a non-zero ambient concentration, can be used for real-time testing of instrument performance.

This instrument could be used for early fire detection in aircraft cargo compartments and other inaccessible locations within an airframe. This type of instrument could be integrated into a sophisticated aircraft control system, such as the *Aircraft Command in Emergency Situations* system prototyped by Boeing [17]. The commercial applications of the proposed instrument extend to fire safety in any location requiring fast and accurate detection of a fire, including, but not limited to: storage warehouses, industrial settings, large office buildings, shopping malls, etc. This technology could also be applied to spacecraft fire safety, providing fire detection for long-duration manned space missions. Additionally, the same technology used for fire detection can be used for air quality monitoring, for a wide range of gases in almost any setting.

7. Acknowledgements

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