Multi-Criteria Fire Alarm

ABSTRACT

Purpose – Since decades ago the ionization smoke detectors have been and continue to be the lowest cost but far from ideal fire detectors. One of the biggest problems with them is their frequent false alarms which could be outright dangerous when people remove the battery to stop the nuisance but forget to replace it afterwards. This paper advances the concept of an improved fire detector called "Mcfa" (Multi-criteria fire alarm) by detecting CO and CO_2 gases along with smoke at fire initiation and thereafter thereby potentially eliminating all false alarms, providing faster speed of response, protection from deadly CO and automatic functional failure enunciation.

Design/methodology/approach – The possibility of the Mcfa fire detector is a direct result of the recent breakthrough in the development of Non-Dispersive Infrared (NDIR) gas sensors, namely the Absorption Biased (AB) NDIR gas sensing methodology, which is capable of significantly eliminating output drifts over time from these sensors in addition to effectively rendering them ultra-small size, low cost and long operating life. The Mcfa fire detector is essentially a smoke detector working in unison with two AB designed NDIR gas sensors, one CO and one CO_2 and a logical component for generating a fire alarm. The logical component is designed so that the detection of a routine level of smoke obscuration, not so high as to indicate a real fire, must be additionally augmented by a well-defined rate of rise of a gas level for either CO or CO_2 before the fire alarm could be sounded.

Findings – The feasibility of the Mcfa fire detector has been irrefutably demonstrated by implementing the design for both AB designed NDIR CO and CO_2 sensors. Using readily available components, the detection sensitivity for the CO and CO_2 sensor can be shown to be respectively +/- 2-3 ppm and +/-10 ppm with a time constant of less than five minutes.

Originality/value – The currently presented concept of the Mcfa fire detector is original and has not been published anywhere in the open literature. Although the reduction of this concept to actual practice has not yet been carried out to date, the possibility is clearly feasible and irrefutable. A successful demonstration of the Mcfa fire detector in the near future would usher in for the first time in almost a century an ideal fire detector that is free from all false alarms and has a faster speed of response. Furthermore, it also has a longer operating life and could even provide protection from deadly CO and enunciate functional failure automatically.

Keywords – Fire detection, Fire detectors, Non-Dispersive Infrared (NDIR) gas sensors

Paper type – Research paper

Introduction

For the past several decades the ionization smoke detectors have dominated the fire detector market. Even though it is far from ideal, it has been and continues to be the lowest cost fire detector available to the general public. Although the photoelectric type is considered by many to be a better smoke detector, it has fallen significantly behind in sales in recent years to the ionization type because of its relatively higher cost. But one of the biggest problems with ionization smoke detectors is their frequent false alarm. Frequent false alarms are not just harmless nuisances; people often disarm their smoke detectors by temporarily removing the battery in order to escape from such annoying episodes. This latter situation could be outright dangerous especially when such people forget afterwards to re-arm their smoke detectors by replacing the battery.

Over the years, intensive efforts have been made but so far in vain to develop a better fire detector. In this regard, it has been known for a long time that as a process, fire can take many forms, all of which however involve chemical reactions between combustible species and oxygen from the atmosphere. In other words, fire initiation is necessarily an oxidation process since it invariably involves the consumption of oxygen in the beginning. The most effective way to detect fire initiation, therefore, is to look for and detect end products of the oxidation process. With the exception of a few very specialized chemical fires (i.e., fire involving chemicals other than the commonly encountered hydrocarbons), there are three elemental entities, namely carbon, oxygen and hydrogen, and three compounds, namely carbon dioxide, carbon monoxide and water vapor, that are invariably involved in the ensuing chemical reactions in the combustion of a fire.

Thus it has been known for a long time that in order to realize a better fire detector, in terms of avoidance of false alarms and faster detection speed, one must take advantage of what fire and fire initiation have to offer. In other words, in addition to paying attention just to detecting smoke from a fire, one must also recognize the importance of detecting gas byproducts from a fire as a result of the combustion taking place right from the beginning. Of the three gas byproducts emanating from a fire at its initiation, namely CO, CO_2 and H_2O, only CO and CO_2 are relevant. The reason is that H_2O or water vapor not only can be found everywhere, its concentration can also change very quickly and unpredictably over time and place. Therefore it would not be a very good parameter to detect and rely upon for indicating the occurrence of fire initiation.

As far as CO_2 gas is concerned, it is a mixed bag. It is well known that CO_2 is also present just about everywhere. Its concentration can be anywhere from ~400 ppm to ~1,000 ppm outdoors and is more dependent upon whether there are any CO_2 sources around. For example in the middle of a busy street where there is motor traffic, the concentration could easily exceed a few thousand ppm. In a park or in areas where are hardly any motor traffic or people, the concentration should just hover around 400-600 ppm and no more. The same situation pretty much prevails inside a house. Again dependent upon how many people gather in a particular place inside the house, the CO_2 concentration seldom exceed 1,000 to 1,500 ppm. In places where there is no people around or just only one or two, the concentration would likely be well under 1,000 ppm. Because of these situations, the detection for CO_2 emanating from a fire at the beginning is meaningful only if the fire breaks out strong right from the beginning like in the case of a burning Christmas tree. If the fire is a smoldering one, there is very little CO_2 gas produced at its beginning. Its concentration level therefore carries little or no weight towards telling whether or not there is a fire initiation taking place.

But for CO gas, it is a horse of a different color. It is safe to say that complete combustion rarely takes place at fire initiation unless it is a chemical fire or a fire without involving the burning of hydrocarbons.

The production of CO gas and smoke therefore always accompanies all types of common fires at their initiation. For smoldering fires which start out mainly with incomplete combustion, smoke and CO gas will be produced predominantly at the beginning. As the fire progresses into a flaming fire, the production of CO_2 gas will gradually take the place of smoke and CO gas. In general the more intense a fire at its initiation, indicative of more complete combustion taking place, the less CO gas and smoke but more CO_2 gas will be produced. Figure 1 portrays the amount of smoke, CO and CO_2 generated in the course of both a smoldering and a flaming fire. For a smoldering fire, both smoke and CO gas are produced more abundantly than CO_2 in the beginning. In the course of time, still more smoke and CO are produced but not CO_2 which continues to be produced at a relatively minimum level. For a flaming fire, all three fire byproducts, namely smoke, CO and CO_2, are produced at initiation. As the fire progresses, both smoke and CO will quickly reach their peak and begin to die off. For CO_2, on the other hand, it continues to be produced in larger and larger quantities unabated as the fire gets to be extremely hot. Thereafter only CO_2 and hardly any other gas byproducts including smoke is produced.

The detection of fire byproducts other than smoke

As mentioned earlier, in order to realize a better fire alarm than what we have today in smoke detectors, one must take advantage of what fire and fire initiation has to offer. In other words, in addition to detecting smoke from a fire, one must also recognize the importance of detecting other byproducts from a fire, in particular CO and CO_2 gases. On the surface the task of detecting these gases at fire initiation in order to help expedite fire detection appears to be far easier than it actually entails. But in actuality, this is far from being the truth. The reason is that the performance characteristics required of these sensors capable of detecting these two gases at fire initiation are so overwhelmingly demanding that until very recently there is seemingly no hope to ever be able to achieve them. Among these very demanding performance characteristics are 1) low cost; 2) small size; 3) no output drift over time; 4) long operating life; 5) low power consumption; 6) interference free from atmospheric gases; 7) extremely high gas detection sensitivity requirement and 8) capability to self-police and enunciate operational failures.

Of the eight very demanding performance characteristics that sensors must possess in order that they can be considered as candidates to detect gas byproducts from a fire including its initiation, only three characteristics, namely 4), 5) and 8) are not absolutely critical. Although long operating life, constraint 4), for a fire sensor is desirable, it is not critical as long as the unit will make itself known that it is no longer functioning. This situation is likened to the life of a battery for a fire sensor. Most battery-operated fire sensors today show a sign like a blinking red light to indicate to the user that its battery is now too low for the unit to function properly. Constraint 5) or low power consumption is desirable, it can be overcome if necessary by going to an AC-powered operating mode without the need for a hefty battery except for a much smaller one as a power fail backup. Constraint 8) or capability to self-police and enunciate operational failures again is desirable but not absolutely necessary. Even for today's low cost smoke detector, a signal is now indicated when the battery is about to fail or too low for the unit to function properly.

Every single one of the remaining five very demanding performance characteristics is critical before a sensor could qualify to be adeptly used for detecting byproduct gases from a fire including its initiation. Four out of the five, namely 2), 3), 6) and 7), are related to the performance capability of the detector technology and only the first one or 1) has to do with the social behavior of the general public as supported and sustained by the smoke detector manufacturers in the name of making only profits. For some completely unknown reasons and totally baffling to a lot of people, professionals and common folks alike, the general public just refuse to pay more than $10 for a decently working fire sensor for protecting their home, their family and even their lives. When faced with annoying frequent false alarms, people are willing to remove the battery in order to silence the alarm and perfectly willing to subject themselves to life-threatening danger in the event of a real fire.

Over the years many gas detection methodologies have been successfully developed covering diverse applications of all disciplines. These gas detection methodologies include technologies such as Electrochemical cells, Catalytic (Platinum beads) sensors, Photo-ionization detectors, Flame-ionization detectors, Figaro (Tin Oxide) semiconductor sensors, MOS or Metal-Oxide-Semiconductor sensors, Thermal Conductivity sensors, Non-Dispersive Infra-Red (NDIR) sensors, NDIR Photo-acoustic sensors, Tunable Diode Laser Absorption Spectroscopy

(TDLAS) sensors and other advanced optical gas sensors utilizing infrared emitting diodes (ireds) such as InAsSb. Of all the gas sensor technologies developed to date as mentioned above, only Electrochemical cells and NDIR gas sensors perform good enough to be considered for use for detecting gas byproducts from fire including its initiation.

Electrochemical gas sensors

Electrochemical gas sensors are gas detectors that measure the concentration of a target gas by oxidizing or reducing it at a sensing electrode and measuring the resulting current. The sensors generally contain two electrodes in contact with an electrolyte commonly a mineral acid. The sensing electrode is typically fabricated by depositing a large area of a precious metal (e.g. Platinum for detecting CO gas) onto a hydrophobic porous membrane served as a diffusion barrier which is in contact with both the electrolyte and the ambient air to be monitored. The target gas diffuses into the sensor through the back of the porous membrane to the sensing electrode where it is oxidized or reduced. This electrochemical reaction results in an electric current that passes through the external circuit. The external circuit for a two electrode sensor maintains an operating voltage between the sensing and counter electrodes to drive the electrochemical reaction in addition to measuring, amplifying and performing other signal processing functions. At the counter electrode an equal and opposite reaction occurs, such that if the sensing electrode is an oxidation, the counter electrode is a reduction.

Electrochemical sensor technology has been around for many decades and over the years has offered highly specific gas sensing in the low ppm range for many gases. While electrochemical sensors offer many advantages particularly in size and unit cost, they are not suitable for every gas. Since the detection mechanism involves the oxidation or reduction of the gas, electrochemical sensors are usually only suitable for gases which are electrochemically active. Although it is possible to detect electrochemically inert gases indirectly if the gas interacts with another species in the sensor that then produces a response. An electrochemical sensor for carbon dioxide is an example although it never receives wide acceptance due to its more complicated sensor design and much higher unit cost.

Among the shortcomings of electrochemical gas sensors are 1) cross-sensitivity; 2) relatively short and unpredictable operating life; 3) sensor output may drift over time and 4) lack of automatic self-policing of functionality except projecting its death. Despite the afore-mentioned shortcomings, the development of electrochemical CO sensors has gone a long way over the past decade. Today, their sensitivity, output stability over time and operating life (minimum of 7 years) are good enough to be effectively used as CO alarms at home to detect lethal levels of CO. But as far as their adeptness today to be used to detect ppm levels of CO emanating from a smoldering fire or any fire at its initiation, more work is still needed in order to further improve their detection sensitivity, output stability and even longer operating life (10 – 15 years minimum).

Non-Dispersive Infrared (NDIR) gas sensors

Non-Dispersive infrared (NDIR) gas sensors have long been considered as one of the best methods for gas measurement since the 1950s. NDIR gas sensors are highly gas specific, sensitive, fast responding, relatively stable over time, rugged, reliable and easy to maintain. But the shortcomings of this technology inclusive of detection sensitivity for certain gases, size, unit cost and output stability over time have been overcome only during the past several years. In a way somewhat similar to electrochemical gas sensors whose performances depend to a large extent upon the electrochemical activities of the target gases, for NDIR gas sensors, their performances have a lot to do with the infrared signatures or the infrared absorption bands of the gases that need to be detected. For example, because of the fact that carbon dioxide (CO_2) gas has a very strong and specific absorption band at 4.26μ, highly sensitive (+/- 25 ppm @ 1,000 ppm detection level), compact, rugged, low cost and interference free NDIR CO_2 gas sensors have been available for purchase since the late 1990s. Despite this fact, NDIR CO_2 gas sensors whose output remain stable over a long period of time (5 years or more) and are therefore suitable for use for detecting a rate of CO_2 level rise due to a fire are available only very recently[1].

Although this so-called NDIR Absorption Biased (AB) sensor design methodology, as far as output stability over time is concerned, is applicable to gases other than CO_2, such as CO, the detection of the latter in the ppm range suitable for fire alarm applications is a horse of a completely different color. It has to do with the infrared signature or the available infrared absorption band for this gas. Unlike the very strong 4.26µ absorption band of CO_2 gas, the only CO absorption band available for the design of an NDIR CO gas sensor is at 4.65µ which is ten times weaker than that for CO_2 at 4.26µ. As is well known in the design of NDIR gas sensors, the weaker the absorption band of a gas to be detected, the longer must be the sample chamber path length. Other factors also come into play such as the desired concentration level of the gas to be detected and the required detection sensitivity assuming a certain response time (0 – 90%) stipulated which is typically 30 seconds. For the detection of CO_2 at a concentration level of 1,000 ppm and a detection sensitivity of +/- 25 ppm at a response time of 30 seconds, the optimum path length is around 2 inches or ~5.0 cm. But for the detection of CO at ~10 ppm concentration level and a detection of +/- 2.0 ppm at the same response time of 30 seconds, the optimum path length for the sample chamber would have to be 2.0 x 10 x 25/2 inches or 250 inches or 20 ft. With a better infrared source and a better infrared detector and a clever trending software providing similar detection sensitivity with a longer response time, the minimum path length would still have to be around 2 ft. or 24 inches in order that an NDIR CO sensor could be of use to adeptly detect the CO gas coming out of a fire including its initiation.

The Multi-Criteria Fire Alarm (Mcfa)

As discussed earlier, it has been known for a long time that in order to realize a better fire sensor than the smoke detector, in terms of avoidance of false alarms and attaining a faster detection speed, one must take advantage of what fire and its initiation have to offer. In other words, in addition to paying attention just to detecting smoke from a fire, one must also recognize the importance of detecting gas byproducts from a fire, particularly CO and CO_2, as a result of the combustion taking place right from the beginning. But the irony is that without the availability of appropriate gas detectors, which must have the required performance characteristics for detecting the gases in terms of sensitivity, operating life, output stability over time, small size and especially affordable unit price. From the standpoint of electrochemical gas sensors, detecting CO_2 is technically possible but totally impractical and complicated because CO_2 gas is electrochemically inert as it can neither be oxidized nor reduced. As far as detecting CO is concerned, although most of the shortcomings of electrochemical CO sensors have been overcome or close to being overcome during the past decade, they are still not completely ready to detect low level of the gas, particularly in the low ppm range, from a fire or its initiation. Sensor sensitivity in the low ppm range, its output stability over time and its life expectancy still remain as formidable challenges for electrochemical gas sensors today.

From the standpoint of Non-Dispersive Infrared gas sensors, detecting CO_2 with the required detection sensitivity, operating life and low unit cost has become a non-issue since more than a decade ago. But the sensor's output instability over time has remained the stumbling block for its potential use as a cooperative fire alarm with the smoke detector in order to speed up the detector's response to flaming or fast-moving fires. Fortunately this shortcoming has been overcome by a recent breakthrough in the development of NDIR gas sensors. A so-called Absorption Biased (AB) design methodology when implemented with NDIR gas sensors is now capable of significantly reducing their output drifts over time[1]. Furthermore this methodology can be applied to almost any gas, e.g. CO, as long as it possesses an infrared absorption band compatible with the NDIR gas sensing technology. Thus this recent NDIR gas sensing technology breakthrough has finally opened the door for one to take full advantage of detecting gas byproducts from a fire and its initiation. The realization of a long-awaited fire sensor that is far better than the false-alarm proned smoke detector is finally very close at hand.

The present paper describes the concept of an improved fire detector that has a faster response time, resistant to false alarms, has an automatic self-policing normal operation indicator and functions additionally as a carbon monoxide alarm. Such a fire detector is called a multi-criteria fire alarm or "Mcfa" because it detects more than just the smoke for enunciating a fire. Figure 2 is a logic diagram of Mcfa, a fast responding and false alarm resistant fire detection system. As illustrated in Figure 2, Mcfa fire detection system 1 generates an alarm signal 2 when any of the following six conditions is met.

First, an alarm signal 2 will be generated if an output 3 of a smoke detector 4 exceeds a threshold 5 of N% light obscuration per 0.3048 meter (1 foot) for greater than T_1, a first preselected time period 6. Smoke concentration measured in units of "% light obscuration per 0.3038 meter (1 foot)" applies to both ionization and photoelectric smoke detectors although the output is different for them in reflecting such a smoke obscuration.

Second, an alarm signal 2 will be generated if output 3 from smoke detector 4 exceeds a reduced threshold level 7 of M% light obscuration per 0.3048 meter (1 foot) for greater than T_2, a second preselected time period 8.

Third, an alarm signal 2 will be generated if the rate of increase in the measured concentration of CO at output 9 of a COP detector 10 exceeds a first predetermined rate R_1, 11, of X ppm/min for a predetermined time period T_3, 12 and light obscuration exceeds the reduced threshold 7. The output of the AND gate 13 indicates the satisfaction of this condition.

Fourth, an alarm signal 2 will be generated if the rate of increase in the measured concentration of CO at an output 9 of a CO detector 10 exceeds a second predetermined rate R_2, 14 of Y ppm/min for a predetermined time period T_4, 15.

Fifth, an alarm signal 2 will be generated if the rate of increase in the measured concentration of CO_2 at an output 16 of a CO_2 detector 17 exceeds a first predetermined rate R_3, 18, of Z ppm/min for a predetermined time period T_5, 19 and light obscuration level exceeds the reduced threshold 7. the output of the AND gate 20 indicates the satisfaction of this condition.

Sixth, an alarm signal 2 will be generated if the rate of increase in the measured concentration of CO_2 exceeds a predetermined rate R_4, 21, of ZZ ppm/min for a predetermined time period T_6, 22.

These six conditions are combined by an OR gate 23 (see Figure 2), the output of which produces an alarm signal 2 that in turn activates an alarm device 24.

Both the CO and CO_2 detectors deployed in the Mcfa fire detector as depicted logically in Figure 2 are preferably NDIR type gas sensors. Furthermore they must be Absorption Biased (AB) designed NDIR sensors in order that their output drifts are significantly reduced over time. The Mcfa fire alarm relies upon the additional gas sensors to assist the smoke detector to detect effluent gases from the fire, namely CO and CO_2, in order to greatly improve its fire detection capability.

One of the greatest advantages of the Mcfa fire detection system over the conventional smoke detector is an almost complete elimination of false alarms. Even though the obscuration threshold of a conventional smoke detector is exceeded by non-fire episodes, Mcfa will not sound an alarm unless additionally either a threshold rate of increase of CO gas or a threshold rate of increase of CO_2 gas is also detected. But to be on the safe side, Mcfa still would sound an alarm if the obscuration threshold of the smoke detector is exceeded for a predetermined but longer period of time. This is because only a real fire can sustain the generation of smoke obscuration but not so for almost all other non-fire episodes. Mcfa would also sound an alarm if the threshold rate of increase of CO gas is detected for a predetermine period of time or the threshold rate of increase of CO_2 gas is detected for a predetermined period of time.

Other advantages of the Mcfa fire detection system in addition to an almost complete elimination of any false alarm without sacrificing the fire detection fidelity of the conventional smoke detector include (1) protection of occupants from deadly CO gas while a smoldering fire is in progress or there is an accidental outbreak of CO from household appliances such as a malfunctioning gas furnace; (2) a much faster response to both smoldering and flaming or fast-moving fires. Because of the fact that Mcfa relies upon additional gas sensors to detect effluent gases from a fire in addition to the smoke detector, it is possible to considerably lower the smoke concentration thresholds without incurring more false alarms. The lowering of smoke concentration thresholds for conventional smoke detectors under ordinary circumstances would be totally unacceptable due to the occurrence of even more false alarm episodes. As to flaming or fast-moving fires, conventional smoke detectors are notoriously known to be slow responding. On the other hand Mcfa is especially adept to detecting flaming or fast-moving fires by sounding an early alarm when a rate of rise threshold for CO_2 gas is detected for a predetermined period of time accompanying the simultaneous detection of smoke obscuration. Finally (3) unlike conventional smoke detectors, the inclusion of a self-policing feature for automatically indicating functional failures for both NDIR CO and CO_2 gas sensors is rather simple and straightforward without having to incur any significant sensor cost increases.

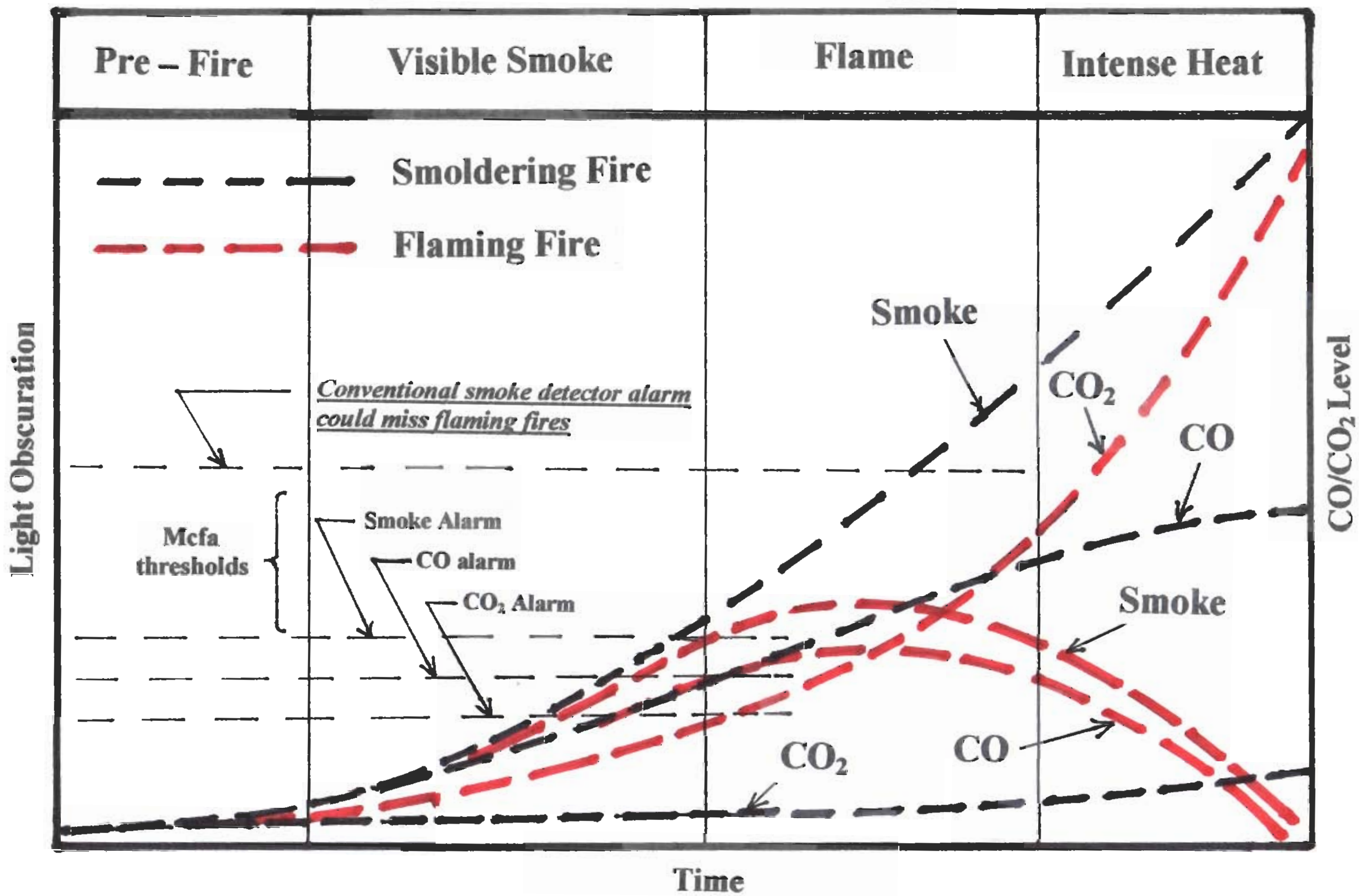
Summary and conclusions

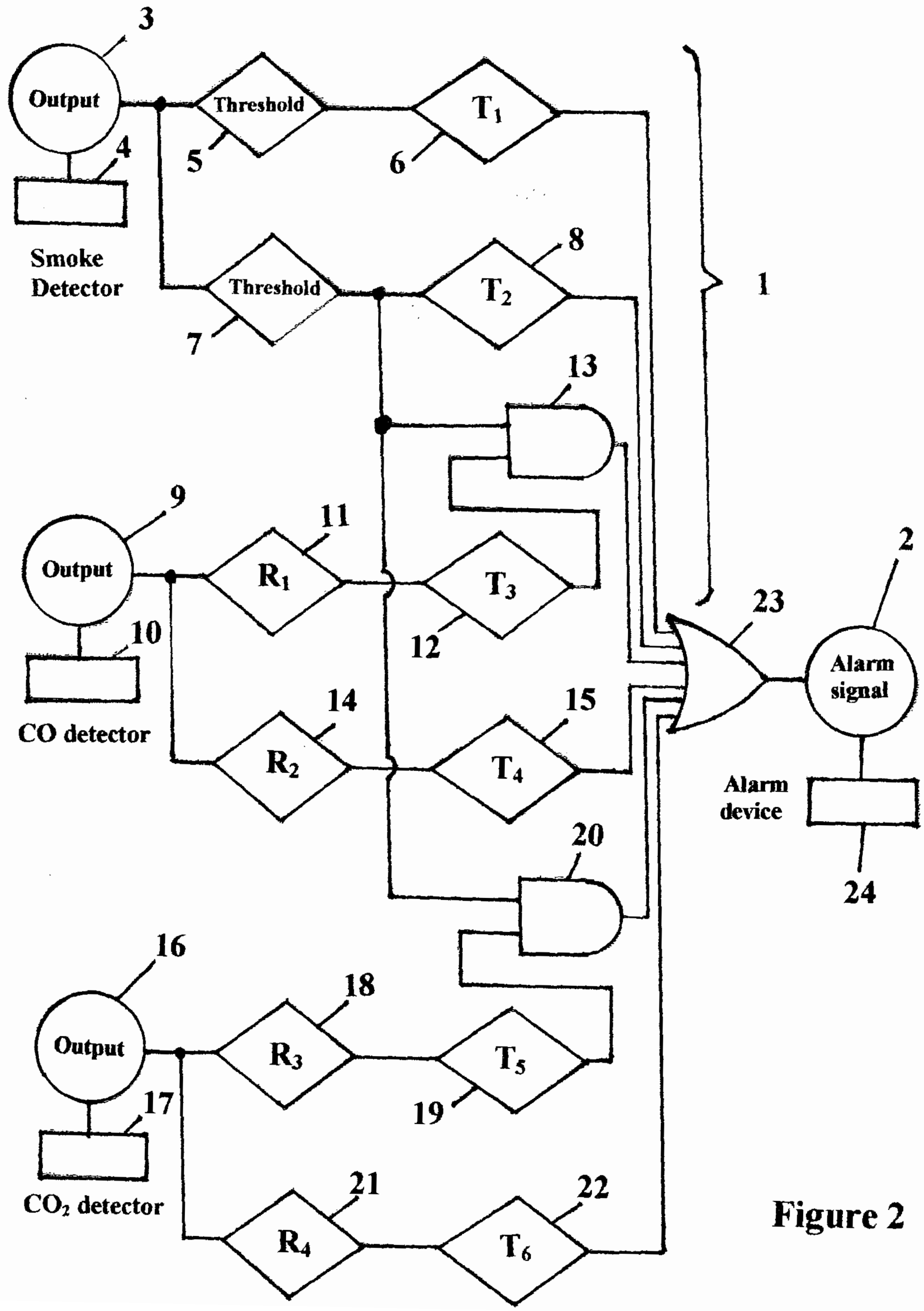
For literally decades the need of a better fire detector other than the false alarm proned smoke detector for the general public has been well recognized but unfulfilled due primarily to the lack of adequate gas detection technology particularly in cases for detecting low ppm levels of CO gas and the output stability over time for gas sensors. This gas detection technical barrier has recently been finally overcome by a breakthrough in the development of Non-Dispersive Infrared (NDIR) gas sensors. Absorption Biased (AB) designed NDIR CO and CO_2 sensors whose outputs are stable over time, relatively small, rugged and low cost are now available. By taking advantage of this technological breakthrough in gas sensing, the concept of a new fire detection system called multi-criteria fire alarm or "Mcfa" is introduced. The Mcfa combines both an NDIR CO and CO_2 sensors with a smoke detector in order to detect gas byproducts from a fire and its initiation in addition to smoke. The result is a much improved fire detector that has a faster response time, resistant to false alarms, has an automatic self-policing normal operation indicator and functions additionally as a carbon monoxide alarm, while still could be economically viable for the general public.

References

[1] J. Y. Wong and M. Schell, "Zero drift NDIR gas sensors," *Sensor Review* Vol. 31 No.1, 2011, pp. 70-77

Figure 1


Pre – Fire
Visible Smoke
Flame
Intense Heat
Smoldering Fire
Flaming Fire
Smoke
CO_2
CO
Conventional smoke detector alarm could miss flaming fires
Mcfa thresholds
Smoke Alarm
CO alarm
CO_2 Alarm
Smoke
CO_2
CO
Light Obscuration
CO/CO_2 Level
Time



3
Output
4
Smoke Detector
Threshold
5
T1
6
Threshold
7
T2
8
1
13
9
Output
10
CO detector
R1
11
T3
12
R2
14
T4
15
23
2
Alarm signal
Alarm device
24
20
16
Output
17
CO2 detector
R3
18
T5
19
R4
21
T6
22

Figure 2