History of Smoke Detection:
A Profile of How the Technology and Role of Smoke Detection Has Changed

A report formulated for:

Siemens Industry, Inc
Building Technologies Division
Fire Life Safety Unit

By:

James A. Milke, Ph.D., P.E.
Department of Fire Protection Engineering
University of Maryland

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Executive Summary

Today, fire detection is recognized to play an essential role in providing fire safety in buildings, to protect people, property and contents. Early fire detection permits people to react at early stages of fire growth to evacuate or otherwise respond to the emergency control while the hazard developed from the fire is still modest. Early fire detection also permits other fire protection systems to be activated to limit hazard development, contain the fire, or suppress it.

Today's view is in stark contrast to the view of about 50 years ago when automatic detection was rarely provided in buildings. If automatic detection was provided, the detector of choice was a heat detector and it was there to provide protect to the contents or property. The change in attitude has been the result of a series of significant fire incidents and research developments.

Several significant fires have occurred where the lack of early detection was identified as a major factor in the outcome of the fire. These fires resulted in the loss of numerous lives and/or involved substantial damage to property and contents. Noteworthy fires incidents have occurred in virtually all types of occupancies, including residential, office, hotel, health-care, night clubs and schools. While most of the noteworthy fires initially grew undetected relatively slowly and posed a modest hazard in that early stage, once they grew to a critical size, they quickly transitioned into a rapid growth fire and produced untenable or damaging conditions.

Research contributed to the development of the smoke detector itself, as well as to assess whether smoke detectors could respond at an early enough stage to preserve fire safety goals, e.g. evacuation of people, activation of other fire protection systems, etc. A means to monitor smoke produced in fires wasn't discovered until 1922 by Greinacher from Berne. In 1929, Walter Kidde obtained the first Underwriters Laboratories' (UL) listing for a smoke detection device used to actuate a total-flooding CO_2 system for shipboard applications. The use of an ionization chamber to detect smoke was noted in the late 1930's by Walter Jaeger while conducting research to develop a poison gas detector. In the early 1940's Meili and Jaegar collaborated to develop the first generation of today's ionization smoke detector. The initial detector was a high voltage unit, requiring 220 V. In the early 1960's, a second generation smoke detector was developed which utilized Amercium 241 as the radioactive source for the ionization chambers and transistors. In 1964, First Alert developed a low-power (24 V) ionization smoke detector. A year later, Duane Pearsall (his company was Statitrol) developed a single station photoelectric smoke detector with Stanley Peterson that was powered by a battery which now made widespread installation in residences highly feasible.

At about the same time as the second generation smoke detector was developed, research was conducted to better understand the potential fire safety roles that heat and smoke detectors could perform given the speed of their response. A landmark set of experiments were conducted in 1959 as part of “Operation School Burning” following the fire at Our Lady of Angels School that resulted in 93 fatalities. In the test program, beam type and ionization smoke detectors were observed to operate before rate of rise heat detectors in most cases and before the onset of untenable conditions. This study was the first to make the momentous conclusion that smoke detectors had greater potential to improve life safety than heat detectors.

In the 1960’s there were a trio of researchers in the U.S. and Canada who further reinforced the value of smoke detectors for life safety. The first of these was conducted in 1962 Canadian by Canadians McGuire and Ruscoe. From their review of fire incidents resulting 342 residential fire deaths in Ontario from 1956 to 1960, they hypothesized that smoke detectors would have reduced the fatalities by 41%, while the heat detectors would have only reduced the number of fatalities by only 8%. McGuire and Ruscoe’s conclusion caught the attention of Bright at the National Bureau of Standards (NBS). In 1971, Bright provided NBS’s input to the Department of Housing and Urban Development (HUD) project called “Operation Breakthrough” which stated that smoke detectors should be required in homes.

When HUD provided manufactured homes in 1971 as temporary housing for people on the East Coast displaced from their homes damaged by Hurricane Agnes, smoke detectors were installed in those homes. During the three-year period when the 17,000 homes were occupied, there were no reported fire injuries or fatalities. With this remarkable experience and the recent research the support was available to motivate the development of policies and standards for smoke detectors in homes. In 1975 the Mobile Home Manufacturing Association adopted a policy of providing one smoke detector outside of a sleeping area in each manufactured home. In the mid-1970’s, Federal Agencies (Federal Housing Administration and Veterans Administration (VA)) involved in mortgage lending required smoke alarms to qualify for loans. In 1974, Montgomery County, MD became one of the first jurisdictions in the U.S. to require smoke detectors in new and existing residences. By 1979, all model codes applying to home construction required smoke alarms in new homes.

With the substantial increase in interest to expand the applications for smoke detectors expressed in the 1960’s and 1970’s, several improvements in smoke detectors and smoke detection systems were sought. At about the same time, an appreciable amount of activity was devoted to develop standards to outline testing procedures to certify smoke detectors as well as to provide requirements for installation.

The changes incorporated into smoke detectors in the 1970's and 1980's included replacing the incandescent light source with a light emitting diode and the use of silicon technology to replace photoconductive cells in photoelectric smoke detector units. With the development of integrated circuits, smoke detectors became somewhat smaller and required less power. A significant reduction in the power requirement for single station detectors was the result of a different sounding device being incorporated into detector. The reduced power requirement enabled a change from a 9V alkaline battery to a 9V carbon-zinc battery, reducing the battery replacement cost for a homeowner.

With the increased popularity of smoke detectors came a large number of nuisance alarms. Some of the problems were traced to the sensitivity setting established at the factory being too high. Nuisance alarms caused by bugs entering the sensing chamber were addressed by the installation of a bug screen outside of the sensing chamber. Nuisance alarm problems were also addressed by alarm verification and cross-zoning.

With some large buildings containing a significant number of smoke detectors, emergency responders complained that in some cases they had difficulty finding the location of a triggered detector, especially where detectors were installed in locations which were hard to access, e.g. under raised subfloors, in plenums above raised ceilings, and in air ducts. Providing assistance in identifying triggered detectors was one of the motivations for the development of multiplex systems which became feasible with the invention of integrated circuits.

Multiplex systems also assisted in monitoring the status of each detector in order to identify maintenance demands. Subsequently, this led to the development of addressable detectors to monitor the status of each detector continuously. In 1982, the Pyrotronics XL3 introduced the first analog/addressable detector/control-unit system. With this advance, some systems permitted alarm decisions to be made at the control panel, whereas previously alarm decisions were made only at the detector.

In 1977, a cooperative effort was initiated between UL and the NBS in the project known as the "Indiana Dunes Tests" to examine the performance of smoke alarms in homes. McGuire and Ruscoe's analysis had assumed only two smoke detectors were located in the home. The results from the Indiana Dunes Tests provided data that led to the spacing requirements included in NFPA 74, "The Standard on Installation Maintenance and Use of Household Fire Warning Equipment."

The most recent advances in smoke detectors have been motivated to make the detectors "smarter", i.e. to be increasingly more responsive to fire signatures representing threats, while also discriminating between to signatures from nuisance and fire sources. These advances have included the incorporation of multiple sensors and multiple criteria detection algorithms. In the 1990's, appreciable interest was expressed in having CO or CO_2 gas sensors be included within smoke detectors and such has become available in some commercial products since 2008.

Throughout much of the last 50 years, research has been conducted on alternative fire detection methods. Some of the more successful ventures have resulted in gas sampling systems, flame detector systems and video detection systems. Given the unique response characteristics of these systems, they have found acceptance, mostly for particular applications, such as gas sampling systems for electronic equipment spaces and flame detectors in diesel generator spaces.

Assessing the performance of smoke detectors can be done by reviewing fire incident statistics and experimental data. By 2006, at least one smoke alarm was present in 96% of U.S. residences. Prior to 1970, when smoke detectors were installed only in selected occupancies, the annual number fire deaths in the U.S. was on the order of 8,000, with most of the deaths occurring in residences. In the last few years, that number of annual fire deaths in the U.S. has declined to approximately 3,300. While there are several factors that may have contributed to the decline in fire deaths, Bukowski, et al., note:

> "Thus the home smoke alarm is credited as the greatest success story in fire safety in the last part of the 20th century, because it alone represented a highly effective fire safety technology with leverage on most of the fire death problems that went from only token usage to nearly universal usage in a remarkably short time."

Based on an analysis of fire incident statistics, Ahrens at NFPA concluded that almost two-thirds (63%) of all home fire deaths in 2003-2006 occurred in homes which lacked working smoke alarms, i.e. the fire death rate in homes without a working smoke alarm was approximately twice that in homes with working smoke alarms.

The substantial reduction in national fire casualty death rates was examined in more detail in a smoke detector giveaway program in Oklahoma City in the late 1980's. The area identified for the program had the highest rate of injuries from residential fires in the city. Four years after 10,100 smoke alarms were distributed to the 9,291 homes, the fire injury rate decreased by 80 percent.

A 2010 review of eight, recent experimental studies confirmed what was observed in the Operation School Burning and Indiana Dunes tests, i.e. smoke detectors respond prior to heat detectors (and therefore sprinklers) in most fires. In addition, tenability analyses conducted using data from several of the programs concluded that sufficient egress time is provided by smoke alarms, considering conditions existing at the time of their response. The analysis of NFIRS data conducted as part of the study considered the response of smoke detectors and sprinklers in approximately 197,000 fire incidents occurring from 2003-2007 in 1-, 2- and multi-family residential dwellings, commercial residential facilities and health-care facilities. In all three of these occupancy groups, the proportion of fires judged to be too small for the operation of the smoke detectors was appreciably fewer than those for sprinklers. The fact that fewer fires are "too small" for smoke detector operation indicates that smoke detectors are more sensitive to the signatures produced at early stages of fire development than sprinklers. As such, smoke detectors are capable of responding to smaller fires than sprinklers. However, even though these fires are "too small", casualties do still occur in some of these incidents. Fires "too small" for smoke detector operation have one-fourth of the casualty rate (casualties per 100 fires) as compared to fires "too small" for sprinklers.

Future developments are likely to further improve the intelligence of smoke detectors, primarily to discriminate between fire and nuisance sources, but also perhaps to discriminate between different fire sources. In the future, with the increased intelligence being incorporated into smoke detectors, they may be asked to do more than simply sound an alarm, e.g. to serve as air quality monitors and contribute to energy efficiency in buildings or assist in providing fire officers with an overview of conditions in the space. Further, information from an array of smoke detectors could be used to predict the future course of a fire to improve fireground operations by the fire service.

1. Introduction

The Role of Detection in Achieving Fire Safety Goals

Fire safety seeks to achieve particular goals for homes, commercial buildings, and other structures such as:

- life safety
- property protection and contents
- mission continuity
- protection of environment

Achievement of those goals is accomplished through the implementation of fire safety subsystems. The six fire safety subsystems recognized in the SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings are [2007]:

- Fire initiation and development
- Spread, control, and management of smoke
- Fire detection
- Fire suppression
- Occupant behavior and egress
- Passive fire protection

Fire detection is one of the six subsystems identified in the SFPE Guide and hence is an essential component for achieving fire safety goals.

Figure 1 depicts the increase in hazard due to a growing fire with increasing time after ignition. A hypothetical hazard limit is indicated in the figure to depict a time when untenability, equipment damage or some other unacceptable consequence occurs. Figure 1 also depicts the situation where early detection is provided which then enables the time for response to be completed prior to the time to reach the hazard limit.

Generally, fires start small. In the early stages, the conditions produced (such as visible smoke, temperature rise and increased toxic gas concentrations) are relatively minor and those pose little threat to people, contents, etc., so that fire safety goals in most buildings are not threatened. Exceptions where even minor amounts of combustion products could be damaging include clean rooms or museums where environmental conditions are carefully controlled.

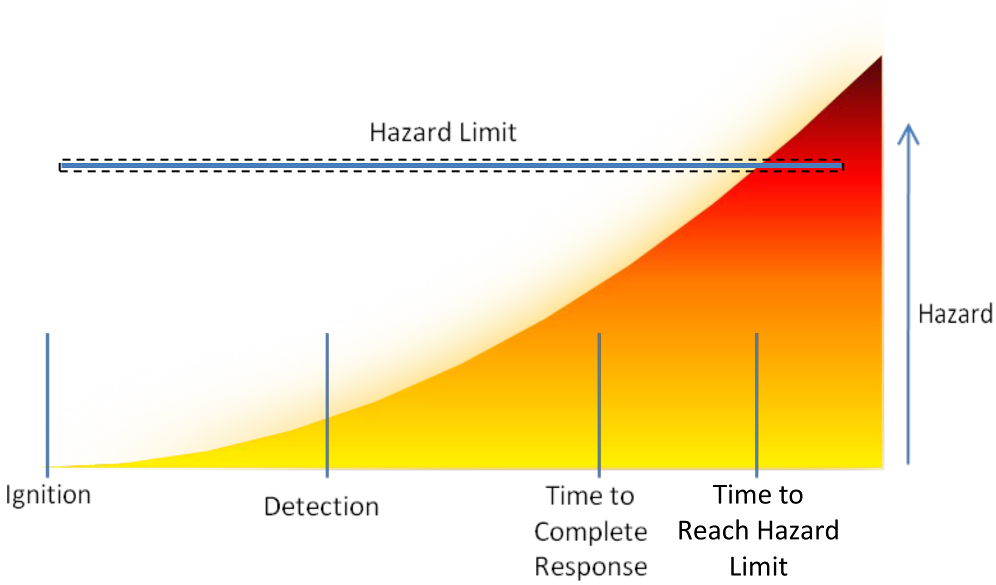

Figure 1. Hazard Development Timeline

Unless the fire is extinguished at the early stage, the fire will continue to grow, forming a smoke layer in the upper portion of the room. The smoke layer will be expected to become deeper and will become visibly more apparent. The temperature and concentrations of toxic gases in the smoke layer will increase. Visibility through the smoke will decline.

If the fire continues to grow, the conditions generated are likely to exceed the hazard limit. The consequences include casualties to people and damage to contents and property. Smoke generated or the byproduct of extinguishment actions can pollute the air or ground water. Should a portion of the building require reconstruction after the fire, the residents or business operations will be displaced until repairs and restoration are completed.

A basic tenet of fire detection is that earlier detection of a fire is better than later. Earlier fire detection permits actions to be initiated by people or other systems while the fire is still small and is at its easiest stage to control. Also, early fire detection provides the greatest amount of time for carrying out and completing that response prior to the generation of damaging conditions.

As an example, a timeline for the various actions needed to satisfy life safety is depicted in Figure 2, adapted from Proulx [2008]. The timeline depicts a “good news” outcome where the occupants evacuate prior to the onset of untenable conditions. The escape time includes the time from ignition of the fire until the individual has completed his evacuation. The evacuation time is defined as the time between alerting and when the person reaches a position of safety, e.g. outside of the building or a protected part of the building which is separated from the fire area, such as an enclosed stairwell.

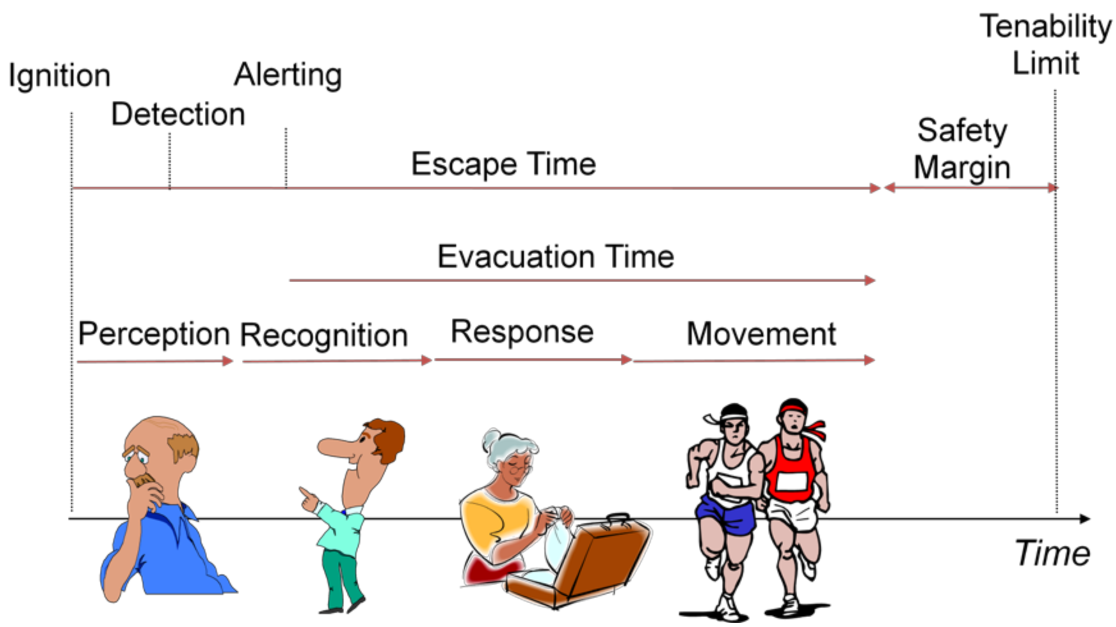

Figure 2. Life Safety Timeline

Fires may be detected manually or through automatic fire detectors. If detected manually, people may smell smoke or see flames from the fire. If people are not in the immediate vicinity of the fire they will need to perceive that their environment is changing, either as a result of a haze, different odor, or in some cases odd noises. In cases where people are present and alert in a particular area, their senses usually permit very early detection of these abnormal conditions. Where people are not alert, as when they are sleeping, manual detection capability is greatly diminished. Automatic fire detectors provide a continuous capability of fire detection, independent of the presence or attentiveness of individuals.

Once individuals perceive an abnormal condition is present, they need to recognize that the abnormal condition is being created by a fire. This may require that they search for the source of the condition. Individuals may alert others about this abnormal condition, or wait until they confirm that it's caused by a fire. If an automatic detector has detected the fire, the alerting usually occurs promptly after detection.

Once alerting has occurred, either by people calling to others or via actuated visual or audible fire alarms, people should begin the process to evacuate. Once aware of a fire, the initial response of people may involve preparing for evacuation, such as gathering a few personal items, putting on a coat, etc. However, in some cases, the "recognition" phase indicated in Figure 2 may continue while individuals delay their response or further alert others, waiting for some reinforcing cue.

Response of Smoke Detectors

Automatic fire detectors respond to particular conditions generated by a fire, referred to as fire signatures, including heat, radiation and airborne combustion products. Fixed temperature and rate-of-rise heat detectors respond primarily to heat carried by moving smoke. Some detectors respond to radiation emitted by the fire in particular wavelengths, including those in the ultraviolet (UV), visible and infrared (IR) ranges. Radiation detectors, more commonly referred to as flame detectors, respond to radiation in the UV and IR ranges. Video camera based systems, i.e. VID systems, respond primarily to radiation in the visible range. Traditional smoke detectors respond to the smoke particles generated by a fire which become suspended in air forming a smoke layer. Some newer technology detectors, described in the next section, have the capability to respond to a particular gaseous products of combustion such as carbon monoxide (CO) or carbon dioxide (CO_2).

2. Historic fires

Numerous serious fires have occurred over the last 100 years. These fires are noteworthy given the significance of the consequences which results, such as multiple fatalities or substantial damage to property or contents. Noteworthy fires incidents have occurred in virtually all types of occupancies, including residential, office, hotel, health-care, night clubs and schools. A summary of selected fires is presented in chronological order in Table 1. The tragedies selected for the table include a variety of incidents, of which several appeared in the media and others had very little discussion. The lack of early detection is identified as a major contributing factor in many of the noted fires.

Most of the fires included in the table started relatively slowly, with an appreciable amount of time between ignition and the development of threatening conditions. Three notable exceptions to that situation where a rapidly growing fire occurred very quickly after ignition include the fires in the Iroquois Theater, Dupont Plaza, and The Station. In these incidents, occupants quickly became aware of the fire and either didn't have

Table 1A. Significant Fires in Recent History (1900-1979)

Building/Location/Date	Occupancy	Location/Scenario	Outcome	Contributing Factors
Iroquois Theater, Chicago, IL, 12/30/1903	Assembly	Spark from stage lighting ignited scenery. Rapid fire development on stage. Smoke and fire spread to seating area.	602 fatalities	No sprinkler system Inadequate stage curtain No venting from stage Interior finish
Our Lady Of Angels, Chicago, IL, 12/1/1958	School	Trash can in boiler room in basement. Smoke spread via open stair and ventilation system.	93 fatalities 75 injuries	No detection system Single stairway which was unenclosed No sprinkler system
Pentagon, Arlington, VA, 7/2/1959	Office	Light bulb ignited combustible ceiling. Magnetic computer tapes involved in fire to provide severe fire.	$30M damage	No detection system No suppression system
Hartford Hospital, Hartford, CT, 12/8/1961	Hospital	Fire in combustible trash chute. Smoke entered hallway from chute, igniting combustible ceiling tile.	9 fatalities	Trash chute openings not protected No sprinkler system in chute
Charles Klein Law Library, Temple University, Philadelphia, PA, 7/25/1972	Library	Electrical cause in concealed space suspected on 2nd floor, extensive spread above suspended ceiling.	50,000 volumes lost, Damage greater than $1M	No detection system No sprinkler system
Joelma Building, São Paulo, Brazil, 2/1/1974	Office	Electrical cause in 12th floor, fire and smoke spread rapidly due to highly combustible interior wall coverings	179 deaths	No detection system No sprinkler system 1 stairwell Interior finish
Beverly Hills Supper Club Southgate, KY, 5/28/1977	Assembly	Zebra Room, electrical cause suspected, fire spread due to interior finish	164 fatalities 70 injuries	No detection system No sprinkler system Inadequate exits
University Nursing Home, Silver Spring, MD, 4/13/1979	Nursing Home	Improperly discarded smoking materials, post-flashover fire develops in patient room.	2 fatalities	One smoke detector in lounge at end of wing of nursing home No sprinkler system

Table 1B. Significant Fires in Recent History (1980-2010)

Building/Date	Occupancy	Location/Scenario	Outcome	Contributing Factors
Chesapeake Hall, Univ. of Maryland, Baltimore County, Catonsville, MD, 2/3/1980	Dormitory	Suspicious origin involving trash piles in corridor, additional spread along carpet.	1 injury	Smoke detection in all dormitory rooms No sprinkler system
MGM Grand Hotel, Las Vegas, NV November 21, 1980	Hotel/ casino	Electrical fault in Deli, flashed over Deli and spread into casino	85 deaths Over 700 injuries	No detection system in vicinity of fire No sprinkler system High fuel load in casino Vertical pathways for smoke spread
Dupont Plaza, San Juan, PR, 12/31/1986	Hotel	Incendiary fire initiated in corrugated cardboard cartons of furniture, fire spread along interior finish, furnishings in lobby	98 fatalities	No detection system No sprinkler system High fuel load in casino
Univ. of North Carolina Fraternity House, Chapel Hill, NC, 5/12/1996	Residential	Smoldering fire initiated in trash in basement. Initial spread via interior finish and open stairways	5 fatalities 3 injuries	No detection system No sprinkler system Open Stairway
Cook County Administration Building, Chicago, IL, 10/17/2003	Office	Storage room, smoke spread above suspended ceiling.	6 fatalities	No detection system No suppression system Inadequate separation of storage room with remainder of floor
The Station, West Warwick, RI, February 20, 2003	Night Club	Pyrotechnic device starts fire on sound insulation material, fire rapidly grows on sound insulation material	100 fatalities 170 injuries	Interior finish No suppression system

sufficient time to react because of the very rapid deterioration of conditions (Iroquois Theater, occupants in the lobby of Dupont Plaza and The Station), or chose not to react quickly, perceiving the threat not to be immediately significant (some occupants in the casino of the Dupont Plaza).

All of the other fire incidents involved situations where detection of the fire was delayed for a substantial amount of time. The fire at the Our Lady of Angels School was one of the cases with delayed detection (see Figure 3). During that initial time period, the fires grew slowly undetected. In most cases, the hazard level during that initial time period remained relatively modest. If detected at that early stage, people could have easily evacuated or fire suppression activities been carried out to extinguish a relatively small fire. In virtually all of these cases, once the fire had an opportunity to grow to a critical size, it then transitioned into a rapid growth fire which quickly produced untenable or damaging conditions.

Figure 3. Our Lady of Angels School
Ref: http://projectdisaster.com/index.php?s=our+lady+of+angels

Two of the fires which were not reported in the national media include the fire incidents at the University Nursing Home and Chesapeake Hall. Both of these fires were analyzed as part of a research project on human behavior [Bryan, DiNenno and Milke, 1980]. In both of these fire incidents, smoke detectors were included in the building, but not in the area of origin of the fires. The fire was noticed by an individual shortly before the nearest smoke detector was triggered. However, by the time the staff member noticed the fire in both events, the fire has already developed to a moderate size. In the University Nursing Home, the fire flashed over shortly after detection creating heavy smoke conditions in the wing of patient rooms where the two patients died. In the fire incident at Chesapeake Hall, after detection, the fire grew appreciably in the corridor, thereby making evacuation by the corridor impossible. The single injury was sustained by a student who jumped from a second floor window.

While the list of serious fires is certainly noteworthy, it's also important to acknowledge the large number of fire incidents that get reported on a weekly basis on the local television news segments that include single fatalities, or a few injuries. These incidents are equally important to demonstrate the need for early fire detection. Two incidents of this type were included in the recent edition of *NFPA Journal* [Tremblay, 2010].

In many of these incidents, the presence or lack of a smoke detector is often noted by the local media as it was in the *NFPA Journal* articles. This comment by the media is a reflection of the recognition by the public of the importance of smoke detection in providing fire safety.

In this era, smoke detectors were mostly found on ships. Virtually all fire detectors installed in buildings were heat detectors. With no demand for smoke detection in buildings, the continued development of a smoke detector represented a true exploratory venture. Smoke detectors were only being installed in buildings in Sweden, with a recently passed law for hotels of timber construction and in selected buildings in Japan [Meili, 1990].

Nonetheless, in 1954 Cerberus had the first ionization smoke detector approved by UL. As is typical for the first approval of any type of product at UL, the process required an appreciable amount of time and expense, in part to develop a standard (later to become UL 167) upon which to make the assessment. In this case, the process took two years. The approval opened up the U.S. market to the Cerberus smoke detector [Meili, 1990]. Given the commitment required to obtain this approval with an unproven market, Cerberus should be recognized for their vision concerning the future of smoke detection.

One significant improvement in the Cerberus ionization smoke detector was introduced in 1956. This improvement consisted of included a flashing light on triggered detector to permit rapid identification of the location of the activated detector [Meili, 1990]. Facilitating the location of a triggered detector would continue to be a topic of interest resulting in subsequent changes about 25 years later.

Near the end of this initial era of smoke detection evolution, questions were starting to be raised concerning the relative performance of smoke and heat detectors. As indicated previously, heat detectors were the mostly commonly applied type of detection in buildings. In most cases, heat detectors were installed primarily for property protection, mostly for protecting electronic equipment rooms in buildings or special shipboard applications.

A landmark set of experiments were conducted in 1959 as part of “Operation School Burning” following the fire at the Our Lady of Angels School. Heat detectors, projected beam smoke detectors and ionization smoke detectors were included in the test program. In the test program, smoke detectors of either type were observed to operate before rate of rise heat detectors in most cases and before the onset of untenable conditions. The conclusions from the study identified the greater potential for smoke detectors to improve life safety when compared to heat detectors. This conclusion was very significant, being the first mention of the improved benefit of smoke detectors over heat detectors [LAFD, 1959].

3. Evolution of Smoke Detectors

The evolution of smoke detectors can be divided into four generations based on the improvements in the smoke detector itself or on electronic communications methods with the detector. This historical sketch will also include reference to developments with other fire detection technologies, including flame detection, heat detection, video camera-based systems and gas sensors. A timeline of the evolution of smoke detectors is presented in Figure 4.

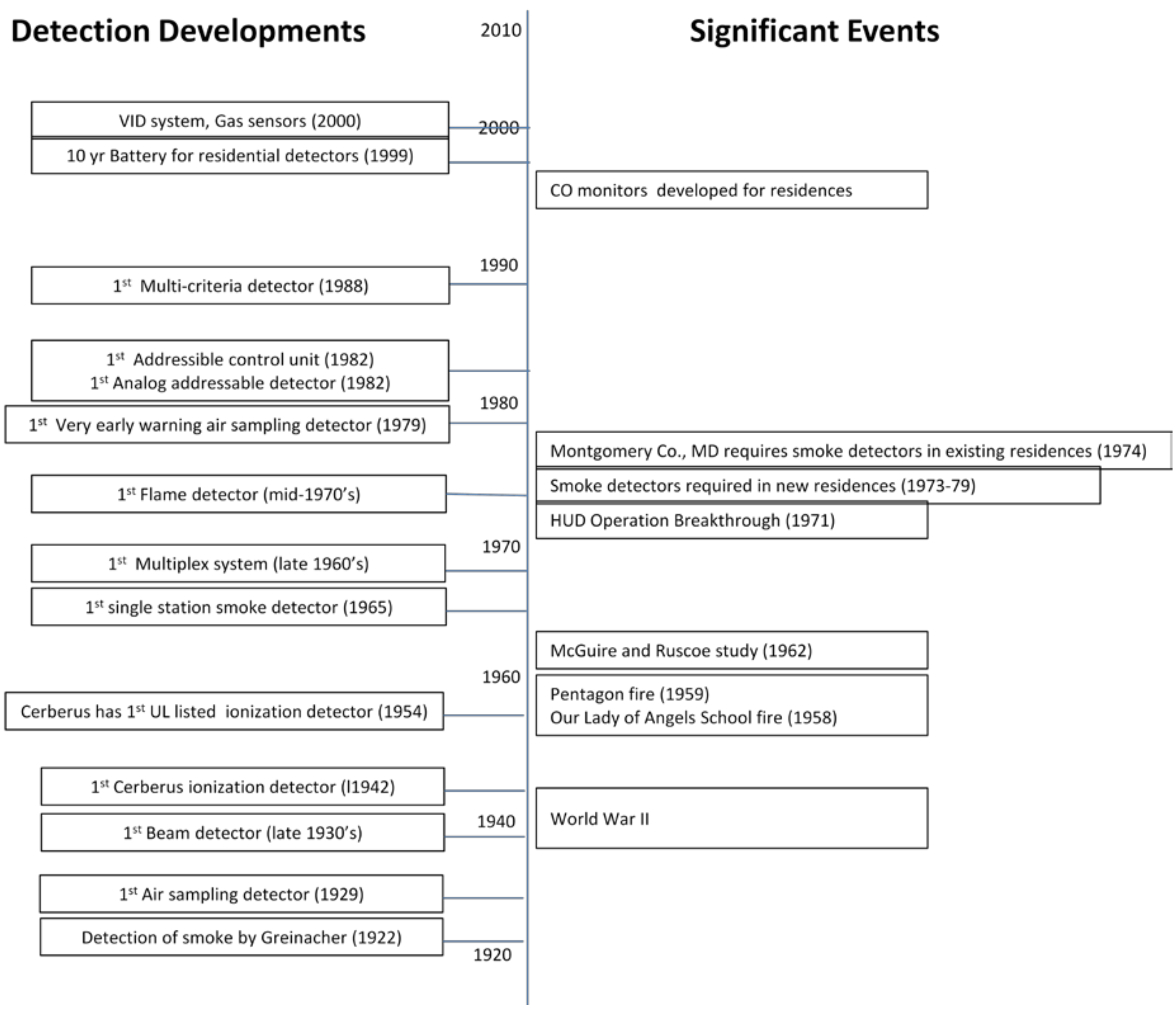

Figure 4. Evolution of Smoke Detectors

1st Generation Smoke Detectors (pre-1960)

In the 1800's, the first fire detectors were heat sensing devices. The first heat detector was developed by Alexander Ross in 1863, with the first commercial unit attributed to William Watkins in 1870 [Richardson, 2003]. This was a pneumatic device and it was not until 1890 that the first electronic heat detector was developed by Francis Upton [Meili, 1990].

A means to monitor smoke produced in fires wasn't discovered until 1922 by Greinacher from Berne. When he was conducting an experiment to measure the dust content in air, he noticed a reduced mobility of ion flow because of the attachment of dust molecules. He hypothesized that such could likely apply to smoke particles as well. His suggestion of the possible use of an ionization chamber for smoke detection purposes was published in a 1922 article in Bulletin of the Swiss Association of Electrical Engineering [Meili, 1990].

In 1929, Walter Kidde obtained the first Underwriters Laboratories' (UL) listing for a smoke detection device for shipboard applications [Richardson, 2003]. This system was manufactured by CO-Two with the principal application being to protect munitions storage spaces on board military ships. When this system detected smoke, it would actuate a total-flooding CO_2 system (this design continued in use through the mid-1940's) [Wilson, 2010]. The detection system was comprised of an air sampling tube which drew the smoke back to a photosensitive vacuum tube where the density of smoke particles was monitored.

In the late 1930's Walter Jaeger in Switzerland was conducting research to develop a poison gas detector. However, as he was conducting his experiments, he noticed current fluctuations in an ionization chamber being used that were caused by his cigarette smoke.[1] With Meili's assistance, they amplified the signal from the ionization chamber through the use of a triode filled with inert gas w/ cold cathode, control electrode and anode.

In 1937, Malsallez and Breitman applied for a French patent for a smoke detector which used an ionization chamber [Meili, 1990]. The ionization chamber used an electrometer tube as an amplifier (electrometers are used to measure particle concentrations in air). The performance of the device was tested in a telephone exchange. That early smoke

[1] The originality of the idea for the use of an ionization chamber to detect smoke is debated. One account is that Jaegar developed this idea on his own, while another account notes that Jaegar was encouraged to consider this approach by Masallez and Breitman, discussed next.

detector experienced a set of problems affecting its ability to be a commercially ready product including high heat generation, durability, large size and cost.

In the late 1930's, there were two developments in the U.S. ADT developed the first projected beam detector and Kidde developed the first spot-type photoelectric detector [Richardson, 2003].

Meili and Jaeger continued development of a smoke detector at Cerberus in 1940 [Meili, 1990]. Meili envisioned that a smoke detector could to serve as an artificial nose. The applications for smoke detectors were uncertain at that time as building codes did not require smoke detection for any application. However, in the early 1940's, Göring did express interest in a smoke detector that could respond to fires in buildings started by fire bombs [Meili, 1990].

The initial design of the smoke detector at Cerberus in the early 1940's used radium as the radioactive source for the ionization chamber [Meili, 1990]. However, radium was scarce during the war years and also posed a radiation hazard. The amount of radium was reduced to address these issues, but this reduced the effectiveness of the detector. Other areas for needed improvement were stability, reproducibility of the response and quality control from the manufacturing process. Stability and long-term reliability were improved later in the 1940's to include a second ionization chamber. A more stable source for the radioactive material would result from military research during World War II and became available to Cerberus in 1949. This source was also less prone to contamination [Meili, 1990].

Because the signal generated by the ionization chamber was so small, an amplifier was needed to make the signal easier to monitor. An improved trigger mechanism, the cold cathode tube, was developed by Meili, using the results of Jaeger's PhD dissertation in 1942. This opened the door for development of a commercial product. Cerberus ionization smoke detectors used this trigger tube in the 5 million units sold from 1942 to 1962 [Meili, 1990].

The initial detector was a high voltage unit, requiring 220 V. It wasn't until the 1960's that low voltage smoke detectors were developed in conjunction with the introduction of commercially available MOS Field Effect Transistor. The cold cathode tube for the initial detector is illustrated in Figure 5.

In 1951, Cerberus signed a contract with CO-Two for distribution of the Cerberus ionization smoke detector in the U.S. Later, this arrangement was organized as a separate company named Pyrotronics, a division of Baker Industries [Meili, 1990].

Figure 5. Early Cerberus Smoke Detector

In this era, smoke detectors were mostly found on ships. Virtually all fire detectors installed in buildings were heat detectors. With no demand for smoke detection in buildings, the continued development of a smoke detector represented a true exploratory venture. Smoke detectors were only being installed in buildings in Sweden, with a recently passed law for hotels of timber construction and in selected buildings in Japan [Meili, 1990].

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A landmark set of experiments were conducted in 1959 as part of “Operation School Burning” following the fire at the Our Lady of Angels School. Heat detectors, projected beam smoke detectors and ionization smoke detectors were included in the test program. In the test program, smoke detectors of either type were observed to operate before rate of rise heat detectors in most cases and before the onset of untenable conditions. The conclusions from the study identified the greater potential for smoke detectors to improve life safety when compared to heat detectors. This conclusion was very significant, being the first mention of the improved benefit of smoke detectors over heat detectors [LAFD, 1959].

2nd Generation Smoke Detectors (1960-1975)

With the recent recognition of the benefit of smoke detectors, further improvements in smoke detectors were sought. In 1962, Cerberus adopted Amercium 241 as the radioactive source for the ionization chambers [Meili, 1990]. Amercium was much more stable, was a pure alpha source (so it did not pose the same radiation hazard as radium because it did not emit long-range rays) and did not release any gaseous decomposition products. Other radiation sources were still used for years, including radium 226 in Statitrol’s ionization residential detector and Nickel 63, a beta emitter that had stability problems in a Gamewell detector [Cholin, 2010]. However, by the mid-1970’s, Amercium 241 became the unanimous choice.

In the mid-1960’s transistors were developed in the electronics industry. This enabled the trigger tube to be replaced with transistors. Even though Cerberus completed the revised design in 1967 using transistors, detectors with the trigger tube were still available until 1982 at the request of some customers, given that it was a proven technology. The switch to transistors enabled a smaller detector to be designed and would also result in a reduced power requirement.

In the early 1960’s, Cerberus started exploring a photoelectric approach for detecting smoke. Because the public was very uneasy about anything radioactive at that time, appreciable concern was expressed about the radioactive source contained within the ionization detector. While much was done to ease the fears of the public about the safety of the radioactive source, an alternative technology was pursued to develop a detector without the “baggage” associated of having a radioactive component [Meili, 1990].

In the late 1960's a Japanese manufacturer developed a completely transistorized ionization smoke detector. Coincidently, in 1969 a requirement was enacted mandating that smoke detectors be included in some buildings in Japan [Meili, 1990].

In 1970, Cerberus started researching the development of a CO detector [Meili, 1990]. This was a precursor to activities that were being pursued in the 1990's, again emphasizing the life safety aspects of fire detectors.

All things considered, the smoke detectors in this era were very sensitive [Papier, 2010]. As detectors were submitted to UL for approval, the design was often altered based on the observed performance in a particular test. As a result, the design was very empirical, including the angle for the photocell to be placed relative to the light beam, the intensity of the beam, and the amount and size of holes in the exterior plastic housing of the detector to permit smoke entry into the chamber [Papier, 2010].

Electronic Equipment Spaces

From the mid-1960's until the early 1970's, the market for smoke detectors was limited primarily to the protection of high-valued electronic equipment, museums and libraries. The applications were driven primarily with a concern to protect the contained commodities, and were not required by codes at the time. The interest in protecting electronic equipment spaces and libraries is attributed to experiences with serious fires. The fire in the Charles Klein Library at Temple University and a series of mainframe fires had received a significant amount of attention. One particular fire occurred in a computer room in an RCA facility in West Palm Beach, FL. The fire started in computers under test, with no fire protection available in the test area. RCA didn't want to use sprinklers because of a fear of damage to the equipment by water, and no alternative protection measures were considered. At about the same time, other serious mainframe fires were experienced at the Pentagon and other DOD facilities [Wilson, 2003]. Consequently, the Factory Insurance Association [1971] recommended smoke detection be included as one of the ten essential aspects of fire protection in all electronic equipment spaces.

During the 1970's, Pyrotronics was continuing to purchase heads from Cerberus based on the previous agreement. One of Pyrotronics' biggest customers for the detector heads was Bell Telephone, maintaining the previous trend of many of the smoke detector applications being for electronic equipment areas [Ellner, 2010].

Residential Smoke Detectors

The interest in providing smoke detectors in residences can be traced back to a 1962 Canadian study by John McGuire and Brian Ruscoe [1962]. They analyzed the life saving potential of fixed temperature heat detectors and ionization smoke detectors in fire incidents that caused 342 residential fire deaths in Ontario from 1956 to 1960. "Fixed temperature detectors were assumed to have been installed at the head of any staircase and, in each instance, in the area of origin of the fire. Two smoke detectors were assumed to have been installed, one at the head of the basement stairs and one at the head of the main staircase in a 2-story dwelling or between the living and sleeping areas in a 1-story dwelling." [McGuire and Ruscoe, 1962, p. 2-3]. They hypothesized that smoke detectors would have reduced the fatalities by 41%, while the heat detectors would have only reduced the number of fatalities by only 8%.

In 1964, First Alert developed a low-power (24 V) ionization smoke detector [Richardson, 2003]. This opened the door to the development of even lower power smoke detectors. A year later, Duane Pearsall (his company was Statitrol) developed a single station photoelectric smoke detector with Stanley Peterson that was powered by a battery [Richardson, 2003].

In 1966, Pyrotector received the first listing by UL of a residential, single station smoke detector following UL 168 [Richardson, 2003]. This detector used incandescent lamps for the light source. Over time, it was noted that as the filament aged, the color temperature of the light emitted would change to affect the sensitivity of the detector. Another problem was that because of the heat introduced to the chamber by the incandescent lamp, the sensitivity of the detector was affected [Papier, 2010].

McGuire and Ruscoe's conclusion caught the attention of Dick Bright at the National Bureau of Standards (NBS) (NBS is now called the National Institute of Standards and Technology) [Bukowski, 2001]. In 1971 Bright provided NBS's input to the Department of Housing and Urban Development (HUD) project called "Operation Breakthrough" which outlined innovative approaches for residential construction. Bright's input stated that smoke detectors should be required in these HUD homes [Benjamin, 1971].

The notion of residential detection was advanced thinking at the time. When the first edition of NFPA 74, Standard on Household Fire Warning Equipment was published in 1967, the minimum requirement for a residential fire alarm system was to provide a heat detector outside the bedrooms, all connected to a control panel. Such systems were installed in less than 1 percent of U.S. homes and had an estimated cost of about $1,500 for a small house [Bukowski, 1993].

With the input of McGuire and Ruscoe and the position taken by NBS, Meili suggests that the early 1970's served as a transitional period. Prior to that time, smoke detectors were considered primarily for property protection. After that time, smoke detectors were installed principally for life safety [Meili, 1990].

In 1971, HUD provided manufactured homes as temporary housing for people displaced from their homes damaged from Hurricane Agnes on the East Coast. HUD required a smoke detector to be installed in those homes following the criteria recently developed in Operation Breakthrough. During the three-year period when the 17,000 homes were occupied, there were no reported fire injuries or fatalities. With this noteworthy experience, in 1975 the Mobile Home Manufacturing Association adopted a policy of providing one smoke detector outside of a sleeping area in each manufactured home [Bukowski, 2001].

In the mid-1970's, Federal Agencies (Federal Housing Administration and Veterans Administration (VA)) involved in mortgage lending required smoke alarms to qualify for loans. Also around this time, a court case involving a fire fatality was decided indicating that heat detectors were not life safety devices [Boyer, 2010]. While the research had provided that opinion, now there was legal precedent for that opinion. In 1974, Montgomery County, MD became one of the first jurisdictions in the U.S. to require smoke detectors in new and existing residences [Brannigan, 1977]. In 1973, Cerberus observed a significant increase in the market for smoke detection as a result of the HUD requirement in manufactured homes [Meili, 1990].

In 1973, Pyrotronics saw the need to develop a battery-powered smoke detector for residential applications. Cerberus declined a request from Pyrotronics to develop a residential smoke detector for this application. Consequently, Pyrotronics proceeded on its own, though with assistance from Cerberus. At Pyrotronics, Ellner selected the battery and worked on the ionization chamber design with the assistance of a mentor at Cerberus, Andreas Schiedweiler. The Pyrotronics Model FB-1 smoke detector was introduced in 1976 using a readily available 9V alkaline battery. Previously other manufacturers used a 13V battery used in photographic work [Ellner, 2010].

BRK Electronics created the First Alert brand and designed the first UL-listed battery operated smoke alarm [ehow, 2010]. In 1974, Sears and BRK partnered to place Sears name on the BRK smoke detector. The popular Sears name and other popular trade names from that era carried over to the detector making them popular detector brands also. A BRK battery-powered detector from this era is illustrated in Figure 6.

Figure 6. Early BRK Battery-powered Smoke Detector
Ref: http://www.ideafinder.com/history/inventions/smokralarm.htm

Air Sampling Detectors

In 1967, development of the Very Early Smoke Detection Apparatus (VESDA) began in Australia by Ahlquist and Charlson. They considered applying a nephelometer for smoke detection (a nephelometer monitors air pollution by measuring the reflected light by smoke particles) [Cole, 2010]. In 1970, Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) used Ahlquist’s and Charlson’s nephelometer on aircraft to measure particles from bush fires in Australia. It was found to be very sensitive, being able to measure the presence of smoke particles where visibility had decreased to only 4 km (current smoke detectors sense the presence of smoke when the visibility has been reduced to 10’s of meters!).

The Australian Post Office (APO) was intrigued by this development and saw a potential application for early fire detection in post office facilities that would minimize service interruption from fires. The APO provided a test site to study the applicability of the device for use in its facilities, as well as telephone exchanges, computer rooms and cable tunnels. The existing fire detectors included in the tests were considered to respond too late, while the nephelometer provided a highly sensitive response in a range acceptable to the APO. Because the nephelometer was too expensive to be viable, the APO teamed with AWA (Australia’s largest electronics manufacturer at the time) to develop an acceptable detector. After three years, this effort was disbanded because of the lack of progress.

In 1977, the APO sought other collaborators to revisit the development of a detector for their facilities and distributed releasing a request for proposal. Two companies (Fire Fighting Enterprises (FFE) and British Aerospace Australia (BAA)) were given the award and worked together to develop a detector within 2 years. IEI Pty Ltd had also submitted a bid, but was not given the award as it was feared that the company was too small to be successful on the project, though was nonetheless given non-financial encouragements to continue. While IEI developed a cheaper system (named VESDA), the contract with FFE and BAA required the purchase of their units for the first five years. The APO purchased 60 of these units, but none were installed. One of IEI's biggest initial clients was the State Electricity Commission of Victoria. Later, Telecom/Telstra became the largest single user of VESDA systems. In the mid-1970's Environment One in the U.S. started marketing an air sampling detector using a different technology (cloud chamber type) which was principally installed to actuate extinguishing systems in electronic equipment areas [Wilson, 2010]. A schematic diagram of a VESDA system is depicted in Figure 7.

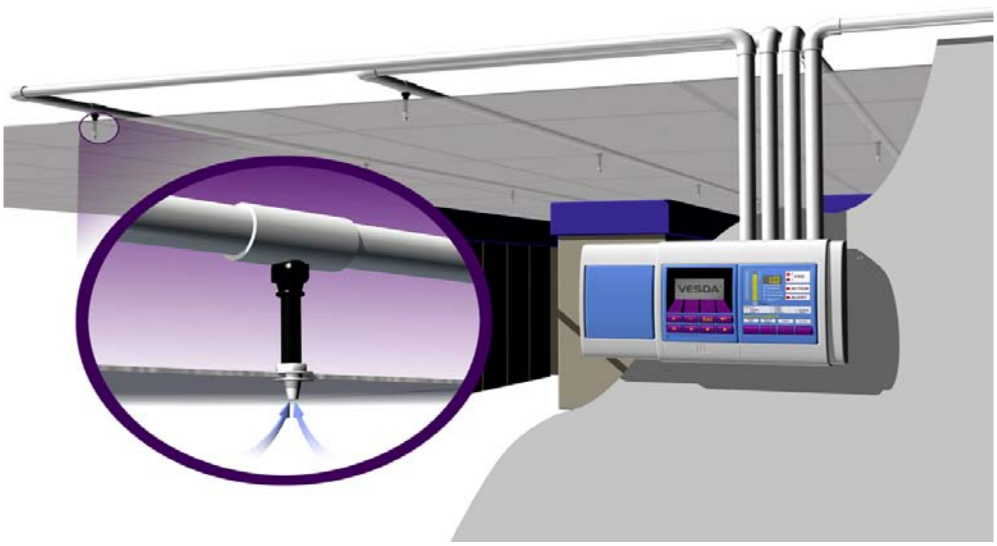

Figure 7. Schematic Diagram of VESDA System
Ref: Xtralis

Flame Detectors

A new detection technology was explored in the early 1970's that could respond to the radiation emitted by flames. Research into radiation detectors (more commonly referred to as flame detectors) was initiated at virtually the same time in three companies: Cerberus, Pyrotector and Honeywell [Cholin, 2010].

Pyrotector used phototransistors to monitor infrared (IR) radiation. Cerberus used an IR sensor which responded if a particular pairing of magnitude of radiation and variation of the radiation (due to flickering of the flames) was detected. The Cerberus DFS3 was a high voltage detector (220V) which could incorporate 3, 10 or 30 sec time delays for alarm confirmation. Common installations for the Cerberus detectors were diesel generator rooms for AT&T and General Telephone [Corson, 2010]. A contemporary Siemens IR flame detector is illustrated in Figure 8.

Figure 8. Siemens DF 1101-Ex IR Flame Detector

Honeywell used a sensor to monitor ultraviolet (UV) radiation using a vacuum photo-diode tube that had been used in burner controls for large industrial boilers and ovens. They briefly explored the potential market for flame detectors and decided not to pursue it further. However, three engineers (Al Peterson, Bill Crosley and Ted Larsen) left Honeywell to form a company Detector Electronics (also called Detronics) in order to further develop flame detectors using the Honeywell UV sensors. Their modifications led to a viable, commercial product.

Closing Statement

Near the end of this era the popularity of smoke detectors had slowly increased. In 1973, annual sales of smoke detectors were 500,000 units. However, three years later the popularity would skyrocket, with later annual sales in 1976 of 2.9 million units [Richardson, 2003].

3rd Generation Smoke Detectors (1975-1990)

The interest in smoke detection increased significantly from the beginning of the 1970's to the end of the decade. By the mid-1970's, smoke detectors were being considered for installations in commercial occupancies such as offices and health-care facilities for life safety purposes, and not only to protect electronic equipment. Smoke detectors were also being placed in residences in increasing numbers. From 1973 to 1979, all three model building codes in the U.S., Council of American Building Officials (developer of the 1-

and 2-Family Dwelling Code) and NFPA 101 had changed to require smoke alarms in homes [Public/Private Fire Safety Council, 2006].

In July 1983, Ford sponsored a series of tests at their main engineering data center in Dearborn, MI principally to compare the performance of several types of smoke detectors (photoelectric, ionization and projected beam) from several manufacturers. A total of 23 tests were conducted as part of the test series which included a variety of smoke sources. Participants included Pyrotronics (ionization and photoelectric detectors), Gamewell (all three types), ADT and Chubb (projected beam), and Firetek (ionization). An air sampling detector was also included from Environment One (ASD) as was an IR flame detector from Gamewell. Ceiling mounted and in-duct detector installations were explored. As a result of these tests, Ford developed a preference for the ionization smoke detector for their data center application considering performance and cost.

Several changes were incorporated into smoke detectors in this era including the replacement of the incandescent light source with a light emitting diode and use of silicon technology to replace photoconductive cells in photoelectric smoke detector units [Papier, 2010]. In 1981 Pyrotronics introduced a commercial ionization unit [Ellner, 2010]. In the mid-1980's Hochiki developed a single radioactive source/dual chamber detector. The single source decreased the amount of Amercium needed and thus helped reduced the cost of the detector [Cholin, 2010]. With the development of integrated circuits, smoke detectors became somewhat smaller and required less power.

Several changes were made in the UL approval standards for smoke detectors from 1976 to 1981. First in 1976, the two separate standards (UL 167 for ionization detectors and UL 168 for photoelectric detectors) were combined into one standard, UL 217 (Single and Multiple Station Smoke Alarms) at the request of industry. The first edition of UL 268 (Smoke Detectors for Fire Alarm Systems) was published shortly thereafter in 1979 [Patty, 2010].[2] Another change in the test standards involved the fire tests that the detectors needed to respond to. Until 1979, the response of ionization and photoelectric smoke detectors were tested only with flaming fire tests. Because ionization and photoelectric detectors were observed to respond appreciably differently in research programs to flaming and smoldering fires, a smoldering fire test was developed and included in UL 217 and UL 268 in 1979. Another change incorporated into UL 217 and 268 in 1979 resulted from field observations that smoke detectors exposed to strong electrical transients (lightning, start-up of a large motor, etc.) were disabling the smoke detector, either due to a portion of the circuit being burned out, a component being destroyed or in some cases detectors starting their own fire. The problem, not seen

[2] UL 217 applies to single and multiple station smoke detectors. UL 268 applies to smoke detectors which are part of a fire alarm system.

previously, was attributed to an oversized resistor that had recently been included in detectors to reduce the voltage to low levels. In response to this field experience, UL introduced transient tests to simulate current surges [Papier, 2010][Patty, 2010].

Residential Smoke Detectors

In 1977, a cooperative effort was initiated between UL and the NBS in the project known as the "Indiana Dunes Tests" to examine the performance of smoke alarms in homes [Bukowski, 1976]. McGuire and Ruscoe's analysis had assumed only two smoke detectors were located in the home. The results from the Indiana Dunes Tests provided data that led to the spacing requirements included in NFPA 74, "The Standard on Installation Maintenance and Use of Household Fire Warning Equipment." The requirements were consistent with McGuire and Ruscoe's recommendation [Bukowski, 2001]. Bukowski and Mulholland at NBS also demonstrated differences in the response of ionization and photoelectric smoke detectors where ionization detectors were more sensitive to flaming fires and photoelectric detectors to smoldering fires [1978]. Even with these differences, the performance of each type of smoke detector was considered to be capable of alerting early enough to provide sufficient escape time. [Bukowski, 2001].

A significant reduction in the power requirement for single station detectors was the result of a different sounding device being incorporated into detector. The original electromechanical sounder was a linear magnet and spring diaphragm which provided sound at low frequencies and had several harmonics much like a bicycle horn. The industry replaced that unit with a circuit utilizing a resonating piezo-ceramic disc to provide the revised tone at about 3 kHz [Cholin, 2010][Ellner, 2010].[3] The reduced power requirement enabled a change in the battery from a 9V alkaline battery to a 9V carbon-zinc battery, reducing the battery replacement cost for the homeowner.

By the late 1970's, the price of a single station residential smoke detector had nosedived from about $50 to $8 due to fierce competition by many companies (there were still about 50 companies in the early 1980's) [Richardson, 2003]. Pyralarm (the residential arm of Pyrotronics), ceased manufacturing residential products in 1980 to focus on its commercial business [Ellner, 2010].

[3] Recently, the need to provide low frequencies and harmonics has been recognized to improve the audibility of the sounders for elderly and hearing impaired individuals and will be incorporated into contemporary smoke detectors.

Nuisance Alarms

By the early 1980's, smoke detectors were in widespread use in numerous occupancies. With this increased popularity came a large number of nuisance alarms with smoke detectors being factory set at a high sensitivity. The Department of Energy (DOE) found that ionization smoke detectors had more nuisance alarms than photoelectric smoke detectors, either due to cleaning requirements or due to the high altitude of the facility [Wilson, 2010]. In the mid-1980's UL's Dubivsky studied the smoke detector experience at the VA and found a significant nuisance alarm problem. Consequently, the lower end of the sensitivity range for smoke detectors specified in UL 217 and 268 was increased from 0.2% to 0.5% [Papier, 2010][Patty, 2010]. A hush feature was also incorporated into residential smoke detectors to temporarily silence the detector in response to a nuisance alarm [Papier, 2010].

Nuisance alarm problems were also addressed by various methods of alarm confirmation. In the mid-1980's, alarm verification was introduced into UL 268. When going into alarm, a detector would temporarily go "blind", then wake up again after a short time period to see if smoke was still present before going into alarm. Cross-zoning was another method that became popular around this time as another means of confirming an alarm. This technique required that a second detector on another zone (i.e. not physically close to the alarming detector) also be in the alarm state [Papier, 2010].

Another change motivated by nuisance alarms was related to the housing and pathway for smoke to travel from the exterior of the detector to the sensing chamber. Small insects were observed to crawl into the interior of a smoke detector to cause a false alarm. The initial solution involved a product known as "tangle foot." Tangle foot was a sticky substance placed on the edge of chamber which would trap the bugs if they stepped onto the substance placed far away from the sensing chamber. However, after a while, the dead bugs would build up around the exterior edge of the detector to affect the entry characteristics of the detector (making it more difficult for smoke to reach the sensing chamber). Manufacturers opted for a bug screen to be placed outside of the sensing chamber, with the hole size adjusted over the years, starting with 0.024", being reduced to 0.016", and settling on 0.022". While this improved the situation, it was not a perfect solution. If not maintained, clogging of the bug screen could occur as particles got lodged in the holes [Papier, 2010].

Communications

In the mid-1980's, the tremendous growth in the number of installations of smoke detectors created a challenge. With numerous smoke detectors being installed in some large buildings and with some of the locations being hard to access, e.g. under raised subfloors, in plenums above raised ceilings, and in air ducts, emergency responders sometimes were faced with significant challenges in identifying a triggered smoke detector. This was especially problematic if the smoke detector was triggered by a nuisance source or perhaps had responded to a small, incipient fire or perhaps a fire that self-extinguished. As such, a means to identify triggered smoke detectors was developed.

In the late 1970's, NFPA 72D, "Standard for the Installation Maintenance and Use of Proprietary Protective Signaling Systems for Watchman Fire Alarm and Supervisory Service", required point notification of detectors (i.e. a light on the detector). Running pairs of wires between the detectors and the control panel became impractical, especially in large buildings containing many detectors. Cholin developed a Priority Matrix for point annunciation. In Europe, a multiplex system was initially used in the 1960's to reduce the number of wires going coming back to control panel and later became a popular approach in the U.S. Multiplex systems became feasible with the invention of integrated circuits [Cholin, 2010].

In addition to the need to determine the location of triggered detectors, with the noted maintenance needs of detectors documented by DOE and VA, monitoring the status of each detector could assist in identifying maintenance demands. As a result, addressable detectors were developed which enabled the status of each detector to be continuously monitored, both to identify sensitivity changes (indicating a maintenance need) and alarm conditions. [Papier, 2010][Wilson, 2010]. In 1982, the Pyrotronics XL3 introduced the first analog/addressable detector/control-unit system [Ellner, 2010][Corson, 2010]. Pyrotronics had the first patent in 1982 to provide a digital address for each smoke detector and to vary the length of an electrical pulse in accordance with the amount of smoke in the chamber. [Papier, 2010] Simplex and BRK followed several years later with addressable systems [Papier, 2010][Fraser, 2010]. This allowed reporting of the percent obscuration (addressing the relative smoke concentration), monitoring for a dirty detector and remotely setting sensitivity levels differently for detectors in different locations from the control panel.

With this advance, some systems permitted alarm decisions to be made at the control panel, whereas previously alarm decisions were made only at the detector. Scheidweiler [1983] described a method to distribute the intelligence with addressable fire detectors to better make alarm decisions as well as to actuate control functions.

4th Generation Smoke Detectors (1990-present)

By 2006, smoke detectors (now called smoke alarms) were common equipment in U.S. residences, with 96% of the homes found to have at least one smoke alarm [Ahrens, 2009]. In an analysis of 378,000 fire incidents that occurred from 2003 to 2006 in U.S. homes, the fire death rate in homes without a working smoke alarm was determined to be approximately twice that in homes with working smoke alarms.

Some of the more significant advances included in the fourth generation of smoke detectors include multiple sensors within a single detector housing, algorithms to evaluate and perhaps combine these multiple sensors, and a ten-year battery (for residential smoke detectors). New sensing technologies have also been developed within the past 20 years.[4] A bibliography compiled by Bukowski and Jason [1991] contains numerous references to papers exploring the use of multiple sensors, multiple criteria (including gas sensors) in smoke detectors. Similarly, AUBE conferences in recent years have included numerous papers on these topics presented by individuals from industry, research and academia of many nationalities, indicating the widespread interest in the topics [AUBE 1995][AUBE 2001].

Residential Smoke Detectors

In 1995, a 10-year lithium-battery-powered smoke alarm was introduced and in 1999, NFPA 72 required residential smoke detectors to be replaced every 10 years [Public/Private Fire Safety Council, 2006]. The basis for the 10-year timeframe resulted from a reliability study conducted by Papier in the mid-1970's [Papier, 2010]. He estimated that after 10 years only 90% of the smoke detectors would still be working.

Multi-criteria and Multi-sensor Smoke Detectors

Improvements in smoke detector technology led to adding more sensors to the detector to increase the amount of information about the fire to analyze the danger level and/or to discriminate between fire and nuisance sources. The additional sensors included smoke sensors having different sensing principles (such as photoelectric and ionization), or sensors responsive to other physical attributes of a fire (such as heat, infrared, or carbon monoxide). Detectors having more than one sensor are defined in NFPA 72 as multi-criteria smoke detectors and multi-sensor smoke detectors. The former type is designed to generate only one alarm as the result of analyzing all of its sensors, while the latter type is designed to generate multiple alarms (e.g. smoke alarm, heat alarm, etc

[4] The word "new" means relative to the fire detection industry.

The principal focus of developments in this era has been to make the detectors “smarter”, i.e. to be increasingly responsive to fire signatures representing threats, and more discriminating relative to signatures from nuisance sources. Pfister demonstrated the benefits of multiple sensor detectors for nuisance source rejection [1997]. Commercially available units have been available since the late 1990’s which incorporate sensors from two or three of the following types of detectors: ionization, photoelectric or fixed temperature heat detectors.

With the inclusion of multiple sensors, logic also needed to be incorporated within the detector. Some of the detectors included “or” logic, meaning if any one of the sensors reached an alarm level, the detector went into alarm. This improved the sensitivity, but exacerbated any nuisance alarm problems with the individual sensors. Another design required an “and” logic for multiple sensors where both sensors need to reach an alarm threshold. This decreased the nuisance alarm susceptibility but delayed the response to an actual fire.

The most advanced option involved smoke detectors that included weighting the signals from the various sensors using a simple equation to determine an alarm condition. Artificial intelligence methods have also been proposed to assist with nuisance alarm discrimination [Thuillard, 1994]. This approach is used to optimize the response of the detector, typically to minimize the responses to nuisance alarms while maintaining a fast response capability to actual fires. These algorithms may be based on the magnitude of the signal, its rate of rise, or even the absence of signal in conjunction with signals from the other sensors [Ellner, 2010]. Where a microprocessor chip was included within the detector itself, this meant that the decision to go into alarm could be returned to the detector itself after being with the control panel in the previous era. A contemporary Siemens detector is illustrated in Figure 9.

Figure 9. Siemens HFP-11, multi-criteria sensor detector

Pyrotronics' first multi-criteria detector (heat and photoelectric) with an algorithm was the FP-11 (FirePrint) which was developed in 1996, and was a leader in this category. Now, many detector manufacturers have multi-criteria detectors [Boyer, 2010] [Papier, 2010].

Gas Sensors

While Cerberus developed a prototype CO sensor in 1970, interest in developing a responsive CO sensor waned until the 1990's. In the 1990's, interest increased in the U.S. to include CO sensors in residences to detect the accumulation of CO from non-fire sources. The speed of response of the early CO sensors was relatively slow, making them inappropriate for fire detection purposes. More recent developments with electrochemical and semiconductor devices have increased the responsiveness of the units.

Milke [2001], Gottuk, et al. [1999], and Milke, et al. [2003], explored the use of gas sensors (CO and CO_2) in fire detectors. The initial feasibility studies indicated a substantial reduction in nuisance alarms were possible while maintaining a response time to actual fires which was comparable to commercial photoelectric and ionization detectors. Now, several manufacturers including System Sensor (see Figure 10), Bosch and Simplex have commercially available multi-criteria smoke detectors where one of the sensors is a CO gas sensor. Edwards 4D smoke detector for duct applications includes a CO_2 sensor which can monitor the air quality to also serve as an indoor air quality monitor.

Figure 10. System Sensor Advanced Multi-Criteria Fire Detector

Flame Detectors

Advances in flame detectors were actually initiated in the mid-1980's with the availability of semiconductors. This permitted pyroelectric cells to be used as the sensors. Flame detectors were developed which were capable of monitoring multiple wavelengths in the UV and IR bands, to further improve the sensitivity of the detectors to a broader range of fire sources, and to ignore nuisance alarm sources. With the incorporation of microprocessors into the detector, the detector could perform a Fast Fourier Transform to further improve the sensitivity and immunity to nuisance alarms.

Video Detection Systems

One of the new detector technologies developed in this most recent 20-year span includes detection systems using video cameras. Video detection systems (VID) have been recently developed by a small number of manufacturers. Elliott suggests that video detection is an extension of flame detectors [2010]. In 2000, the initial VID systems using cameras were developed only to monitor flame radiation in the visible wavelengths. Wieser and Brupbacher [2001] obtained favorable results of the performance of VID systems obtained from tests in road tunnels. These systems have been further developed over the last 10 years to include flickering or reflected flames and smoke plumes.

The initial VID systems sent signals back to a control panel (or computer) in order to analyze the signal for a possible alarm. The latest generation of VID systems has microprocessors contained within the camera housing in order to make the alarm determination. Video signals received by the VID system can also be forwarded to emergency responders via an Internet connection.

The performance of an early generation VID system developed by axonX with a typical black and white security camera was assessed in tests conducted in an indoor arena at the University of Maryland. These tests demonstrated the capability of the system using a typical security camera located on the concourse to promptly detect smoldering fires in the center of the arena and at the opposite side of the arena [Milke and Kouchinsky, 2007]. The SigniFire system tested at the University is depicted in Figure 11.

Figure 11. SigniFire VID System

Spectrex has included video capture as a supplement to an IR flame detector. In this case, once the detector is triggered due to an IR signal, streaming video from the 10 seconds period prior to the trigger point is available to observe the conditions that led to the threshold event [Cholin, 2010].

4. Impact of smoke detectors and smoke alarms[5]

Prior to 1970, when smoke detectors were installed only in selected occupancies, the annual number fire deaths in the U.S. was on the order of 8,000, with most of the deaths occurring in residences. In the last few years, that number of annual fire deaths in the U.S. has declined to approximately 3,300. While there are several factors that may have contributed to the decline in fire deaths, Bukowski, et al., note:

> "Thus the home smoke alarm is credited as the greatest success story in fire safety in the last part of the 20th century, because it alone represented a highly effective fire safety technology with leverage on most of the fire death problems that went from only token usage to nearly universal usage in a remarkably short time."

The trend in the annual number of fire deaths and increasing proportion of homes with at least one smoke detector since the 1970's is presented in Figure 12. Currently, 96% of U.S. homes have at least one smoke detector.

[5] "Because the term smoke alarm is a relatively new term (originally all smoke sensing devices were called smoke detectors), the references in this section that refer to smoke detectors would actually be called smoke alarms today. To avoid confusion, smoke detectors and smoke alarms are used interchangeably in this section."

As a result of the recognition of the benefit of smoke detectors, several organizations strongly encourage the use of smoke detectors in residences. For example,

The United States Fire Administration (USFA) noted the following [2001]:

- Smoke alarms save lives and money.
- 38% of residences had an operable alarm during a fire, but these fires accounted for only 8% of total property loss.
- Only 6% of U.S. homes are not equipped with smoke alarms, yet 40% of residences with fire had no installed alarm.
- Alarms operate with more frequency in apartments than in one-and two-family homes. The reason may be that professional property managers are generally responsible for maintaining the alarms, not the apartment dwellers.
- Multiple-fatality fires are less likely to have working smoke alarms.

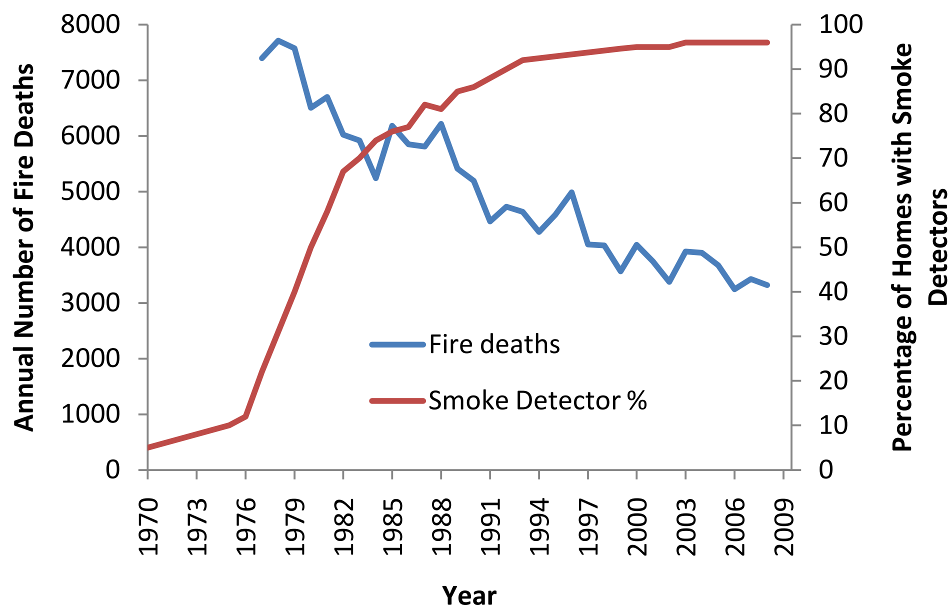

Figure 12. Annual Number of US Fire Deaths and Percentage of Homes with Smoke Detectors

In 2004, the USFA website indicated [USFA, 2004]:

> "Smoke alarms are one of the best safety features you can buy and install to protect yourself, your family and your home."

The Smoke Alarm Installation and Fire Safety Education (SAIFE) program is funded through CDC's Injury Center to deliver smoke alarms to homeowners in 16 states. Through this program, over 312,000 smoke alarms have been installed in over 174,000 homes. As a result, an estimated 1,218 lives have been saved since the program began in 1998 [Ballesteros, et al., 2005].

In a similar smoke detector giveaway program in Oklahoma City in the late 1980's, the fire department distributed 10,100 smoke alarms to 9,291 homes in a 24 square mile area of the city. The area targeted had the highest rate of injuries from residential fires in the city. In the four years after the smoke alarms were distributed to the homes, the fire injury rate decreased by 80 percent [Mallonee, et al., 1996].

From the NFPA website [2010]:

> "Smoke alarms that are properly installed and maintained play a vital role in reducing fire deaths and injuries. Having a working smoke alarm cuts the chances of dying in a reported fire in half."

Analysis of Smoke Detector Performance

A project was completed in 2010 to assess the relative performance of smoke detectors and sprinklers in one- and two-family dwellings and apartments, commercial residential (i.e. hotels), and institutional occupancies [Milke, et al., 2010]. The study included a review of statistical analyses of smoke detector and sprinkler performance from fire incident data and data from experimental programs. A previous analysis of fire incident statistics conducted by Ahrens at NFPA resulted in the conclusion that almost two-thirds (63%) of all home fire deaths in 2003-2006 occurred in homes which lacked working smoke alarms [2009]. This means that the fire death rate in homes without a working smoke alarm is approximately twice that in homes with working smoke alarms.

A review of the experimental studies confirmed what was observed in the Operation School Burning and Indiana Dunes tests, i.e. smoke detectors respond prior to heat detectors (and therefore sprinklers) in most fires. In addition, tenability analyses conducted using data from several of the experimental programs concluded that sufficient egress time is provided by smoke alarms, considering conditions existing at the time of their response. Notarianni noted in her experiments that sufficient warning and protection is also provided by sprinklers, with the principal exception being those fires where an obstruction is present preventing the sprinkler spray from reaching the burning fuel, referred to as a "shielded fire" [1993].

The analysis of NFIRS data conducted as part of the study by Milke, et al., considered the response of smoke detectors and sprinklers in fire incidents occurring from 2003-2007 in 1-, 2- and multi-family residential dwellings, commercial residential facilities and health-care facilities. Approximately 197,000 fire incidents were included in the analysis. In all three of these occupancy groups, the proportion of fires judged to be too small for the operation of the smoke detectors was appreciably fewer than those for sprinklers. The results for the three occupancies are summarized in Table 2.

The fact that fewer fires are "too small" for smoke detector operation indicates that smoke detectors are more sensitive to the signatures produced at early stages of fire development than sprinklers. As such, smoke detectors are capable of responding to smaller fires than sprinklers. Those fires which are "too small" for smoke detector or sprinkler response still pose a significant hazard, as indicated by the casualty rates (fatal and non-fatal) incurred in such fires. The respective casualty rates per 100 fires for smoke detector and sprinkler responses in buildings with sprinkler protection are indicated in Table 3.

Table 2. Proportion of Fire Incidents Judged to be Too Small for Operation

	Smoke Detectors		Sprinklers
	Non-sprinklered property	Sprinklered Property	
1- and 2-family dwelling	13.1	12.8	38.9
Commercial residential	9.7	10.8	54.2
Health-care	11.4	17.8	65.4

Table 3. Casualty Rates for Fires Judged Too Small for Operation (Casualties per 100 fire incidents)

Occupancy	Too Small for Smoke Detector	Too Small for Sprinkler	Ratio: Sprinkler/ Smoke Detector
1- & 2-Family and, Multi-Family Residential	0.36	1.47	4.1
Commercial Residential	0.11	1.70	15.5
Health-care	1.06	3.08	2.9

The significant difference in casualty rates in the “too small” fires is an indication of the potential contribution of smoke detectors to life safety in sprinklered buildings. In those fires in 1- & 2-family and, multi-family residential occupancies where sprinklers did not respond, smoke detectors alerted occupants in over 89% of the incidents. Similarly, in fire incidents in commercial residential occupancies, smoke detectors alerted occupants in approximately 94% of the cases where sprinklers did not operate. In health-care occupancies, smoke detectors alerted occupants in all of the cases where sprinklers did not operate.

5. Future

Future developments are likely to further improve the intelligence of smoke detectors, primarily to discriminate between fire and nuisance sources, but also perhaps to discriminate between different fire sources.

Results from informal surveys of students at the University of Maryland for approximately the last 15 years have indicated that virtually all have heard smoke detectors in their homes respond to a nuisance alarm. However, few have heard a smoke detector respond to an unwanted fire. The prevalence of nuisance alarms over alarms due to actual fires, observed formally by Pfister [1997] and Hall [1989], leads to a tendency for individuals to ignore the alarm. The current improvements of including multi-criteria, multi-sensor and especially gas sensors along with the algorithms are likely to decrease nuisance alarm frequency, while maintaining a response time that is at least as short as single sensor, traditional smoke detectors. Decreasing the nuisance alarm frequency is likely to be a very significant factor in improving the recognition that smoke detectors are an important fire safety component.

In the future, with the increased intelligence being incorporated into smoke detectors, they may be asked to do more than simply sound an alarm. With the recent incorporation of gas sensors in detectors, smoke detectors can also serve as air quality monitors. These may then be used to regulate the operation of the HVAC system to improve energy efficiency in buildings.

Further, having information from an array of smoke detectors can be fed to a control panel to chart the recent course of the fire and direct people to exits away from the fire or heavy concentrations of smoke. Initial research has been conducted on this latter issue through “Smart Buildings” types of initiatives, including the Embedded Intelligence in Buildings project currently being conducted at NIST.

Improved intelligence may also enable the smoke detector to be used to monitor fire conditions within a space. Having a recent history of fire conditions within a space may enable future conditions to be predicted through the use of a reverse algorithm. This would involve using the detector measurements to infer the characteristics of the fire source, e.g. heat release rate, location, fuel composition, etc. These characteristics can then be used as input to enable the use of a computer fire model to predict the future course of the fire [Neviackas, 2007].

Finally, including an array of gas sensors within a smoke detector begins to approximate an artificial nose. This was the initial concept noted by Meili about 70 years ago. Artificial noses are already used for process control in some industries. Currently, such artificial noses are relatively expensive. However, if a decrease in cost can be achieved, having an artificial nose has the potential to further improve the sensitivity and nuisance alarm rejection capability of even today’s most advanced detectors.

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