SMOKE DETECTION: A STATUS REPORT

by

M. Sultan

ANALYZED

Division of Building Research, National Research Council Canada

Ottawa, February 1984
SMOKE DETECTION:  A STATUS REPORT

by

M. Sultan

Ottawa
February 1984
# TABLE OF CONTENTS

1. ABSTRACT ........................... 1

2. INTRODUCTION ....................... 1

3. CHARACTERISTICS OF COMBUSTION AEROSOLS 1

4. MECHANISM OF SMOKE DETECTOR OPERATION 2
   4.1 Photoelectric-Type Detectors 2
   4.2 Ionization-Type Detectors 2
   4.3 Combined Ionization/Photoelectric Detectors 3
      4.3.1 The "OR" Detector 3
      4.3.2 The "AND" Detector 3

5. POSITIONING OF SMOKE DETECTORS IN RESIDENCES 3
   5.1 Location of Smoke Detector Inside a Room 3
   5.2 Installation of Smoke Detectors in Long Halls 4
   5.3 Installation of Smoke Detectors in Corridors 4
   5.4 Detection of Bedroom Fires 4

6. WAKING EFFECTIVENESS OF SMOKE DETECTORS 4
   6.1 Factors Affecting the Waking Response 5

7. CAPABILITIES AND LIMITATIONS OF SMOKE DETECTORS 6

8. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK 6

9. REFERENCES .......................... 7

10. TABLE ................................ 10
1. ABSTRACT

After a discussion on the characteristics of combustion aerosols, various aspects of the performance of residential smoke detectors are reviewed with emphasis on operation mechanisms, positioning, waking effectiveness, and capability and limitations. Recommendations for future research are made to improve the understanding of smoke detection practices.

2. INTRODUCTION

Loss of life by fire is a significant problem throughout the world. Bright reported that 40 to 50% of the people killed in fires each year could be saved if early warning fire detection devices were installed\(^1\). Fire death statistics for various countries are presented in Figure 1 (from Banks and Rardin\(^2\) and Banks\(^3\)). Despite some improvement in fire statistics during the last few years\(^3\), the United States and Canada share the highest death rate per million persons among the nations covered, almost twice that of any other country reported.

In their early stages, most fires are innocuous and can be easily controlled. The earlier the detection, the better the chances of escape and the sooner suppression methods can be applied.

3. CHARACTERISTICS OF COMBUSTION AEROSOLS

As reported by Custer and Bright\(^4\), combustion releases into the atmosphere solid particles (aerosols) ranging in size from \(5 \times 10^{-4}\) \(\mu m\) to 10 \(\mu m\). Particles less than 0.3 \(\mu m\) do not scatter light efficiently, and thus are practically invisible.

In the event of a fire, only detection at the start of combustion, whether flaming or smouldering, can ensure effective intervention. The effectiveness of detection depends on the nature of the alarm signal produced by combustion products. Of the available models of detectors, two types respond to the presence of particles: optical detectors measure smoke concentration either by light absorption or light scattering, and ionization chamber detectors respond to the presence of smoke by changed dynamic resistance of an ionization chamber, which results in the reduction of the quiescent current produced by a radioisotopic source.

In order to enhance the performance of a smoke detector, one must know the characteristics of combustion aerosols. The aerosol size distribution from smouldering and flaming combustion of various materials has been determined by Moliere et al.\(^5\), King\(^6\), Bankston\(^7\) and Lee and Mulholland\(^8\). The aerosol distribution curves obtained by Moliere et al.\(^5\) are shown in Figure 2 for different combustible materials (Table 1) involved in real fires. Two distinct sets of
distributions can be observed: one corresponds to a smouldering fire, where the aerosol has an average particle diameter of more than 0.3 μm (visible aerosol) and one corresponds to a flaming fire with substantial invisible aerosol (average particle diameter less than 0.2 μm). These distributions are even more striking when presented in the form of a cumulative probability scale from 0 to 100% for each fire, as shown in Figure 3.

4. MECHANISM OF SMOKE DETECTOR OPERATION

There are three types of smoke detectors: the point-type detector, which detects smoke at one position, the sampling detector, which is a point-type detector taking samples from a number of positions, and the beam-type detector, which covers a length up to 100 m. Only point-type detectors will be considered in this report.

4.1 Photoelectric-Type Detectors

Photoelectric detection of smoke has been employed for some time, particularly where the fire is expected to generate a substantial amount of smoke. This type of detector operates on the principle that smoke obscures a light beam or scatters light into a photocell, as shown in Figure 4 (from Northey). The change in current resulting from partial obscuration or light reflection of a photoelectric beam by smoke between a receiving element and a light source is measured and an alarm is tripped when the obscuration or scatter reaches a critical value. Photoelectric detectors respond quickly to optically dense smoke, but they are far less sensitive than ionization chamber detectors to clean-burning fires.

4.2 Ionization-Type Detectors

An ionization detector consists of one or two ionization chambers and amplification circuits. Air in the ionization chamber is made electrically conductive (ionized) by bombardment of the nitrogen and oxygen molecules with alpha particles emitted by a minute radioactive source. A voltage applied across the ionization chamber causes a very small electric current to flow as the ions travel to the electrode of opposite polarity. When combustion particles enter the chamber they attach themselves to the ions, as schematically shown in Figure 5 (from Northey), and cause a reduction in current flow. The reduced current flow increases the voltage on the electrodes. When a predetermined level is reached, an alarm is activated. One of the problems with ionization detectors is their reduced sensitivity to large aerosol particles produced mainly by smouldering types of fires. An optical detector cannot provide the sensitivity of an ionization detector when the particles are small, and conversely an ionization detector cannot provide the sensitivity of an optical detector if the particles are large.
4.3 Combined Ionization/Photoelectric Detectors

Since photoelectric detectors and ionization detectors are sensitive to particles of different size spectrums, combination smoke detectors (photo-Ion) can be used to cover the full spectrum of particles. These detectors have both ionization and photoelectric sensors. The circuitry can be arranged so that if either sensor 'sees' smoke an alarm is given. There are two types of combined smoke detectors.

4.3.1 The 'OR' detector. This type of detector, shown in Figure 6 (from Solomon and Reiss), sets off an alarm when either the ionization or the optical sensor detects smoke; in other words, the 'OR' detector is sensitive to both small and large particles. The false alarm incidence is approximately the sum of the false alarms for the two individual detectors.

4.3.2 The 'AND' detector. This type of combination detector, shown in Figure 7 (from Solomon and Reiss), will give an alarm only if both detector sensors detect smoke. The advantage of an 'AND' detector is its greater immunity to false alarms. If only one detector is activated, the other usually holds off the alarm.

5. POSITIONING OF SMOKE DETECTORS IN RESIDENCES

There are very little field data to back up the current smoke detector installation standards for residences. More research is required to evaluate the current practice of positioning smoke detectors, as specified in the fire protection standards.

5.1 Location of Smoke Detector Inside a Room

The positioning of smoke detectors in residences has been studied by Waterman et al. Both ionization and photoelectric smoke detectors were considered. Forty experiments were performed at two different sites. The ambient conditions included summer conditions at one site with the building air-conditioned, and winter conditions at both sites with the building heated. Fire was initiated in furnishings at various locations throughout the site. The time between the fire initiation and the response of smoke detectors at several locations was recorded. The results obtained indicated that wall-mounted detectors responded on an average about three minutes earlier than those mounted on the ceiling. These results are consistent with those obtained by Bukowski for smouldering fires. Bukowski found, however, that in flaming fires, ceiling-mounted detectors respond at approximately the same time as wall-mounted detectors. He attributed this to the fact that there is a stronger thermal buoyancy in flaming fires than in smouldering fires. However, as the smoke moves along the ceiling, the particles begin to settle, and therefore wall-mounted detectors are exposed to higher smoke levels earlier and respond faster.
5.2 **Installation of Smoke Detectors in Long Halls**

The response time for smoke detectors may vary considerably depending on the size and configuration of the hall. For a long hall, the installation of one smoke detector at each end would significantly improve the warning time potential in comparison with only one detector installed at one end of the hall. Coulter, among others, suggested that in a long hall a smoke detector should be placed at least every 9 m.

5.3 **Installation of Smoke Detectors in Corridors**

Kennedy et al. studied the response of smoke detectors in a corridor when the smouldering fire occurred in an adjacent room. They found that with small smouldering fires, the rate of smoke generation was not high and the temperature in the corridor remained low. When the door was open, the room and the corridor tended to fill with smoke uniformly so that detection of smoke occurred within a relatively narrow band of time at all detector locations.

In flaming fire, the time of detection is governed mainly by the velocity of the smoke front as it advances down the corridor. Consequently, for flaming fires the positioning of smoke detectors becomes important.

5.4 **Detection of Bedroom Fires**

A fire that starts in a bedroom will be detected rapidly by a smoke detector in an adjacent corridor only if there is an opening through the wall between the room and the corridor. The usual route for smoke through the wall is via an open doorway. Platt found that when the door is closed, a corridor-mounted smoke detector takes two minutes or more to respond to a flaming fire within the room; a similar detector in the bedroom signals the alarm within 30 seconds. The difference between these two response times is very important. Based on results of full-size experiments, Kennedy et al. and Bukowski reported that corridor-mounted smoke detectors respond to bedroom fires behind closed doors only after lethal smoke and gas conditions are reached within the room.

A study has begun at the Fire Research Section, NRCC, to develop methods of providing early warning of a bedroom fire behind a closed door, using corridor-mounted detectors.

6. **Waking Effectiveness of Smoke Detectors**

Although extensive research conducted during the last decade has provided a better understanding of many aspects of smoke detection, the waking effectiveness of household smoke detectors has received little attention. Consumers, architects, builders, firefighters, and professionals involved in consumer safety should have available
detailed information concerning the acoustic spectral characteristics of alarm signals, energy distribution of alarm signals, and their relation to hearing sensitivity against different acoustic backgrounds.

Sleep is a complex multiphase process. The ability of smoke detectors to awaken a sleeping household has been investigated by Nober et al.\textsuperscript{20} as a function of sex differences, hours into sleep, and night of the week. The sound levels were evaluated from a ten-foot distance as required by NFPA (85 dBA), at pillow site, with bedroom door open (70 dBA), and at pillow site, with bedroom door closed (55 dBA), for seventy college-aged people (18-29 years). Their results indicated that the three detector alarm levels were adequate to awaken young, normal-hearing adults from sleep at any hour of the night. Background noise, such as a taped 63 dBA noise from an air conditioner, significantly decreased the waking response at the 55 and 70 dBA levels.

6.1 Factors Affecting the Waking Response

Waking response is dependent on the following factors:

1. Time of night

Time of night has been cited as a variable affecting response. There is not always agreement among experimenters on this point. For example, Zimmerman\textsuperscript{21} found that responsiveness of people increased as a function of time into night (hours of sleep). On the other hand Williams et al.\textsuperscript{22} and Williams\textsuperscript{23}, observed a decrease in responsiveness, and Nober et al.\textsuperscript{24} noted no significant effect. Perhaps the time effect was not apparent in Nober's study because it covered only young, normal-hearing adults.

2. Age

Age clearly affects sleep and response during sleep. Lukas and Dobbs\textsuperscript{25} reported that older people awaken faster and have shorter 'grogginess' periods after arousal. It would be presumptuous to predict sleep response behaviour of a geriatric population from data collected on college-aged people.

3. Sex

Differences in sex relative to sleep arousal have also been noted. Lukas and Dobbs\textsuperscript{25} reported that regardless of age, sleep arousal thresholds were lower in women. In Nober's studies of college-aged students (18-29 years), 50% were female and 50% male. He found no significant difference in response between men and women.
7. CAPABILITIES AND LIMITATIONS OF SMOKE DETECTORS

As discussed earlier, the sensitivity of ionization-type detectors is higher for smoke containing small particles such as are produced by flaming fire, whereas the sensitivity of optical smoke detectors is higher for smoke consisting of large particles, such as are produced by smouldering fire. Kennedy et al.\textsuperscript{16}, observed that though ionization detectors did not operate at the very high concentrations of smoke produced by smouldering, they responded rapidly after the first appearance of flames. Apparently the ionization smoke detector was not blocked by the presence of large-particle smoke in flaming fire.

Bukowski\textsuperscript{26} reported that residential smoke detectors of either the ionization or photoelectric type with a short response time would provide adequate warning for most residential fires, if the detectors are properly installed.

In summary, the effectiveness of smoke detection is limited by the following factors\textsuperscript{20,27,28}:

1. Type of detection device, due to restricted capability to respond to smoke particle size.
2. Alarm level; it must be not less than 55 dBA at the sleeper's pillow\textsuperscript{20}.
3. Source of power; if battery operated, it must be replenished from time to time.

8. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

Extensive experimental research conducted in the last decade has provided some insight into the fundamentals of detection. Some areas of the detection problem, however, need better understanding in order to select the right detector for the specific applications. The following items are proposed for further study.

1. Since hearing becomes less sensitive after prolonged exposure to high sound levels, experiments should be performed to determine waking effectiveness of smoke detectors at different noise backgrounds, such as air conditioning and traffic, disco and aircraft noise, the last for those who live in the vicinity of an airport.

2. The optimum location of a residential smoke detector should be investigated in order to ensure that the warning signal is clearly audible in all bedrooms of a dwelling.

3. Research is urgently needed to determine the best way of detecting smoke in a corridor when the fire originates inside a bedroom with the door closed.

4. Further research is required to investigate the contribution of heating and air-conditioning systems to the movement of smoke originating from flaming or smouldering fires.
9. REFERENCES


17. A.S. Eastwell, "Calculation of the Effectiveness of Corridor Smoke Detectors in Detecting Fires in Adjoining Rooms", Fire Prevention Science and Technology (20), (1978).


<table>
<thead>
<tr>
<th>Fire No.</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ethyl alcohol</td>
</tr>
<tr>
<td>2</td>
<td>Wood, slow combustion</td>
</tr>
<tr>
<td>3</td>
<td>Wood, quick combustion</td>
</tr>
<tr>
<td>4</td>
<td>Cardboard inside DEF smoke generator discharger</td>
</tr>
<tr>
<td>5</td>
<td>Cardboard inside box</td>
</tr>
<tr>
<td>6</td>
<td>Polyurethane foam</td>
</tr>
<tr>
<td>7</td>
<td>PVC cable (by overheating)</td>
</tr>
<tr>
<td>8</td>
<td>Neoprene cable (by overheating)</td>
</tr>
<tr>
<td>9</td>
<td>Cotton</td>
</tr>
<tr>
<td>10</td>
<td>Petrol</td>
</tr>
<tr>
<td>11</td>
<td>Transformer overload</td>
</tr>
<tr>
<td>12</td>
<td>Acetone</td>
</tr>
<tr>
<td>13</td>
<td>Damp wood, quick combustion</td>
</tr>
<tr>
<td>14</td>
<td>Methyl alcohol</td>
</tr>
<tr>
<td>15</td>
<td>Diesel oil</td>
</tr>
<tr>
<td>16</td>
<td>Wood, quick combustion</td>
</tr>
<tr>
<td>17</td>
<td>Rubber cable</td>
</tr>
<tr>
<td>18</td>
<td>Damp wood, slow combustion</td>
</tr>
<tr>
<td>19</td>
<td>Sodium</td>
</tr>
<tr>
<td>20</td>
<td>Magnesium</td>
</tr>
<tr>
<td>21</td>
<td>Gauchard aerosol generator</td>
</tr>
<tr>
<td>22</td>
<td>Geosyl aerosol generator</td>
</tr>
<tr>
<td>23</td>
<td>Foam</td>
</tr>
</tbody>
</table>
FIGURE 1
COMPARISON OF FIRE DEATH INDICES FOR VARIOUS COUNTRIES (FROM BANKS AND RARDIN AND BANKS)
FIGURE 2
GRANULOMETRIC DISTRIBUTION CURVES
(FROM MOLIERE ET AL. NUMBERS CORRESPOND TO MATERIALS LISTED IN TABLE 1)

FIGURE 3
CUMULATIVE DISTRIBUTION OF THE VARIOUS AEROSOLS PRODUCED (FROM MOLIERE ET AL. NUMBERS CORRESPOND TO MATERIALS LISTED IN TABLE 1)
FIGURE 4
PHOTOELECTRIC-TYPE DETECTOR (FROM NORTHEY)

FIGURE 5
IONIZATION-TYPE DETECTOR (FROM NORTHEY)