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MASTER’S THESIS

Reliable Fire Detection Systems for Residents with Drug and Psychiatric Disorders

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Western Norway University of Applied Sciences

Master Thesis in Fire Safety Engineering

Haugesund
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Reliable Fire Detection Systems for Residents with Drug and Psychiatric Disorders

Master thesis in Fire Safety Engineering

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This thesis is a part of the master's program in Fire Safety Engineering at Western Norway University of Applied Sciences. The author(s) is responsible for the methods used, the results that are presented, the conclusion, and the assessments done in the thesis.

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Preface

This master thesis is conducted as partial fulfillment of the requirement for the degree of Master in Fire Safety Engineering at the Western Norway University of Applied Sciences(HVL), Haugesund. The master's degree is taught at the Department of Safety, Chemistry and Biomedical Laboratory Sciences, campus Haugesund.

As a part of the work package (WP-5) of the BUILDER project of HVL, this study is conducted with the cooperation of RISE FR (FRIC project 4.3) by aiming to find a reliable and effective fire detection system for people at-risk groups, particularly for the residents with drug and psychiatric disorders(ROP). To address several challenges in the dwellings with such residents, full-scale experiments have been conducted on an apartment at the 'Hall of Flame' of HVL. The performance of aspiration detection systems, Multi-sensor detectors (with Optical, Heat, and CO sensors), and Photoelectric smoke detectors for different fire scenarios has been assessed.

The primary motivation for choosing this topic was to contribute towards safety for the vulnerable portion of society who are often perishing most and over-presented in the cases of fire fatalities in Norway.

Jishan Mahmud Rumi

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Above all, I would like to express my love for my wife and son and gratitude to my parents, who inspired and supported me to pursue my dream throughout my life, especially to my best friend, my father, whom I lost during my master's in HVL due to Corona. He would have read the first draft of the thesis (as he always used to do whenever I wrote something) and be the proudest person on the earth for me for whatever I am. May Almighty grant peace to his departed soul.

Jishan Mahmud Rumi

Western Norway University of Applied Sciences

Abstract

Over the past decades, domestic fire has dominated the fatal fire statistics in Norway, and at-risk groups are overrepresented in those fatalities. Western Norway University of Applied Science (HVL) research project BUILDER (Building design for At-risk groups) seeks to improve fire safety for at-risk groups by achieving an understanding of the different challenges & suggesting relevant safety solutions.

As a part of the work package (WP-5) of that project, this study is conducted with the cooperation of RISE FR (FRIC project 4.3) to find a reliable smoke detection system solution for the at-risk group, especially for residents with drug and psychiatric disorders (ROP). GAP analysis for the housing for ROP residents and several interviews conducted under the BUILDER project with Fire Service personnel, people at-risk group, their relatives, and care services indicates that; the technical solutions now provided within smoke detection, and fire protection at the dwellings of the residents with substance abuse and mental disorder does not overcome the challenges and ultimately not satisfying the particular requirements to ensure fire safety.

GAP analysis for the housing for ROP residents shows a smoke detector in such dwellings shall overcome the following challenges,

- The smoke detectors or alarms shall be least visible and accessible to the user.
- The smoke detectors or alarms must preferably be able to be tested without having to enter the ROP home and have minimal maintenance requirements.
- A smoke detector must not be sensitive to cigarette smoke and other types of pollution (narcotic fume/excessive cooking smoke). The smoke detectors shall be relatively early and accurate to sense fire/smoke hazards.
- The detection system shall assist in sensible activation of the gas-based extinguishing agent.

As an aspiration detection system, it overcomes the first two challenges mentioned by its detection principle and installation setup, but its usability in such dwellings shall be assessed. Thus, eight different smoldering and flaming fire scenarios were designed based on different conditions (such as fire locations, apartment ventilation status, indoor openings, amount of fuel, and the spread of fire and smoke). A total of 33 test was conducted in an apartment in the Hall of Flame of HVL to find the reliability, sensitivity, and performance of the aspiration detection system compared to multi-sensor and photoelectric detectors.

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Summary

Background:

The overall risk picture of the at-risk group drawn from the statistics of fatal fire indicates that domestic fire dominates the fatal fire statistics in Norway, and at-risk groups are found to be over presented in those fatalities. Several aspects such as victims' age, lifestyle, psychiatry condition, cause and consequences of fire, cause of death, etc., indicate the urge to mitigate fire risk at the societal level through political and organizational measures (such as adequate social housing) along with the improvement of the physical environment of the dwellings according to the need of the at-risk group.

It is acknowledged that smoke detectors save lives, emphasizing the importance of having a smoke detector in every home; in Norway, more than 90% of homes have at least one functioning smoke detector. But considering the GAP analysis for the housing for ROP residents (Drug and Psychiatric disorders: Rus og Psykiatrilidelser) residents; as a part of the Western Norway University of Applied Science (HVL) research project BUILDER (Building design for At-risk groups) under work package 5(WP-5) in this master's thesis; to improve the physical environment of such dwellings, a comprehensive approach has taken to seek a more reliable smoke detection system than present solution available.

Objectives:

The objectives of this thesis were:

- To find an/more alternative to commonly used smoke detectors; that are least visible and accessible to the user and have minimal maintenance requirements with an option to be tested without entering ROP home. Moreover, it shall overcome the challenges and fulfills the particular needs of ROP residents.
- For different fire scenarios, compare the selected smoke detectors' performance (early, efficient and accurate detection of fire and hazardous smoke) with commonly used photoelectric and multi-sensor detectors.
- To find a sensible way to activate an automatic fire suppression system (Inergen gas-based system IG-541) by the assist from the detection unit.

Method:

Firstly, a comprehensive review of the present advanced detection systems was conducted to address the first objective. Thus, the aspiration detection system was found, which requires minimal installation inside dwellings (requires only an air inlet inside the apartment and therefore can be hidden within lighting and other fixtures) with advanced and efficient detection ability.

To assess its reliability, sensitivity, and performance compared to commonly used photoelectric and multi-sensor detectors with CO sensors; based on different conditions (such as locations of the fire, status of apartment ventilation, indoor openings, amount of fuel, and the spread of fire and smoke), eight different smoldering and flaming fire scenarios and one smoking scenario were designed. Thus 33 tests were conducted in an apartment in the Hall of Flame of HVL.

Conclusion:

- Aspiration detection unit can detect a broad range of fire and smoke scenarios reliably and efficiently compared to multi-sensor and photoelectric detectors. The aspiration system's detection time is more consistent and has the slightest variation for similar fire scenarios compared to other detectors.
- In terms of early detection, the aspiration detection system, in most cases (Almost 50%), detected fire earlier than multi-sensor and photoelectric detectors. The sensitivity range can be adjusted for further early activation in most cases.
- Aspiration detection system can detect smoke and assist activation of fire extinguishing system before the tenability limit exceeds in most flaming and smoldering fire scenarios.
- Aspiration detection system can be installed with minimum visibility in the dwellings, thus fulfilling the particular need of at-risk group/ ROP residents. Also, it requires less maintenance inside the apartment.
- Both aspiration detection systems and multi-sensor detectors are less sensitive to cigarette and excessive cooking smoke. Therefore, it may create fewer False alarms than traditionally used photoelectric detectors.
- Fire detection by installing a multi-sensor detector outside the apartment by feeding with air from the apartment does not provide a satisfactory outcome. But connecting it with an aspiration detection unit can sensibly activate the fire extinguishing system. Also, it provides Fire and Rescue services a standard frame of time to respond for ensuring life safety of victim.
- In case of fire spread extinguishing system is activated within shortest required time by the combination of multi-sensor and aspiration detection unit.
- Ventilation system significantly affects aspiration detection system and delays its detection time. But still, it can detect within the tenability limit.
- In the case of a slow smoldering fire, the aspiration detection units' performance is less satisfactory compared to multi-sensor and photoelectric detectors.
- Pre-alarm feature of the aspiration detection system can initiate precautionary measurement by people in at-risk groups or by the neighbour, relatives, care services, voluntary organizations, security and emergency services.

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List of Abbreviations

BUILDER:	Building design for At-risk groups
WP-5:	Work Package 5
ROP :	Rus og Psykiatrilidelser (Drug and Psychiatric disorders)
TEK 17:	Technical regulations to the Planning and Building Act
NIST:	National Institute of Standards and Technology
NFPA:	National Fire Protection Association
FED:	Fractional Effective Dose
CO :	Carbon Monoxide
HCL:	Hydrogen Chloride
$CO_{2:}$	Carbon di oxide
PPM:	Parts per Million
HF :	Hydrogen fluoride
$SO_{2:}$	Sulphur Dioxide
CH_2, CH, CHO:	Acrolein
CoHb:	Carboxyhemoglobin
LC	Lethal Concentration
LD	Lethal Dose

1. Introduction

Over the past decades, domestic fire has dominated the fatal fire statistics in Norway, and at-risk groups are found to be overrepresented in those fatalities. According to the Norwegian Directorate of Civil Protection reports, almost 75% of victims can be described as vulnerable. In contrast, in official Norwegian documents, vulnerability is described as related to old age, reduced mobility or cognitive abilities, mental health problems, and substance abuse [1,2]. Whereas, in the field of fire prevention, vulnerability is often described as individuals' ability to identify fire risk or hazard, prevent the outbreak, and manage or evacuate from the threat [9]. Therefore, the analysis of relevant domestic fire fatalities aspects (victims' age, lifestyle, psychiatry condition, cause, and consequences of fire, cause of death, etc.) indicates the urge to mitigate fire risk at the societal level through political and organizational measures (such as adequate social housing) along with the improvement of the physical environment of the dwellings according to the need of the at-risk group.

Western Norway University of Applied Science (HVL) research project BUILDER (Building design for At-risk groups) seeks to improve fire safety for at-risk groups by achieving an understanding of the different challenges & suggesting relevant safety solutions. As a part of the work package (WP-5) of that project, this study is conducted with the cooperation of RISE FR (FRIC project 4.3) to find a reliable smoke detection system solution for the at-risk group, mainly to ensure life safety for residents with drug and psychiatric disorders (ROP).

Under the research project, "Development of new housing facilities adapted to ROP residents with low capacity to live with an emphasis on user participation" under NORCE Samfunn ved NORCE Norwegian Research Centre AS [4], which is attached with the BUILDER project, three small separate houses for citizens with addiction or psychiatric problems will be built in Karmøy community (The ROP project Karmøy). The proposed detection system may be used in those facilities for ROP residents in the Karmøy community, Norway.

1.1. Problem Statement:

Technical solutions now provided within smoke detection and fire protection at the dwellings of the residents with substance abuse and mental disorder may satisfy the requirements of regulation but may not satisfy fire safety requirements.

1.2. Research Question:

How can innovation within detection- and extinguishing systems increase the protection of at-risk groups?

1.3. Thesis objective:

The work of this thesis is conducted by fulfilling the following objectives.

- To find an alternative to commonly used smoke detectors; that are approved according to standards, least visible and accessible to the user, and have minimal maintenance requirements with an option to be tested without entering ROP home. Moreover overcomes the challenges and fulfills the unique needs of ROP residents.
- For different fire scenarios, compare the selected smoke detectors' performance (early, efficient and accurate detection of fire and hazardous smoke) with commonly used photoelectric and multi-sensor detectors with CO sensors.
- To find a sensible way to activate an automatic fire suppression system with assistance from the detection unit.

1.4. Structure of the Thesis:

The following report maintains the below-mentioned structure.

Chapter 2: Literature Review

This chapter includes a background of the studies and the risk picture of the at-risk group (which describes who perishes mostly in fire fatalities and how). This discussion also sets up the background of the fire scenarios to be tested in the experimental part of the study. Also, this chapter briefly consists of the GAP analysis for the housing of at-risk groups, especially ROP residents, which defines the selection criteria of the detection system and the performance criteria to be assessed.

Chapter 3: Theory

This chapter includes an overview of existing technologies, present solutions, and an overview of the selected detection system. It also describes the underlying theories and quantification of the measuring parameters for the experimental part of the studies.

Chapter 4: Description of method

This chapter describes the experiments fulfilling the thesis objective, including the description of fire scenarios, test apartment, instrumentation, and data analysis.

Chapter 5: Result

This chapter contains the results of the experiments, the performance of different detection units, comparison, observations during the experiment, and overall observation-based performance criteria.

Chapter 6: Discussion

This chapter describes how experimental result address thesis hypothesis and the outcome of the studies.

Chapter 7: Further Scope of Work

This chapter briefly describes future scope of work and suggestion.

Chapter 8: Conclusion

This chapter summarize the outcome of the thesis and concludes the report.

1.5. Limitations

This study has assessed specific one model of an aspiration detection system, multi-sensor detection system, and photoelectric detection system. Thus, the comparative analysis for a particular detection principle by testing products from multiple manufacturers has not been performed.

Smoldering and flaming fire scenarios were designed and tested following NS-EN 54-7 (Annex G-J) methods but not exactly as the standard described. Mainly instead of the standard test room, the experiments were held in an apartment (built following the proposed layout of The ROP project Karmøy) in the 'Hall of Flame' of HVL. Also, the amount of fuel, ignition of the fuel, run time of the experiment, location of the fire, and other parameters have been modified to create a fire/smoke scenario more realistic than the standardized method.

Some parts of the apartment were not adequately concealed, which caused minor leakage of smoke out of the apartment (and in some tests, from one room to another, although walls and door separated them) during some experiments. Also, a set of tests were performed in 'Hall of Flame' during end of winter (March 2022: 1st Trial) and Spring (May 2022:2nd Trial) which affected some of the tests due to extreme weather (wind and humidity) as the apartment was not perfectly concealed.

The installed ventilation system was supplying air in the apartment with a vent flow rate of 500 m^3/h and was extracting air from the bedroom, bathroom, and kitchen with a vent flow rate of 100 m^3/h, 100 m^3/h, and 300 m^3/h consecutively. Though this was balanced and installed according to the specifications of the ROP project (Karmøy), the flow rate was significantly higher than the usual ventilation systems used in European countries [20]. As a result, during 2nd trial of the experiment, detection and activation time were affected by this amount of excess ventilation.

Including 33 experiments of this study; in the same apartment, more than 50 trials of different fire scenario has been tested; which includes several full-scale experiments (from the start of the fire to detection and activation (with extended release) of the Inergen Gas Extinguishing system (IG541) for over three months. Thus, it may affect the performance and sensitivity of the detection unit (especially the aspiration detection unit).

2. Literature Review

2.1 Background of the studies

Several studies from Norway and other countries provided significant insight into fire fatalities from several aspects, such as the

- trend of fire and fatality rate,
- time and place of fire,
- personal characteristics of victims,
- cause of fire and death,
- prevention etc.

Previous studies show a significant decline in the number of people perishing in the fire in most countries such as Norway, Great Britain, and Sweden [21]. But domestic fire dominates the fatal fire statistics; in Norway, approximately eight out of ten fire-related fatalities occur in dwellings [1].

In Norway, unlike some other countries such as Sweden, Denmark, the US, and Great Britain, it is observed that residential fires occur most frequently in winter, particularly more often on weekends [3, 21, 22]. Several US studies suggest that gender and age are two of the most significant factors in most fire fatalities. It is repeatedly found that men are more likely to perish than women and elderly people are the most vulnerable group here [23,24]. The article *Comparative investigation of 'survival' and fatality factors in accidental residential fires* [25] (a comparative analysis conducted between 177 deaths to 183 survivors of fatal fires in Australia) relates several personal characteristics of victims who perished compared to those who survived are

- Consumption of psychoactive drugs or sedatives
- Cigarette residues
- Single person
- Age 70+
- Asleep
- Was in the room of origin when the fire started
- Alcohol abuse

This study of Australia also suggests that; nearly half of the victims had a history of mental disorders and several common risk factors such as living status and location during the fire. Whereas in Norway, it has been identified that in many cases, the alcohol-impaired person was probably guilty of starting the fire, and they were unable to save themself. [26].

Thus, it is evident that vulnerable groups (people at-risk groups) are over-presented in fire fatalities and according to the Norwegian Directorate of Civil Protection reports, almost 75% of victims can be described as vulnerable [1]. In the field of fire prevention, vulnerability is often defined as individuals' ability to identify fire risk or hazard, prevent the outbreak, and manage or evacuate from the hazard, whereas, in official Norwegian documents, vulnerability is described as related to factors such as old age, reduced mobility or cognitive abilities, mental health problems, and substance abuse [1,2].

The study *"Analysis of fatal fires in Norway in the 2005 – 2014 period"* indicates that most of those who are perishing in fatal fire belongs to the at-risk group and how risk factors such as individuals' ability, lifestyle, and psychiatric condition leads them to be the ultimate victim [3]. Thus, an overall risk picture of fire fatalities can be drawn from this study.

2.1.1 Overall Risk picture

2.1.1.1 Overview of fatalities: Who is perishing!

The overall risk picture of the at-risk group can be drawn from the analysis of fatal fires from 2005 to 2014 conducted by RISE FR [3]. This study shows that among 435 reported cases, almost 85% of fatal fires occur in residential buildings, while 54% and 20% occur in detached houses and multi-unit dwellings consecutively.

Among 386 fatalities, half had aged between 44-78 years. Figure 2.1 shows the age distribution of the fatalities.

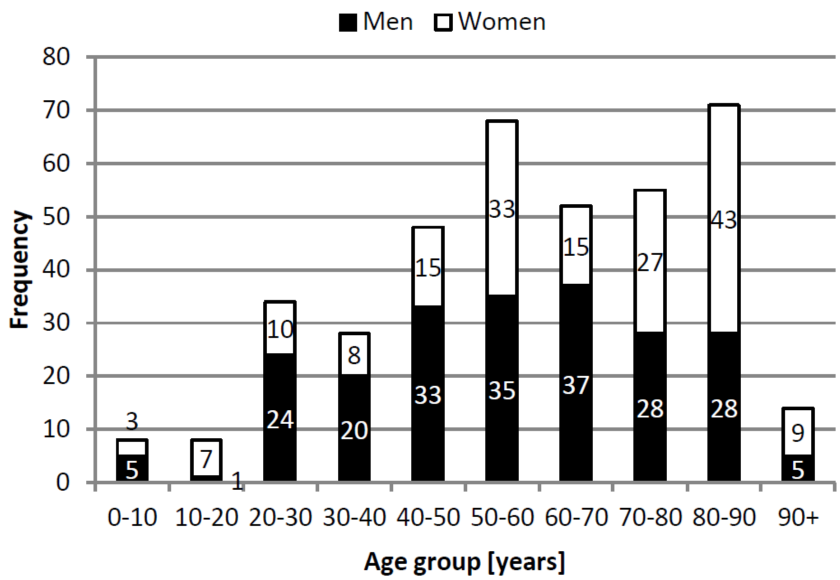


Figure 2.1: Age distribution of gender for fatalities [3]

Several risk factors related to victims' age, lifestyle and physical and psychiatric conditions are linked to the fatalities of the fatal fire. Half of the fatalities at pension age had reduced mobility, whereas 1/3rd had impaired cognitive ability. Almost an equally substantial portion suffered from mental illness. Most distinguishingly for the younger age group, half of the fatalities had a reputation for known substance abuse or mental illness. The almost equal portion was under the influence of alcohol during the fire.

Vision	Normal	Visually impaired	Blind	n
All	86.8 %	13.2 %	0.0 %	257
<67 years	92.4 %	7.6 %	0.0 %	145
≥67 years	79.5 %	20.5 %	0.0 %	112
Hearing	Normal	Hearing impaired	Deaf	n
All	89.9 %	10.1 %	0.0 %	257
<67 years	95.2 %	4.8 %	0.0 %	145
≥67 years	83.0 %	17.0 %	0.0 %	112
Reduced mobility	Normal	Reduced	Immobile	n
All	69.2 %	27.4 %	3.4 %	266
<67 years	84.6 %	12.1 %	3.4 %	149
≥67 years	49.6 %	47.0 %	3.4 %	117
Impaired cognitive abilities	No	Yes	Unknown	n
All	16.0 %	18.7 %	65.3 %	262
<67 years	20.7 %	7.6 %	71.7 %	145
≥67 years	10.3 %	32.5 %	57.3 %	117
Known substance abuse	No	Yes	Unknown	n
All	9.1 %	36.5 %	54.4 %	263
<67 years	9.2 %	54.0 %	46.1 %	152
≥67 years	9.0 %	25.2 %	64.8 %	111
Mental illness	No	Yes	Unknown	n
All	6.5 %	44.3 %	49.2 %	262
<67 years	6.6 %	51.7 %	41.7 %	151
≥67 years	6.3 %	34.2 %	59.5 %	111
Alcoholic influence	No	Yes	Unknown	n
All	38.9 %	41.2 %	19.9 %	386
<67 years	28.4 %	59.0 %	12.7 %	229
≥67 years	54.1 %	15.3 %	30.6 %	157
Women	50.0 %	27.6 %	22.4 %	170
Men	30.1 %	51.9 %	18.1 %	216
Smoker	No	Yes	Unknown	n
All	9.3 %	34.6 %	56.1 %	387
<67 years	6.6 %	35.8 %	57.6 %	229
≥67 years	13.4 %	32.5 %	54.1 %	157

Figure 2.2: Registered Risk factors related to fatalities of fatal fire during 2005-2014 [3]

Figures 2.2 and 2.3 clearly show that most fire fatalities had more than one lifestyle, and psychiatry risk factors thus can be described as vulnerable, limiting their ability to respond to such fatal incidents.

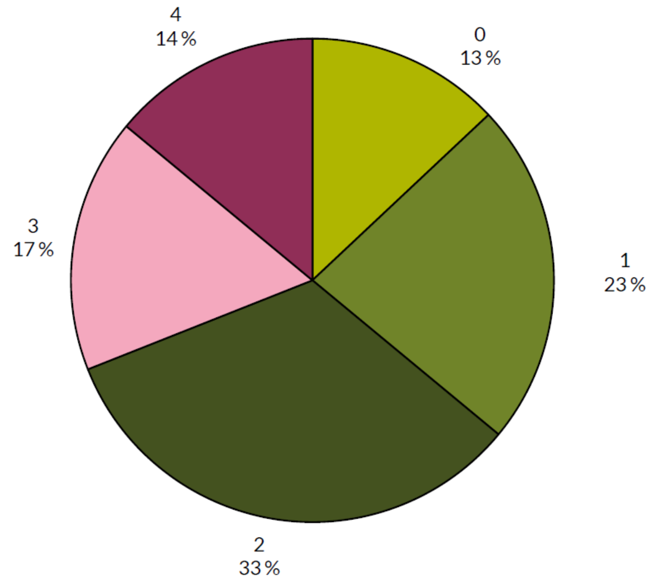


Figure 2.3: Among 139 cases of victims below 67 years old the distribution of how many factors of known substance abuse, alcoholic influence in fire, smoking, and mental illness registered for fatalities below the age of 67 in fatal fires during the 2005-2014 period [3].

2.1.1.2 Type and cause of Fire

According to this study, most fatal fires were flaming (98.6%), and only 1.2% were smoldering fires. Among 347 catastrophic fires, 37% were caused directly by the victim, while several reasons started other fires. Some of the prime causes of fire are

- Open flame (39%): Candlelight (7.3%), Smoking (34.4%)
- Incorrect use: kitchen appliance, open heater coverings
- Electrical Fault: Series and parallel arc, overheating, and faulty installation
- Arson

2.1.1.3 Origin of Fire

According to the study living/sitting room is the most frequent place where the domestic fire originated. Table 2.1 represents the origin of fire during this period

Table 2.1: Distribution of room of origin for fatal fires during the 2005-2014 period [3].

Point/room of origin	Proportion [%]	N
Sitting room	37.0	128
Kitchen	18.8	65
Bedroom	12.7	44
Unknown	11.0	38
Others	20.5	71

2.1.1.4 Consequences

In most cases (71.6%), the victim was alone when the fire started, and in 92.6%, they perished in the fire. And the study also shows only 20.1% of them could evacuate alone; the fire brigade saved only 6.1% of cases and 5.2% by the other person who came for assistance.

In most cases, only one person was present during the incident, and 40.1% of fatalities were found in the same place as the fire's point of origin. Rest 42.7% was found in another room.

2.1.1.5 Existing Fire protection Measure

This study shows that due to damage caused by fatal fire, in almost 50% of cases, it is uncertain whether there was a smoke detector installed or functioning during the incident. Thus, available data states that a smoke detector was installed in 47% of cases, and it worked. In 30.3% of cases, the alarm was heard, but the percentage of successful evacuation represents how the victim responds to that. In 91% of the fires, no automatic extinguishing systems were installed.

Meanwhile, the study shows that in more than 50% of cases, the fire was fully developed in response to this fire when the fire brigade arrived.

2.1.1.6 Cause of Death

the cause of death in the fire fatalities shows 57% of death caused by asphyxiation, 15% by burns, and 10% by burn and asphyxiation. The toxic effect of carbon monoxide is found in 74.1% of fatalities.

2.1.2 Gap Analysis

As a part of the project, Under the project "Development of new housing facilities adapted to ROP residents with low capacity to live with an emphasis on user participation" under NORCE Samfunn ved NORCE Norwegian Research Centre AS; the report "GAP-analyse for boliger for beboere med rus- og psykiatrilidelser (ROP)" defines the GAP between laws and regulations, and the needs of ROP residents [6]. This report shows how the technical solutions we have today within smoke detection and firefighting satisfy the requirements of laws and regulations but not the needs of ROP residents. The relevant context of the report regarding this thesis is presented below.

2.1.2.1 Fire technical requirements for housing

Fire technical requirements for new homes are described in the Planning and Building Act [10] and TEK 17 (Technical regulations to the Planning and Building Act) [11], and other fire technical requirements for existing homes in the Fire and Explosion Protection Act [12], with associated Regulations on fire prevention [13]. Below are the technical fire requirements for homes with a floor and a living unit in the summarized laws and regulations, focusing on detection, extinguishing, and escape.

Table 2.2: Fire technical requirements for housing [6]

Specification	Planning and Building Act	Fire and Explosion Protection Act
General safety requirements	Buildings with living spaces for people shall be designed and constructed so that requirements for sound energy use, floor plan, and indoor environment, including views, lighting conditions, insulation, heating, ventilation, fire protection, etc., are met. (§ 29-5 Technical requirements)	The owner of a building, area, means of transport, production equipment, other facilities, or product is obliged to provide the necessary safety measures to prevent and limit fire, explosion, or other accidents. (§6 Preventive safety measures and maintenance) The owner and user of a building, area, means of transport, production equipment, other devices, or product is obliged to keep building technical constructions, safety devices, and other safety measures for protection against fire, explosion, or other accidents in a safe condition and ensure that these work at all times for their intended purpose. (§6 Preventive safety measures and maintenance)
Specification	**Technical regulations**	**Regulations on fire prevention**
General Requirement	Buildings shall be designed and constructed in such a way that satisfactory safety is achieved in the event of a fire for persons staying in or on the building, for material values, and for environmental and social conditions. (§11-1 point 1)	Everyone is obliged to exercise caution when carrying out activities that may lead to a fire. (§3) The owner of a structure shall ensure that building components, installations, and equipment in the structure that are to detect fire or limit the consequences of fire are inspected and maintained so that they function as intended. The inspection shall clarify whether the safety devices: a) meets the requirements for fire safety that apply to the building b) works separately and together. (§5) The scope and frequency of the inspection shall be adapted to the safety facilities and the size, complexity, use, and risk of the structure. (§5)

Requirements for detection	Buildings must-have equipment for early detection of fire so that the necessary escape time is reduced. The following must at least be met (§11-12 point 2): a) Buildings intended for activities in risk classes 2 to 6 shall have fire alarm systems. b) In buildings intended for a few people and buildings of smaller size, smoke alarms can be used if the escape conditions are particularly simple and clear. Smoke detectors must be connected to the power supply and have a battery as a backup solution. In a fire cell with a need for more smoke alarms, the alarms must be connected in series. In buildings without a power supply, battery-powered smoke alarms can be used.	The owner of homes and holiday homes must ensure that the buildings have fire alarm systems or a sufficient number of smoke alarms. (§7)
Requirements for extinguishing equipment	Buildings shall be adapted for efficient manual extinguishing of fire. (§11-16 point 1) In or on all buildings where a fire may occur, there must be manual fire extinguishing equipment for effective extinguishing efforts in the initial phase of the fire. This is in addition to a possible automatic fire extinguishing system. (§11-16 point 1)	The owner must ensure that homes and holiday homes are equipped with at least one of the following extinguishing equipment that can be used in all rooms: a) dimensional fire hose with an inside diameter of at least 10 mm permanently connected to the water supply network b) powder apparatus of at least 6 kg with ABC powder c) foam or water apparatus of at least 9 litters d) foam or water apparatus of at least 6 litters with 11 efficiency class of at least 21A e) other manual extinguishing equipment with equivalent extinguishing capacity. (§7)
Requirements for escape	Structures must be designed and executed for fast and safe escape and rescue. Persons with disabilities must be considered. (§11-11 point 1)	The person who has the right to use a building must: b) avoid unnecessary risk of fire, and ensure that the escape routes maintain their function, including that accessibility is not reduced (§11 - point b)
Technical installations	In §11-10, there are several requirements for materials in connection with ventilation, etc. For these, it must be considered whether a technical room should be established as a separate fire cell.	

Other		The person who has the right to use a building must: a) ensure that the structure is used in accordance with the fire safety requirements that apply to the structure b) avoid unnecessary risk of fire, and ensure that the escape routes maintain their function, including that accessibility is not reduced c) inform the owner of changes, decay and damage to the structure or safety devices such as may affect fire safety d) in conditions that significantly reduce fire safety, immediately carry out extraordinary measures until the risk is normalized. (§11)

2.1.2.2 Challenges for current fire technical Solutions in ROP Residence

According to the studies, ROP residents often pick down smoke alarms out of annoyance of maintenance, the sound of the alarm, the fear of false alarms due to smoking, and continuous flashing of indicator lights or from the fear of being surveillance [14]. Thus, the user's obligation to take care of the safety equipment or measures (according to the regulation) shall not be expected from them. The study also shows that operating manual extinguishing during a fire incident system can be expected from such residents as they face difficulties using them.

2.1.2.3 Hazard Classes

According to TEK-17, dwellings in which most ROP residents reside now fall under Hazard class 4, which requires a smoke detection system and manual fire extinguishing equipment. If the part of the structure involves lift access shall be equipped with automatic fire extinguishing equipment. On the other hand, housing intended for people in need of round-the-clock care and care or housing specially adapted and designed for persons with disability, including old-age and senior housing, is placed in risk class 6, and such structure shall be equipped with automatic fire extinguishing system.

In Norway, most dwellings of ROP residents (as well as the housing proposed in the ROP project, Karmøy) do not require lifts as they are mostly within two to three-story buildings and are in Hazard class 4. But as their physical and psychological condition indicated, they require similar attention and precautions as required for the population living in the structure of Hazard class 6. Although the regulation only requires a manual extinguishing system in such dwellings, automatic fire extinguishing is necessary to address underlying risks and challenges. The housing dedicated to ROP residents shall fulfil the particular requirement of an automated fire extinguishing system. But these systems require sensible activation as the risk of false alarm in such residents is much higher.

2.1.2.4 Fire detection & Extinguishing Equipment: Requirements for ROP Residents

Based on ROP residents' requirements, a commonly used smoke alarm is not a good option. In general, the following challenges must be addressed by the smoke detector to be used in such residences,

- Smoke detectors must not be sensitive to cigarette smoke
- The smoke detectors or alarms must not emit flashing lights
- The smoke detectors or alarms cannot be left open.
- The smoke detectors or alarms must preferably be able to be tested without having to enter the ROP home

Based on Uni Research Polytec's report [15], the aspiration detection system seems appropriate for such residence, but its sensitivity to smoke and performance in such an apartment shall be assessed.

Similarly, the study suggests; that manual equipment for fire extinguishing is not a good option for such residents as they often feel difficulties operating them. Also, there remains a chance of misusing them without fire. There are several options for an automatic fire suppression unit and a manual suppression unit (which is required according to laws and regulations). A gas-based extinguishing system can be particularly useful but requires a sound detection system to assist sensible activation because misuse of the gas-based extinguishing system is not expected as it is expensive, and the secondary damage caused by the release of the extinguishing agent may require moving the resident for an interim period which is also challenging.

2.2 Summary

Firstly, from the risk picture of fatal fire analysis, it is understandable that at-risk groups, especially those with drug and psychiatric disorders with multiple risk factors present in lifestyle, are the most perishing and how. Then the GAP analysis can relate to those statistics; how the exact fire safety measurement present in such ROP residents is failing to fulfil their particular requirements and put them in the most vulnerable position in the cases of the fatal fire. Additionally, relevant studies indicate that aspiration detection and gas-based extinguishing systems could fulfil such residents' specific requirements [15].

Thus, to improve the physical environment of ROP residents, the challenges mentioned in the GAP analysis set the objective of this study as follows.

- To find an alternative to commonly used smoke detectors; that are approved according to standards, least visible and accessible to the user, and have minimal maintenance requirements with an option to be tested without entering ROP home. Moreover overcomes the challenges and fulfills the unique needs of ROP residents.
- For different fire scenarios, compare the selected smoke detectors' performance (early, efficient and accurate detection of fire and hazardous smoke) with commonly used photoelectric and multi-sensor detectors.
- To find a sensible way to activate a gas-based automatic fire suppression system with assistance from the detection unit.

This study assessed the reliability, sensitivity, and performance aspiration detection system as an alternative to the present detection system. While designing the fire scenario following aspects of fatal fire analysis have been kept in consideration

- Type and cause of Fire
- Origin of Fire
- Fire spread
- Consequences
- Cause of death

3. Theory

3.1 Smoke detection solution

A reliable smoke detector system may improve the physical environment of the dwellings for at-risk groups, and it is acknowledged that a smoke detector is an essential tool that saves lives through effective & early detection [7]. Previous studies show that the victim directly caused 37% of the fire; in most cases, the victim was alone during the incident. In around fifty percent of those incidents, the fire brigade arrives for rescue and firefighting operations when the fire is fully developed [3]. Thus, it indicates the necessity of early detection and notification time, especially for at-risk people who need assisted evacuation.

Also, the cause of death in the fire fatalities shows 57% of death caused by asphyxiation and 10% by burn and asphyxiation. In contrast, the toxic effect of carbon monoxide is found in 74.1% of fire fatalities [3]. Thus, it indicates while selecting a smoke detection for at-risk groups, efficient detectability of CO is a vital feature that the solution shall cover.

A previous study on the mapping of smoke detectors used in dwellings shows that more than 90% of homes have at least one functioning smoke detector in Norway. It also shows that most use photoelectric (60%) and ionic (29%) smoke detectors. Various multicriteria detectors are used in 9% of homes, and the other 2% use heat detectors [8]. Here photoelectric detectors function better than ionic detectors by virtue of earlier detection. However, previous studies also show that CO dose may exceed critical value before photoelectric detectors are activated. The multi-sensor detectors with CO sensors are more convenient in terms of early detection, with the flexibility of placing anywhere in the dwellings [7].

Aspiration detectors, mostly used in commercial settlements, may be a solution for at-risk groups and are also suggested as a solution for at-risk groups [6]. Its detection principle may be significantly efficient in detecting smoldering and flaming fire. Also, it can be installed with the least visibility with a scope of minimal and remote maintenance.

In this study, aspiration detection system from several manufacturers has been reviewed, and experiments were conducted with the VESDA LaserCOMPACT system.

3.1.1 Detection Principle of Aspiration detection System

In the aspiration detection system, the air is continually drawn through a simple pipe network to a central detection unit by an aspirator. Air entering the unit then passes through a flow sensor before a sample is passed through a dual-stage dust filter. The first stage usually removes dust and dirt from the air sample before entering the chamber for smoke detection. The second ultra-fine stage provides a clean air supply to be used inside the detection chamber to form clean air barriers, which protect the optical surfaces from contamination. The detection chamber uses a stable, highly efficient laser light source and unique sensor configuration to achieve the optimum response to a wide range of smoke types. When smoke passes through the detection chamber, it creates light scatter, which the highly sensitive sensor circuitry detects [16].

3.1.1.1 Limitations of Aspiration detection System

In the aspiration detection unit, the simple pipe network draws air to the central detection unit. Here there is only one detection unit for the complete network. Therefore, when air comes to the detection unit from multiple inlets, the system detects fire efficiently, but the fire's origin remains unknown to the responder. Whereas with a multicriteria detection unit, it is possible to identify a fire's origin from the addressable control panel. The addressability of different inlets is also necessary during maintenance and troubleshooting. For a simple network in such dwellings, this addressability of the detection point may seem not that essential. Still, this feature is necessary for effective search and rescue operations and remote maintenance work during emergencies, large apartments, or systems. Also, this system detects a broad spectrum of fire by optical detection sensors. In contrast, a parallel CO detecting sensor may improve the system efficiency and reliability in the cases of a slowly developing smoldering fire.

3.1.2 Photoelectric and Multi-sensor Detectors

In this study aspiration detection system will be tested with the photoelectric detector and multi-sensor detector under various fire scenario. Previous studies show photoelectric detector by the virtue of early detection perform better than ionic detector in case of both smoldering and flaming fire. Whereas more recent studies show multi-sensor detector with CO sensor performs better than photoelectric detector [4]. Where photoelectric detector which contains a source of infrared, visible, or ultraviolet light and detects the fire smoke by measuring reduction of light intensity due to the scattering occurred by smoke particle, multi-sensor detector uses additionally a heat sensor and a CO sensor.

3.2 Factors potentially affecting detection time

Several factors may potentially affect the detection type of smoke detector, such as

- Type of fire
- Composition of burning materials
- Room ventilation or openings

The previous study shows that most of the fires in such dwellings were flaming fires, but the cause of death suggests a large portion of fatalities occurred due to asphyxiation, where CO was found in most victims. Thus, it is understandable that such fires may, in some cases, start from smoldering fire, which leads to incomplete burning, and by the time it becomes fatal, turns into a flaming fire.

Smoldering and flaming fire impact the movement and volume of smoke differently inside the room. In the case of flaming fire, smoke rises to the ceiling and forms a smoke layer that gets thicker over time, whereas in smoldering fire (which is much colder), the colder smoke spreads into the whole volume of the room.

Also, the smoke particle generated in smoldering fire is much larger than the flaming fire. It thus can be detected in the photoelectric smoke detector much earlier than the ionic smoke detector. On the other hand, incomplete burning in smoldering fire creates more CO, which is detected earlier in the multi-sensor detector with a CO sensor. But in flaming fire, the amount of CO_2 increases rapidly.

The composition of smoke also varies with burning materials. For example, mattresses used in beds and sofas, or plastic products create much thicker smoke with high soot within a short time, while the wood burn is relatively clean.

Ventilation of the room also potentially affects the detection time as its controls the airflow pattern of the room. Sometimes airflow through openings may drive small cooking smoke toward the detector, causing a false alarm. On the other hand, sometimes, if the ventilation is of some kitchen fire remains undetected and starts to spread when it becomes a flaming fire as ventilation drag out most of the smoke generated. Thus, it affects the detection time.

3.3 Inergen Gas Extinguishing system

Inergen is a mixture of 52% Nitrogen, 40% Argon, and 8% CO2. In the event of a fire, when Inergen is discharged, it mixes with the air in the room to create a mixture comprising 67.3% Nitrogen, 12.5% Oxygen, 17% Argon, and 3.2% Carbon Dioxide. Inergen gas extinguishes fire by reducing the oxygen level in the room from about 21% to about 12.5%. By adding 8% CO2, we stimulate the heart to beat something faster. This means that inhabitant will be compensated for the lack of oxygen. This, in turn, means that it is absolutely safe to stay in the room when the extinguishing system is triggered [30].

Thus, it has a unique ability to preserve life in an oxygen-poor atmosphere, thus making extinguishing safe. Inergen is often used where sensitive content in rooms is to be protected. One does not want to risk extinguishing agents causing personal injury or damage to inventory and equipment.

3.4 Hazard to Occupants from Flaming and Smoldering Fire

From the viewpoint of product composition that burns on fire and the toxic hazard, fire scenarios can be possible to distinguish into four types of fire [17] as follows

- Non-flaming thermal decomposition and smoldering fires are hazardous to victims in the room of origin of the fire
- Early flaming fires are hazardous to victims in the room of origin
- Small oxygen-vitiated fires in poorly ventilated enclosures (pre-flashover under-ventilated fires) are hazardous to victims both in the room of origin or a remote location
- Fully developed or post-flashover fires hazardous to victims remote from the fire

Studies discussed earlier in chapter 2 show most fire death occurs in domestic dwellings. In over half of these cases, casualties happen in the same compartment or origin of the fire. As these fires mainly occur in Kitchen, living room, and bedroom thus, the toxic hazard depends on whether there is a long period of smoldering or a rapidly growing flaming fire.

Table 3.1: Classification of toxic hazards in fires as revealed by large-scale fire simulation tests [17]

Fire	Rate of growth	CO_2/CO	Toxic hazard	Time to incapacitation	Escape time available
1. Smoldering/non-flaming: victim in room of origin or remote	Slow	$\simeq 1$	CO 0–1500 ppm low O_2 15–21 % irritants, smoke	Hours	Ample if alerted
2. Well ventilated Flaming: victim in room of origin	Rapid	1000 decreasing toward 50	CO 0–0.2 % CO_2 0–10 % low O_2 10–21 % irritants, heat, smoke	A few minutes	A few minutes
3. Small vitiated flaming: victim in room of origin or remote	Rapid, then slow	<10	CO 0.2–4 % CO_2 1–10 % O2 < 12 % HCN to 1000 ppm irritants, heat, smoke	A few minutes	A few minutes
4. Fully developed: (postflashover) victim remote	Rapid	<10	O2 0–3 % in upper layer flowing from fire; CO 0–3 %[a]; HCN 0–1000 ppm some irritants, smoke, and possibly heat	<1 min near fire, elsewhere depends on degree of smoke dilution	Escape may be impossible or time very restricted. More time at remote locations

[a]Concentrations depend on position relative to fire compartment

3.4.1 Smoldering Fire

Materials are decomposed into pyrolysis products and oxidation fragments at mid-range temperatures (400–700 ºC) found in smoldering fires or within the flaming zone of early flaming fires containing a mixture of asphyxiant and irritant gases and particulates [27]. Under such conditions, a variety of potentially toxic products are formed on which; many are irritants. Hence CO is therefore likely to be a vital toxic component.

Although toxic products form significantly under these conditions, the rate of evolution is slow, So the smoke is seldom dense, and room temperature remains relatively low. Therefore, a potential victim has sufficient time to escape if alerted sufficiently early. The main danger in such a condition is certainly asphyxia by CO, with a small contribution from low oxygen if the victim is in a room with a poor air supply [17].

The ability of smoldering fires to build up CO concentrations capable of causing incapacitation and death in potential victims can be found in the FED analyses of a series of tests carried out at NIST [28].
The major asphyxiant gas present in the test was CO, which gradually increased in concentration in the burn room from 180 ppm during the first 13 min to 1000 ppm between 67 and 75 min. This amount was sufficient to cause incapacitation (i.e., loss of consciousness) in just over one hour in the test room. The situation escalated dramatically during the evolution of flaming fire from smoldering fire, thus producing high concentrations of asphyxiant gases that would have been almost immediately fatal. The condition of the test room can make the victim unconscious within one minute, and the victim may receive a lethal dose within two minutes. Also, the irritant smoke produced in the room may cause fatal lung injury after spending one hour of exposure in such conditions, even if they are being rescued.

3.4.2 Flaming Fire

The hazard relates to the early stages of fire growth for flaming fires where the victim is in the room of origin. In rapidly increasing flaming fires, it takes approximately 3 min to reach levels of heat and gases hazardous to life [29] unless the victim is intimate with the fire. The hazards in such a situation are related to several factors (shown in Figure 3.1), all of which may simultaneously reach life-threatening levels as the fire reaches the rapid phase of exponential growth. In the high temperature, well-oxygenated flames of early flaming fires, much of the thermal decomposition products are consumed to form simple, comparatively innocuous products such as CO_2 and water. The CO_2 to CO volume ratios is high initially, even up to the 500–1000 range and then decrease to the region of 50–100% (soon as the CO_2 concentration in the fire compartment approaches 5 % and the O_2 concentration decreases toward 15 %, the combustion becomes less efficient thus CO concentration increase gradually [17].

Rapidly growing fire can develop asphyxiant concentrations of CO_2 (greater than 5 %), CO (greater than 1000 ppm), and low oxygen (less than 15 % O_2), as well as some dense irritant smoke from products escaping the flame zone. Initially, the toxic hazards are low because the mass loss rate of the fuel is low, and for most common non-flame retarded natural and synthetic polymers, the yields of toxic products and smoke are low.

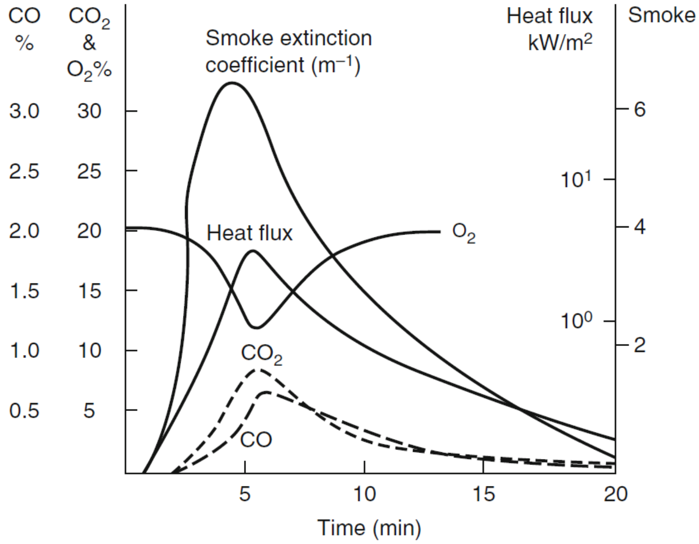


Figure 3.1: Smoke, heat, and gases during single armchair room burn. The armchair is polystyrene with polyurethane cushions and covers. The room is 39 m^3 with an open doorway. Gases were measured in the door at 2.1 m height [29].

Also, any products formed are carried into the upper layer under the ceiling and above heat height for the occupants. If the fuels are flame-retarded, the combustion efficiency is reduced, resulting in higher yields of toxic products. Still, the initial fire growth rate and the upper layer filling and descent tend to be slower, allowing more time for escape before exposure [17.

3.5 Tenable conditions for Evacuation

The main objective of a life safety design is to provide occupants with an acceptable level of safety from fire [17]. According to the NFPA life safety code to prevent danger to life through “construction, protection, and occupancy features” and to provide egress facilities capable of supporting the “prompt escape of occupants” in the event of fire [18].

Early fire detection is necessary during a fire incident, as the person present during the fire requires a tenable condition to evacuate or initiate extinguishing measures. Several parameters define the fire compartment's tenability, such as visibility, thermal state, temperature, toxicity, etc. Thus, it affects victims’ behavioral and physical ability to evacuate and initiate extinguishing Measures. A required tenable condition during a fire can be represented by the Table 3.2

Table 3.2: Tenable conditions during evaluation of safe egress time (NKB,1994 and adaptation by INSTA)

Parameter	Criteria	
Visibility	Visibility no less than 3 m in the primary fire compartment at area of ≤ 100 m^2). Visibility no less than 10 m at height of 2 m in escape routes and compartments of areas > 100 m^2. As an alternative to determine visibility, a smoke-free height of 1,6 m + 0,1 x H.	
Thermal[a]	Continuous radiation intensity of maximum 2.5 kW/m^2 and,a short-term radiation intensity of maximum 10 kW/m^2 if the maximum radiant dose is less than 60 kJ/m^2.	
Temperature	Gas temperature not higher than 80 °C.	
Toxicity[b]	CO CO_2 O_2	< 2 000 ppm < 5 % > 15 %
[a] In addition to the energy from background radiation. [b] Toxicity does not need to be calculated when the visibility surpasses 5 m.		

As the fire develops, a person's ability which depends on sub-factors such as the victim's state of health, body weight, age, level of activity, etc., starts to reduce. Factors that minimize tenability conditions and their effects are mentioned briefly.

- Soot:
    - reduces visibility
    - makes breathing difficult and damages the respiratory system
    - Radiation exchange causes fast fire to spread.
- Toxic gases
    - Narcotic gases: Carbon Monoxide (CO), Carbon dioxide (CO_2), low oxygen (O_2), HCN, etc.
    - Irritant gases: Hydrogen Chloride (HCl), hydrogen fluoride (HF), Sulphur Dioxide (SO_2), Acrolein (CH_2, CH, CHO),
- Heat:
    - Cause incapacitation or death by
        - Heatstroke (Hyperthermia)
        - Skin burn
        - Respiratory tract burn

3.5.1 Effect of toxic substance

Fatal fire statistics suggest toxic gases (narcotics and irritant gases) are the primary reason for fatalities during a fire, and exposure to narcotic gases is the leading cause of death [3]. Toxic gases affect mainly four organs of the human body

- the skin
- the digestion system
- the blood
- the respiration system

The effect of toxic gases is described below

Narcotic gases

- Cause incapacitation and, in extreme cases, death
- Attacks central nervous system causing loss of awareness and reducing escape capability
- Prolonged exposure causes loss of consciousness and death

Table 3.3: Tenability limit for incapacitation or death from exposure to common asphyxiant product [18].

	5 min		30 min	
	Incapacitation	Death	Incapacitation	Death
CO	6000–8000 ppm	12,000–16,000 ppm	1400–1700 ppm	2500–4000 ppm
HCN	150–200 ppm	250–400 ppm	90–120 ppm	170–230 ppm
Low O_2	10–13 %	<5 %	<12 %	6–7 %
CO_2	7–8 %	>10 %	6–7 %	>9 %

Carbon Monoxide (CO):

During most residential fires, CO is the dominant gas. CO will always be present in a residential fire, while the presence of other toxic gases is dependent on which materials are burning. It is produced when any combustible material burns incompletely or in reduced O_2. When CO is inhaled, it leads to carboxyhemoglobin (CoHb) formation. This reaction inhibits the absorption and oxygen transport to the body tissue. The accumulated dose of CoHb is expressed in terms of the percentage of total hemoglobin in the form of CoHb (percent CoHb)

- 10-20% CoHb causes headache
- >30% CoHb causes severe headache, nausea, vomiting, and loss of consciousness
- 50~70% CoHb causes death

CO_2 Carbon Dioxide:

Produced by combustion of any fuel and CO_2 makes HYPOXIA (a reduction in the amount of O_2 available for tissue respiration) as it is itself toxic. It causes the Respiration rate to increase, thus increasing the rate of uptake of other toxic fire gases,

- 3-6% respiratory distress (6% intolerable within 20 min)
- 6-7% dizziness, headache, and fatigue
- 7-10% loss of consciousness within 2 min at 10%)

Effects of low Oxygen:

- 20.9-14.4% slight loss of exercise tolerance
- 14.4-11.8% reduction in mental task performance, reduced exercise tolerance
- 11.8-9.6% severe incapacitation, loss of consciousness
- 9.6 7.8% loss of consciousness, death

Irritant gases

Produce incapacitation during and after exposure in two distinct ways

Sensory irritation: this causes painful effects to the eyes and upper respiratory tract and, to some extent, also the lungs, from mild irritation to severe pain.

Inflammatory reaction: this can cause respiratory difficulties and may lead to death 6-24 h after exposure to sensory irritation. The effects occur immediately upon exposure, and the degree of irritancy increases escape abilities decreases. The effect is dependent on the concentration of the irritant gases. High ingested concentrations of irritants may result in incapacitation and death [17]

3.6 Quantification of toxicity

To quantify the toxicity of various components, the terms LC_{50} and LD_{50} are applied, where LC_{50} is the concentration at which 50% of an exposed population dies and LD_{50} is the dose at which 50 % of a susceptible population dies. The tenability values in terms of IC50, LC50, ID50, and LD50 are different in different literature. For example, CO, amongst others, Stensaas gives a tenability value for LC50 from 5 sources spanning from 2500 – 8300 ppm [19]. Thus, from different sources, multiple values of some gases are given in Table 3.3

Table 3.4: Overview of the tenability values for incapacitation from various gases [17].

Gas	IC_{50} [ppm]	LC_{50} [ppm]	ID_{50} [ppm min]	LD_{50} [ppm min]
CO	1400 – 1700	4600 5500 8300 3000 2500 - 4000	35 000 - 45 000	70 000 – 135 000
CO_2	100 000	146 000		
HCN	100 – 200	110 – 160 200 135	750 – 2500 1200 – 2700	1500 – 7500
O_2		75 000		

3.7 Hypothesis

3.7.1 Hypothesis A

The Aspiration detection system equipped with a multi-sensor and a Photoelectric detector will be able to efficiently detect a broad spectrum of fire or smoke with an early time to activation. Thereby will give a person a better chance of escaping than other smoke detectors.

H0: The aspiration detection system will not be able to detect and provide early notification for all of the fire scenarios tested

H1: The aspiration detection system will be able to detect and provide early notification for all of the fire scenarios tested

As described in 3.1, multi-sensor detectors were found to be more efficient in detecting a broad spectrum of fire, especially smoldering fire. In this study, the performance of the aspiration system shall be assessed whether it really can detect considerable variation in fire and smoke conditions in dwellings. As there is a large set of variables that may affect the detection time thus, it is desired from this study to quantify the detection time and activation efficiency under various conditions.

3.7.2 Hypothesis B

The multi-sensor detector placed outside the apartment (at the exhaust of the aspiration detection unit) can detect the fire or smoke simultaneously with other detectors.

H0: The multi-sensor detector placed outside the apartment will not be able to detect and provide early notification for all of the fire scenarios tested

H1: The multi-sensor detector placed outside the apartment will be able to detect and provide early notification for all of the fire scenarios tested

As mentioned in the GAP analysis (2.3.2 and 2.3.4), ROP residents often tear down visible smoke detection units. Thus, this alternative approach has been taken to assess whether early detection of fire is possible by placing a detection unit outside the apartment.

3.7.3 Hypothesis C

Before The Aspiration detection system responds to smoke from the fire, the tenability limits for incapacitation from toxic gases and other means shall not exceed. Also, the activation of the fire extinguishing system shall be efficient.

H0: Tenability values for incapacitation from toxic gases and other means have not been exceeded before the aspiration detection system responds to smoke from the fire. And fire extinguishing system is activated when the tenability condition tends to exceed/ or exceeds.

H1: Tenability values for incapacitation from toxic gases and other means have been exceeded before the aspiration detection system responds to smoke from the fire. And fire extinguishing system is not activated when the tenability condition tends to exceed/ or exceeds.

As described in 3.3 and 3.5 proposed solution must respond in such a manner early notification shall be provided to the dwellers when the tenability condition is present in the dwellings. Also, it shall successfully activate the attached gas-based extinguishing system sensibly.

3.7.4 Hypothesis D

The Aspiration detection system shall not be sensitive to cigarette smoke or trigger a false alarm.

H0: The aspiration detection system is not overly sensitive to cigarette or similar smoke (due to other narcotic activities or extra kitchen smoke)

H0: The aspiration detection system is oversensitive to any kind of smoke.

As mentioned in the GAP analysis, over-sensitivity to the smoke that ROP residents often produce by smoking or cooking without turning on the exhaust generates false alarms which annoys them and often lead them to destroy the smoke alarm device. So, the aspiration detection system shall be able to differentiate between a real threat and other smoke.

4. Description of Method

For this project, the fire safety objective is reliable and early detection of fire to ensure life safety in the dwellings for the at-risk group, fulfilling the residents' particular needs and reducing false alarms. A full-scale experiment was conducted in an apartment in the Hall of Flame of HVL, campus-Haugesund, to observe the different smoke detectors' reliability, sensitivity, and performance under multiple fire conditions.

To meet the needs of the at-risk group, ***aspiration detection systems*** will be assessed with two other types of detection units as follows

- Photoelectric smoke detector
- Multi-sensor detector with CO, light scattering (Optical), and temperature(Heat) sensors.

The detectors were placed following manufacturer guidelines, and additionally, a multi-sensor detector was placed at the exhaust of the aspiration detection unit.

This alternative approach has been taken to assess whether this multi-sensor detector can detect early by measuring CO in exhaust air. For different fire scenarios performance of this detection unit will suggest whether it is possible to place the detection unit out of the apartment. Additionally, this detector was programmed with the controller to activate the gas-based extinguishing system (IG-541) only in those cases when both the aspirating detection system and the multi-sensor detector at the exhaust detect fire/smoke were activated. This may provide a sensible activation of the extinguishing system.

4.1 Test Matrix

Table 4-1 list the tests conducted in this study and describes the location of the source of fire in the various tests.

Table 4.1: Fire Scenario with location

Fire Scenario	Test No	Location
Trial 1: March 2022		
Smoldering (Pyrolysis) Wood Fire (With no ventilation)	101_1 to 101_4	Kitchen
Glowing Smoldering cotton Fire (With no ventilation)	102_1 to 102_4	Living room
Burning Polyurethane (With no ventilation)	103_1 to 103_4	Living room
Burning Heptane (With no ventilation)	104_1 to 104_4	In between Kitchen & living room
Trial 2: May 2022		
Smoldering Wood Fire (with ventilation System)	201_1 to 201_4	Kitchen
Slow Smoldering Cotton Fire (With ventilation System)	202_1 to 202_4	Living room
Burning Polyurethane (With ventilation system)	203_1 to 203_4	Bedroom
Burning Heptane Fire (With ventilation System and extended spread of Fire)	204_1 to 204_4	In between Kitchen & living room
Smoking Cigar	205	Bedroom & Living Room

4.2 Test Room

The test was conducted in an apartment measuring 7.4 m × 4.68 m × 2.43 m (l × w× h), which gives a base of approximately 35 m2. The apartment has a bedroom and a bathroom measuring 2.44 m × 2.32 each (separated by a wall and door measuring length and width of 2.01 m × .81 m). There are two other doors in the apartment to exit, measuring 2.01 m × .81 m (Door 1) and 2.01 m × .78 m) Door 2 and four windows. The door and windows were closed during the tests.

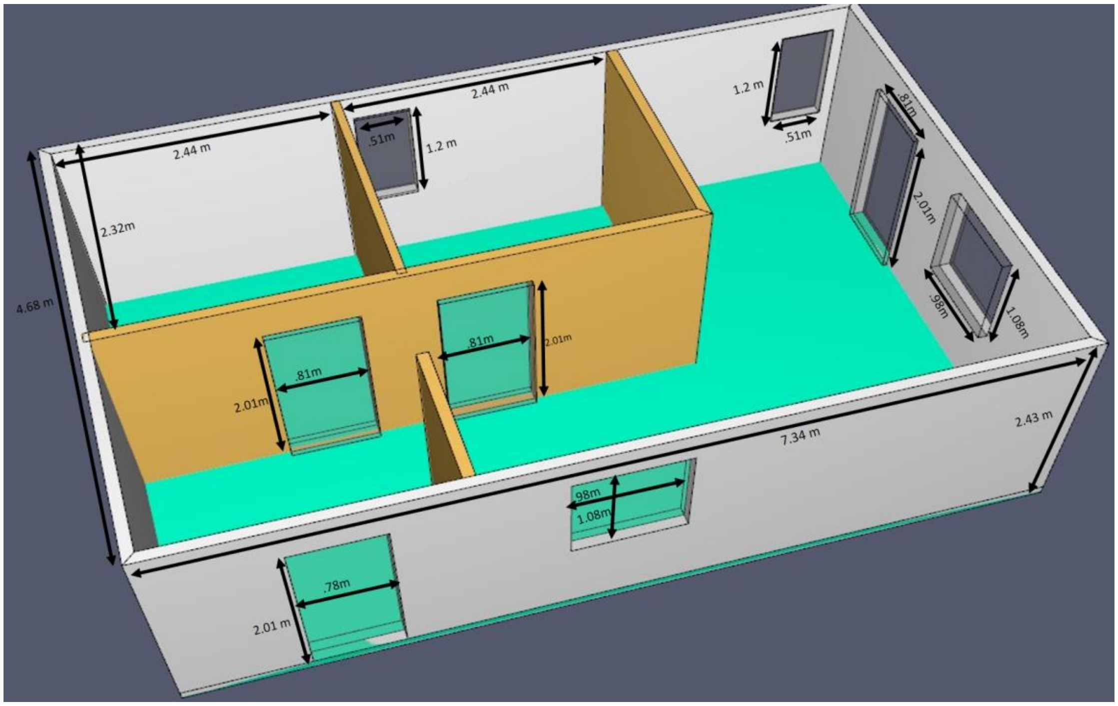


Figure 4.1: Sketch of the test room. The design is according to the similar apartment proposed to be built in Karmøy municipality for ROP residents.

4.3 Instrumentation

The fire test room was equipped with the following instruments.

Table 4.2: Detection and measuring equipment used in the experiment

S/L	Manufacturer/Brand	Function/Type of Measurement
1	No-Flame Røykvarsler	Photoelectric smoke detector
2	Tyco 830PC 3oTec Triple Sensor Detector	Multi-sensor detector with sensors for CO, light scattering and temperature
3	Vesda LaserCOMPACT	Aspirating smoke detector
4	Dräger X-am 8000	Multi Gas detector (CO, CO_2 and O_2 detector)
5	Thermocouple Type-K	-at the source of the smoldering & flaming fire. -three stacks of thermocouples placed in a marked location -nearby, the nozzle of the inergen gas extinguishing system
6	Zettler P405D	Addressable fire alarm control panel
7	Logging system for Thermocouple	HEWLETT-PACKARD 34970A.

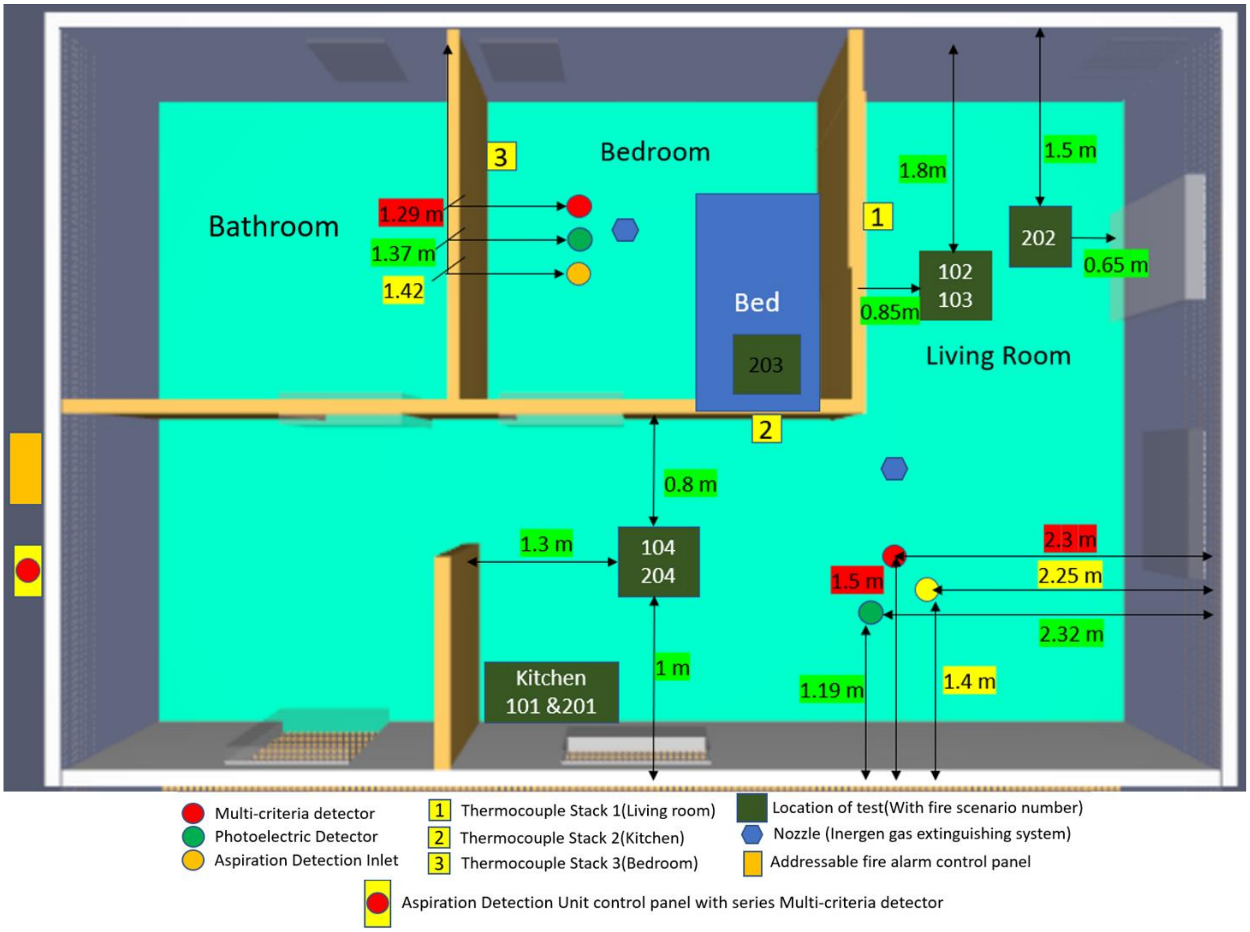


Figure 4.2: Sketch of the test room, including instrumentation.

4.3.1 Placement of Detectors and extinguishing system:

The common space between the kitchen and living room and the bedroom of the test apartment was equipped with multi-sensor and photoelectric detectors. Also, the simple pipe network of the aspiration detection system to draw air to the detection unit was installed. Multi-sensor detectors, Photoelectric detectors, and the inlet of the aspirator detection unit were placed in the marked location of the apartment (Figure 4.2). An inergen gas extinguishing system (IG-541) was installed in the apartment.

A multicriteria detector was placed at the exhaust of the aspiration detection unit. The exhaust air that came through the aspiration detection unit was confined within a small, boxed chamber where the multicriteria detector was placed. The exhaust line of the aspiration unit is used as the air inlet for the boxed chamber, and several holes were made in the chamber to extract excess air naturally. Multi-sensor detector is activated when the boxed chamber gains the CO concentration above 40 ppm thus.

4.3.2 Location of Fire Scenario and Thermocouple:

As shown in Figure 4.2, tests were conducted in the marked location (Numbered 101 to 104 and 201 to 204). Following fatal fire statistics, different fire scenarios were created in Kitchen, living, and bedroom. Three stacks of thermocouples (each containing five thermocouples) were placed within the height of 1.1m from the ground to 2.10m (with a .25 m interval) at the marked yellow places (1,2 &3) to measure the evaluation of room temperature during each experiment. During each experiment, two thermocouples (movable) were placed in the fire scenario. Additionally, on each nozzle of the inergen gas extinguishing system, a thermocouple was placed to observe the temperature drop during the extinguishing agent's release.

Table 4.3: Overview of Thermocouple installed (According to data logger)

Position/ Height From Ground (m)	Thermocouple Stack 3 Bedroom (Channel No)	Thermocouple Stack 2 Kitchen (Channel No)	Thermocouple Stack 1 Living Room (Channel No)
1.10 m	Channel 1	Channel 11	Channel 6
1.35 m	Channel 2	Channel 12	Channel 7
1.60 m	Channel 3	Channel 13	Channel 8
1.85 m	Channel 4	Channel 14	Channel 9
2.10 m	Channel 5	Channel 15	Channel 10
Nozzle Living Room		Channel 1	
Detection System Living Room		Channel 2	
Thermocouple at Bed height (0.70 m)	Channel 6		
Ceiling/Nozzle Bedroom	Channel 8		
Ext 1	Channel 11		
Ext 2	Channel 12		
Ext 3	Channel 13		

4.3.3 Measurement of Gas and Visibility:

The inlet of the multi-gas detectors (Dräger X-am 8000) was placed at 1.7m height with the thermocouple stacks 1(Living room) & 3(Bedroom). No tests were conducted on the bedroom during Trial 1(First 16 tests: Test numbers 101 to 104). Thus, no gas detector was placed in the bedroom during this trial. During the 2nd trial, gas detectors were placed in the living room and bedroom.

Additionally, one gas detector continuously measured the gases of the boxed chamber outside the apartment for the multi-sensor detector. By this, a complete status of the exhaust air can be found by which the performance of the multi-sensor detector can be evaluated. Every test was recorded by placing a recording camera 3m and 6m from the kitchen wall and entrance(left) wall consecutively, where a poster was placed to indicate visibility during the test.

During the 2nd Trial of the experiment ventilation system was installed. Ventilation inlet placed in Livingroom corner and extraction point was at bedroom, bathroom and above the kitchen hood.

4.4 Description Fire Scenario:

Smoldering and flaming fire scenarios were designed and tested following NS-EN 54-7 (Annex G-J) methods but not exactly as the standard described. The experiments were held in an apartment (built following the proposed layout of ROP Residence). Also, the amount of fuel, ignition of the fuel, run time of the experiment, location of the fire, and other parameters have been modified to create a fire/smoke scenario more realistic than the standardized method. As the number of possible fire scenarios is very large in such dwellings (by interviews held with the Fire Service personnel, reviewing fatal fire statistics, accident investigations, and combined with the needs of the at-risk group), those are reduced to a small set of fire scenarios. Eight different smoldering and flaming fire scenarios were designed and tested in

- Kitchen
- Living Room
- Bedroom

A total of 33 tests were conducted, including the repetition of each scenario by four times and a single test with smoking in the apartment. Before every test, by turning on the heater and ventilation, the room temperature was maintained between 15 to 20 ^{o}C. A complete description of each fire scenario is given below.

4.4.1 Fire Scenario 1: Smoldering (Pyrolysis) Wood Fire (With no ventilation)

Trial: 1 (March 2022) **Location: Kitchen**

No of Test: 4, Serial No: 101_1, 101_2, 101_3 & 101_4

Other Remarks: Bedroom door was closed. The fire scenario is similar to a kitchen fire /incorrect use of the appliance. No ventilation system was installed in the apartment. Bedroom door was closed.

Fuel:

Approximately 20 dried beechwood sticks (moisture content about 5 %) have dimensions of 100 mm x 10 mm x 10 mm. were burnt. Every four sticks have been placed together in a pack and placed in a row of five packs in the hotplate.

Hotplate:

BEHA Stove (3.3 kW) has been used as a hotplate. During the test experiment, 101_1 to 101_4 stove was operated at full power(3.3kW).

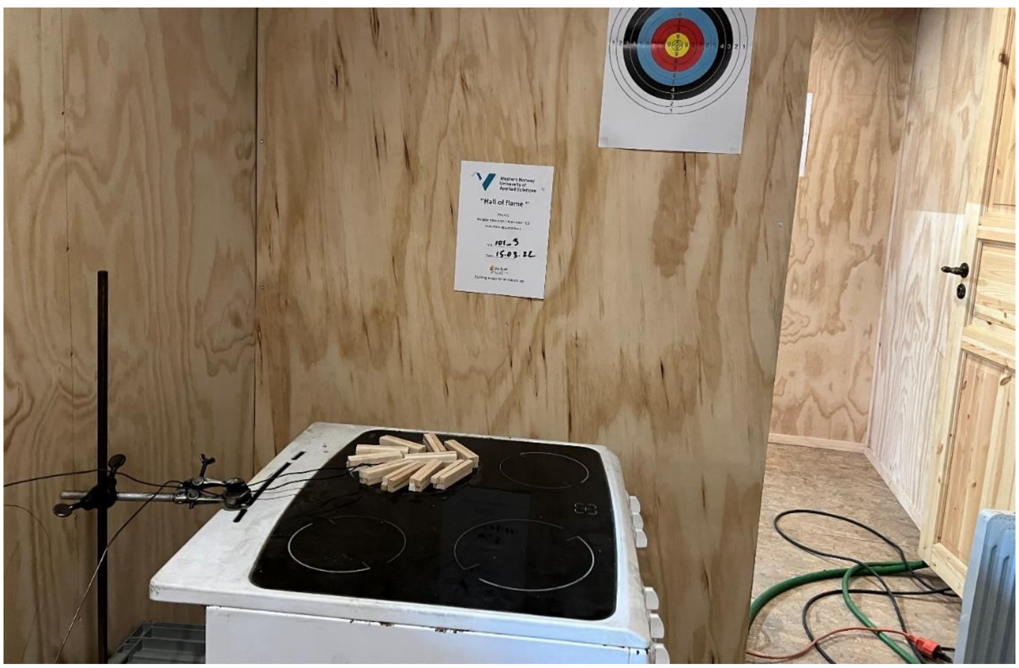


Figure 4.3: Experimental setup of Smoldering (Pyrolysis) Wood Fire (With no ventilation) (101_1 to 101_4)

4.4.2 Glowing Smoldering Cotton Fire (With no ventilation)

Trial: 1 (March 2022) **Location: Living Room**

No of Test: 4, Serial No: 102_1, 102_2, 102_3 & 102_4

Other Remarks: Bedroom door was closed. The fire scenario is similar to a smoldering fire caused by an open flame (from a cigarette)

Fuel: Approximately 270 gm of cotton was placed in 10cm diameter cylindrical mesh (length 80cm) and suspended 1m above the ground for the trial 102_1-4.

Ignition: Ignited by flame at the bottom. Any flame has been extinguished, keeping the lower portion of cotton glowing.

Figure 4.4: Experimental setup of Glowing Smoldering cotton Fire (With no ventilation) (102_1 to 102_4)

4.4.3 Burning Polyurethane (With no ventilation)

Trial: 1 (March 2022) **Location: Living Room**

No of Test: 4, Serial No: 103_1, 103_2, 103_3 & 103_4

Other Remarks: Bedroom door was closed. A fire scenario is similar to a flaming fire caused by an open flame or Arson. (Source of open flame could be candle)

Fuel: Soft polyurethane foam, without flame retardant additives and having a density of approximately 20 kg m−3, has been used. Three mats, approximately 50 cm × 50 cm × 2 cm(equivalent) placed one on top of another on a base formed from aluminum foil with the edges folded up to provide a tray.

Ignition: Ignited by flame at the bottom corner.

Figure 4.5: Experimental setup of Burning Polyurethane (With no ventilation) (103_1 to 103_4)

4.4.4 Burning Heptane (With no ventilation)

Trial: 1 (March 2022) **Location: In between Kitchen & Living Room**

Other Remarks: Bedroom door was closed. A fire scenario is similar to a flaming fire caused by a cooking fire or arson.

No of Test: 4, Serial No: 104_1, 104_2, 104_3 & 104_4

Fuel: Approximately 600 gm of Heptane has been burnt in a square steel tray with dimensions of 20 cm x 20 cm x 10 cm.

Ignition: Ignited by a spark.

Figure 4.6: Experimental setup of Burning Heptane (With no ventilation) (104_1 to 104_4)

4.4.5 Smoldering Wood Fire (with ventilation System)

Trial: 2 (May 2022) **Location: Kitchen**

No of Test: 4, Serial No: 201_1, 201_2, 201_3 & 201_4

Other Remarks: Bedroom door was closed. The fire scenario is similar to a kitchen fire /incorrect appliance use.

Fuel:

Approximately twenty dried beechwood sticks (moisture content about 5 %), each with dimensions of 100 mm x 10 mm x 10 mm, were burnt. Every four sticks have been placed together in a pack and placed in a row of five packs in the hotplate.

Hotplate:

BEHA Stove (3.3 kW) has been used as a hotplate. The stove operated at approximately 2 kW, which provided a temperature rise at the hotplate from 0°C to 600°C within about 10-11 minutes.

Figure 4.7: Experimental setup of Smoldering Wood Fire (with ventilation System) (204_1 to 204_4)

4.4.6 Slow Smoldering Cotton Fire (With ventilation System)

Trial: 2 (May 2022) **Location: In between kitchen and living room**

No of Test: 4, Serial No: 202_1, 202_2, 202_3 & 202_4

Other Remarks: Bedroom door was open. This experiment created a fire scenario due to incorrect use of electrical appliances (such as smoldering fire due to an open heater covering). As it is a slow smoldering fire, ventilation affected the indoor airflow acutely (As the ventilation rate was much higher).

Fuel: Approximately 270 gm of cotton was densely placed in a 20*20cm metal enclosure and heated in a hotplate to create slow smoldering.

Ignition: BEHA Stove (3.3 kW) has been used as a hotplate. The stove operated at approximately 2kW, which provided a temperature rise at the hotplate from 0°C to 600°C within about 10-11 minutes.

Figure 4.8: Experimental setup of Slow Smoldering Cotton Fire (With ventilation System) (202_1 to 202_4)

4.4.7 Burning Polyurethane (With ventilation system)

Trial: 2 (May 2022) **Location: Living Room**

No of Test: 4, Serial No: 203_1, 203_2, 203_3 & 203_4

Other Remarks: Bedroom door was open. A fire scenario is similar to a flaming fire caused by an open flame or Arson. (Source of open flame could be the candle or cigarette)

Fuel: Soft polyurethane foam, without flame retardant additives and having a density of approximately 20 kg m−3, has been used. Three mats, approximately 50 cm × 50 cm × 2 cm(equivalent). As the setup was established on the bed, thus foam was placed in a steel tray.

Ignition: Ignited by flame at the bottom corner.

Figure 4.9: Experimental setup of Burning Polyurethane (With ventilation system)

(203_1 to 203_4)

4.4.8 Burning Heptane Fire (With ventilation System and extended spread of Fire)

Trial: 2 (May 2022) **Location: In between kitchen and living room**

No of Test: 4, Serial No: 204_1, 204_2, 204_3 & 204_4

Other Remarks: Bedroom door was open. A fire scenario is similar to a flaming fire caused by a cooking fire or arson. Using several blocks of wood, a spread/development of fire has been tested from 11min 45 sec for test 204_3 and from 11min for test 204_4

Fuel: Approximately 1L of Heptane has been burnt in a square steel tray with dimensions of 20 cm x 20 cm x 10 cm.

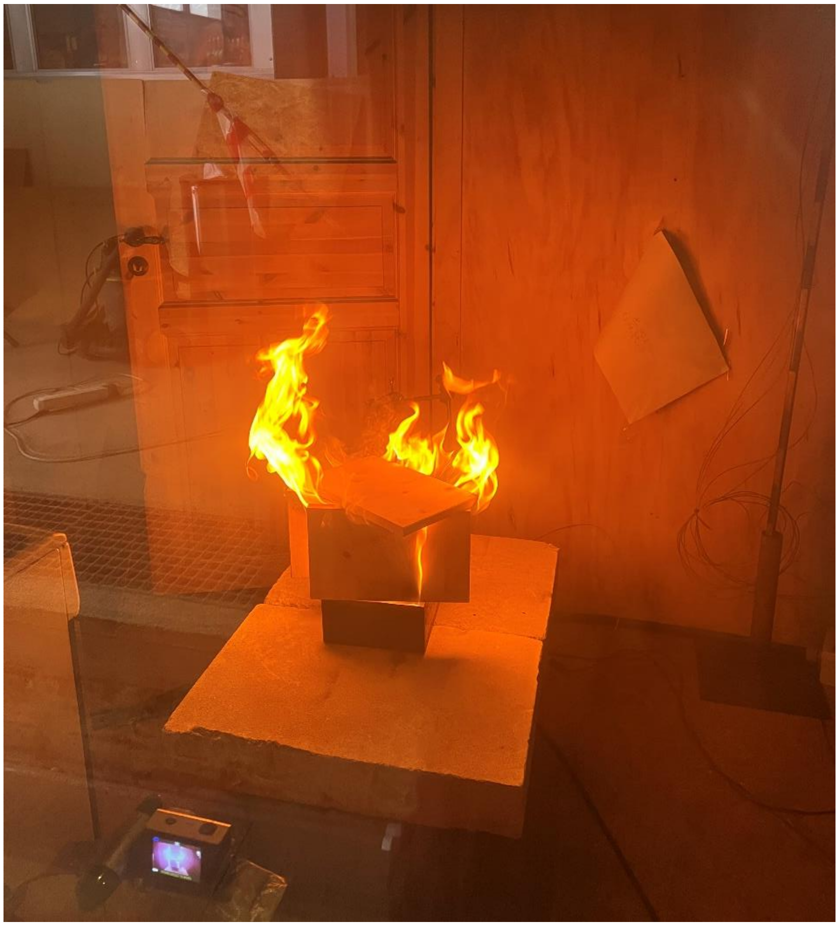


Figure 4.10: Burning Heptane Fire (With ventilation System and extended spread of Fire) (204_1 to 204_4)

4.4.9 Smoking in the apartment

Trial: 2 (May 2022) **Location: Bedroom & Living room**

No of Test: 1, Serial No: 205_1

Status of ventilation: Ventilation was off.

Other Remarks: Bedroom door was open.

Disclaimer:

Two-person participated in this experiment (voluntarily), understanding the physical hazard. They were strictly instructed not to inhale smoke. Two cigars were burnt simultaneously in the bedroom and living room.

4.5 Data Analysis

To estimate the average time to activate the smoke detector test in which the smoke detector was not activated was excluded. While calculating average activating time, fire scenarios 202_1 to 202_4 and 201_3 were excluded. Because due to the effect of the ventilation system and extreme weather, those tests produced exceptionally irregular data. Thus, they were discussed in the results separately. Also, the extended burn of a smoldering fire in test 102_3 will be excluded from further analysis.

Data sample duration CO measurements are different in every test. While calculating gas concentration during the Mean Activation Time of the detector and Mean Activation Time of the gas-based extinguishing system, if the complete data sample is less than the required duration, the integral of CO concentration for the total runtime of the experiment has been considered.

5. Results

5.1 General Consideration

As the total number of tests is 33, results are represented and compared based on a set of a fire scenarios.

The multi-sensor detector has three detection sensors (CO, optical, and heat) and is connected to an addressable fire alarm control panel; thus, which detector was activated first can be found. In the case of multiple sensors detecting the fire, the earliest that responded was considered as the activation time of multi-sensor detectors. Sensitivity of the aspiration (Photodetectors) detection has been reduced to 2.6 obs/m during 2nd trial of experiment to adjust its sensitivity match with Photoelectric and multi-sensor detector.

The multi-sensor detector connected to the exhaust of the aspiration detection unit was programmed with a controller to activate the fire extinguishing system only when both the aspiration detection unit and the multi-sensor detector detect fire. So, in the analysis, it is marked as

- Activation of Extinguishing System (by the optical detector)
- Activation of Extinguishing System (by CO detector)

List of detectors and detecting sensors (Type of alarm) title used in this section

1. Aspiration detection System
   a. Pre-alarm
   b. Aspiration detection
2. Multi-sensor detector (Bedroom/Living Room/ Outside)
   a. Optical detection
   b. Heat detection
   c. CO detection
3. Photoelectric Detector (Bedroom/ Living Room)

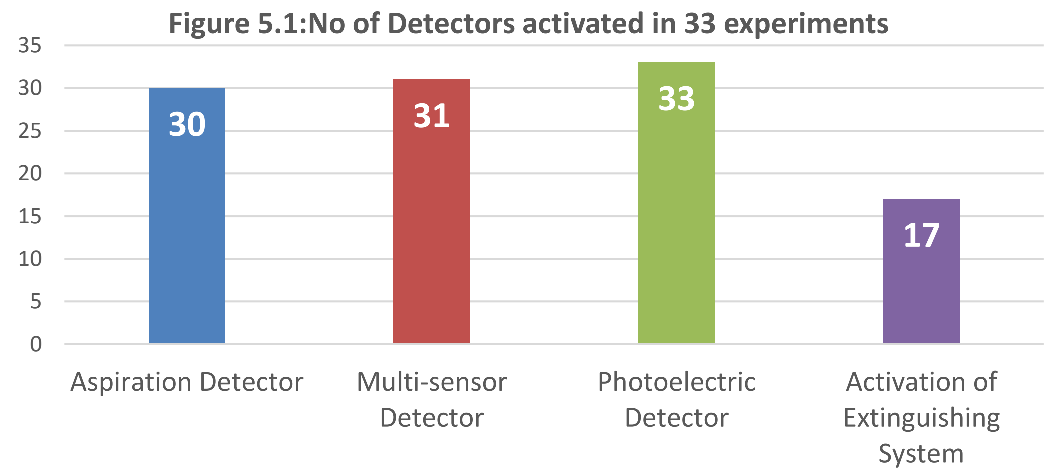
Table 5.1: List of Experiments

Fire Scenario	Test No	Number of Experiment	Location
Trial 1: March 2022			
Fire Scenario 1: Smoldering (Pyrolysis) Wood Fire (With no ventilation)	101_1 to 101_4	4	Kitchen
Fire Scenario 2: Glowing Smoldering cotton Fire (With no ventilation)	102_1 to 102_4	4	Living room
Fire Scenario 3: Burning Polyurethane (With no ventilation)	103_1 to 103_4	4	Living room
Fire Scenario 4: Burning Heptane (With no ventilation)	104_1 to 104_4	4	In between Kitchen & living room
Fire Scenario 5: Smoldering Wood Fire (with ventilation System)	201_1 to 201_4	4	Kitchen
Fire Scenario 6: Slow Smoldering Cotton Fire (With ventilation System)	202_1 to 202_4	4	Living room
Fire Scenario 7: Burning Polyurethane (With ventilation system)	203_1 to 203_4	4	Bedroom
Fire Scenario 8: Burning Heptane Fire (With ventilation System and extended spread of Fire)	204_1 to 204_4	4	In between Kitchen & living room
Smoking Cigar	205	1	Bedroom & Living Room

5.2 Introductory Analysis

5.2.1 General Overview: Activation of Different detection Systems

Figure 5.1 and 5.2 shows that out of 33 tests of 9 different scenarios; the aspiration detection system was activated 30 times, and the multi-sensor detector was activated in 31 test. In contrast, the photoelectric detector was activated in all the scenarios. Here in 17 tests, the multi-sensor detector placed outside was activated (represented in Figure as activation of Extinguishing System.



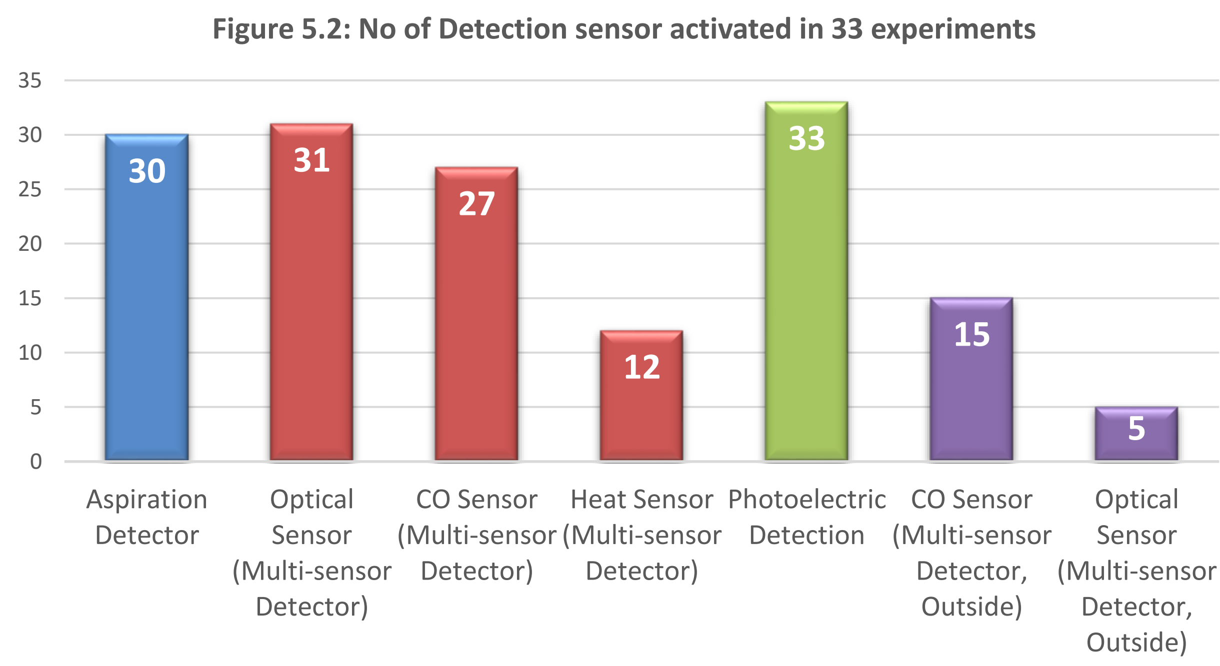
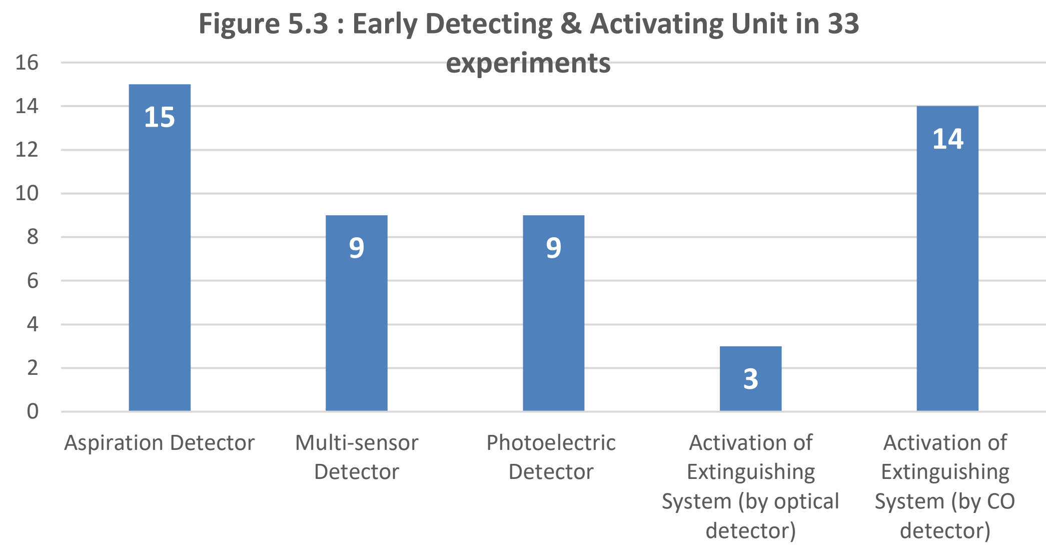
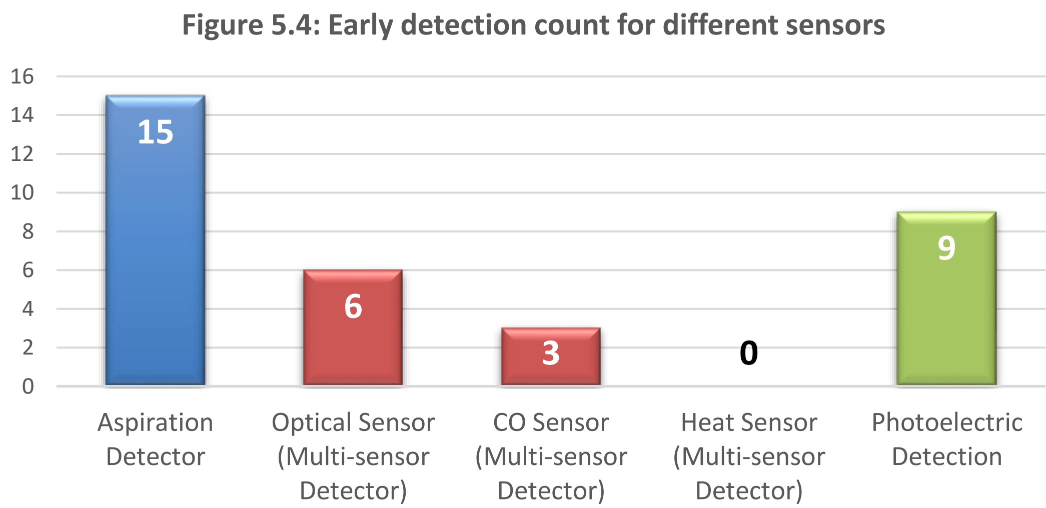


Figure 5.2 elaborates that among 31 successful detections by the multi-sensor detector, its optical sensor detected the fire every time, whereas the CO sensor and heat sensor detected consecutively 27 and 12 times. On the other hand, the multi-sensor detector placed outside the apartment could sense the fire 17 times, where the CO sensor activated 15 times and the optical sensor was 5 times.

5.2.2 Early detection overview

Figure 5.3 shows that different sensors were activated at different times in the multi-criteria detector. Still, overall data shows that the aspiration detection system responded earlier in 15 cases (highest), and both the multi-criteria and photoelectric detector detected the fire earlier in 9 cases. Out of 33 tests, 17 times, the multi-criteria detector placed in the exhaust of the aspiration detection unit was activated. Thus, it triggered the extinguishing system. But it never responded earlier than the detectors placed inside the apartment.





From figure 5.4, it is observed among all the sensors, the aspiration detection unit could detect most of the fires early than any other detectors.

5.3 Timeline of Smoke Detection & Fire Extinguishing System Activation

In this section, a timeline of activation for different smoke detection systems (including activating sensor and location) and fire extinguishing systems has been presented and discussed in tabular format for different fire scenarios. Detection time is represented in (min: sec) form. For the detection times of four test from each scenario, Mean activation time (Mean), Standard Deviation (SD), and Coefficient of Variation (CV%) has been calculated and presented. Activation of Smoke detection of the Multicriteria detector (Outside) ultimately represents the time of activating the inergen Gas Extinguishing System.

5.3.1 Fire Scenario 1: Smoldering (Pyrolysis) Wood Fire (With no ventilation)

Table 5.2: Timeline of Smoke Detection & Fire Extinguishing System Activation for *"Smoldering (Pyrolysis) Wood Fire (With no ventilation)"*

	Activated Detectors Name						
Test No.	Pre-Alarm Aspiration	Aspiration Detector	Multi-sensor (Outside) Optical Detection	Multi-sensor (Outside) CO Detection	Multi-sensor (Living Room) Optical Detection	Multi-sensor (Living Room) CO Detection	Photoelectric Detection Living Room
101_1	0:02:49	0:03:05	0:10:27	0:09:40	0:04:39	0:06:00	0:03:40
101_2	0:02:45	0:02:54	0:06:16	N/A	0:04:30	0:06:21	0:04:30
101_3	0:02:55	0:03:03	0:06:48	N/A	0:04:11	0:06:22	0:03:47
101_4	0:02:26	0:02:32	0:03:59	0:05:45	0:03:04	0:03:59	0:03:15
Mean	**0:02:44**	**0:02:53**	**0:06:53**	**0:07:42**	**0:04:06**	**0:05:41**	**0:03:48**
SD	**0:00:11**	**0:00:13**	**0:02:19**	**0:01:57**	**0:00:37**	**0:00:59**	**0:00:27**
CV%	**6.625**	**7.543**	**33.736**	**25.405**	**15.120**	**17.403**	**11.846**

During this experiment, there was no ventilation system in the apartment. The table shows that such a fire scenario aspiration detection unit can efficiently detect the fire at an early stage compared to any other detector.

5.3.2 Fire Scenario 2: Glowing Smoldering Cotton Fire (With no ventilation)

During this scenario, the aspiration detection system effectively detects the initial smoke generated while igniting the cotton. Other detectors may have taken much longer to respond as the fire developed relatively slowly. Though previous studies show that multi-sensor detectors with CO sensors are found to respond earlier in such fire conditions, this experiment suggests differently. But as there was no ventilation installed in the apartment, this outcome varied significantly from a further test of smoldering fires held with a ventilation system.

Table 5.3: Timeline of Smoke Detection & Fire Extinguishing System Activation for *"Glowing Smoldering Cotton Fire (With no ventilation)"*

Activated Detectors Name						
Test No.	Pre-Alarm Aspiration	Aspiration Detector	Multi-sensor (Outside) CO Detection	Multi-sensor (Living Room) Optical Detection	Multi-sensor (Living Room) CO Detection	Photoelectric Detector (Living Room
102_1	0:00:05	0:00:37		0:17:36	0:09:53	0:03:26
102_2	0:02:39	0:03:35		0:09:02	0:08:47	0:10:10
102_3	0:00:45	0:00:54	0:29:07		0:15:24	0:06:27
102_4	0:00:33	0:00:43		0:19:50	0:00:46	0:09:38
Mean	**0:01:00**	**0:01:27**	**0:29:07**	**0:15:29**	**0:08:42**	**0:07:25**
SD	**0:00:59**	**0:01:14**	**0:00:00**	**0:04:39**	**0:05:14**	**0:02:42**
CV(%)	**97.01**	**84.82**	**0.00**	**30.05**	**60.01**	**36.46**

5.3.3 Fire Scenario 3: Burning Polyurethane (With no ventilation)

In this scenario with burning polyurethane, almost all the detectors were activated in the early stage. Soon as all the sensors were activated, the fire was extinguished. The multi-sensor detector outside the apartment was not activated, so data is unavailable. The result also shows that the aspiration detection system detected the fire early with consistent performance. Heat sensors were found to detect this fire scenario but did not respond earlier than other detecting sensors.

Table 5.4: Timeline of Smoke Detection & Fire Extinguishing System Activation for *"Burning Polyurethane (With no ventilation)"*

Activated Detectors Name						
S/L	Pre-Alarm Aspiration	Aspiration Detector	Multi-sensor (Living Room) Optical Detection	Multi-sensor (Living Room) CO Detection	Multi-sensor (Living Room) Heat Detection	Photoelectric Detector (Living Room
103_1	0:01:12	0:01:13	0:01:18	0:01:38	0:01:53	0:01:23
103_2	0:01:10	0:01:16	0:01:25	0:01:40		0:01:36
103_3	0:01:01	0:01:10	0:01:53	0:02:18	0:02:38	0:01:55
103_4	0:01:08	0:01:13	0:02:04	0:02:24	0:02:47	0:01:21
Mean	**0:01:08**	**0:01:13**	**0:01:40**	**0:02:00**	**0:02:26**	**0:01:34**
SD	**0:00:04**	**0:00:02**	**0:00:19**	**0:00:21**	**0:00:24**	**0:00:14**
CV(%)	**6.12**	**2.91**	**19.07**	**17.60**	**16.18**	**14.46**

5.3.4 Fire Scenario 4: Burning Heptane (With no ventilation)

The first test was conducted in a larger pool during this experiment, significantly increasing the heat inside the apartment. So, in later tests, the pool size was reduced. In such cases, heat sensors and observed not to be able to detect the fire. Also, in this scenario aspiration detection unit detected the fire in the early stage.

Table 5.5: Timeline of Smoke Detection & Fire Extinguishing System Activation for *"Burning Heptane (With no ventilation)"*

Activated Detectors Name						
S/L	Pre-Alarm Aspiration	Aspiration Detector	Multi-sensor (Living Room) Optical Detection	Multi-sensor (Living Room) CO Detection	Multi-sensor (Living Room) Heat Detection	Photoelectric Detector (Living Room
104_1	0:00:33	0:00:39	0:00:28	0:00:49	0:01:19	0:00:35
104_2	0:00:28	0:00:41	0:01:42			0:01:03
104_3	0:00:25	0:00:40	0:01:08			0:00:46
104_4	0:00:30	0:00:40	0:01:07			0:00:49
Mean	**0:00:29**	**0:00:40**	**0:01:06**	**0:00:49**	**0:01:19**	**0:00:48**
SD	**0:00:03**	**0:00:01**	**0:00:26**	**0:00:00**	**0:00:00**	**0:00:10**
CV(%)	**10.05**	**1.77**	**39.54**	**0.00**	**0.00**	**20.69**

5.3.5 Fire Scenario 5: Smoldering Wood Fire (with ventilation System)

In this scenario, similar tests as Fire scenario 1 were conducted with the ventilation. During the first two tests ventilation system was kept ON, and in the last two tests ventilation system was kept off. The ventilation system significantly affected the performance of all the detectors compared to the fire scenario 2.

Table 5.6: Timeline of Smoke Detection & Fire Extinguishing System Activation for *"Smoldering Wood Fire (with ventilation System)"*

Activated Detectors Name										
S/L	Pre-Alarm Aspiration	Aspiration Detector	Multi-sensor (Outside) Optical Detection	Multi-sensor (Outside) CO Detection	Multi-sensor (Bedroom) Optical Detection	Multi-sensor (Bedroom) CO Detection	Multi-sensor (Living Room) Optical Detection	Multi-sensor (Living Room) CO Detection	Photoelectric Detector (Living Room	Photoelectric Detector (Bedroom)
201_1	0:05:02	0:05:40		0:14:38	0:07:55		0:06:01	0:09:07	0:05:10	
201_2	0:05:22	0:07:13			0:07:13		0:09:21		0:05:34	
201_3	0:09:10								0:09:03	0:08:59
201_4	0:05:50	0:06:21	0:10:05	0:09:09	0:07:59	0:10:20	0:06:15	0:07:36	0:06:12	
Mean	**0:06:21**	**0:06:25**	**0:10:05**	**0:11:53**	**0:07:42**	**0:10:20**	**0:07:12**	**0:08:22**	**0:06:30**	**0:08:59**
SD	**0:01:39**	**0:00:38**	**0:00:00**	**0:02:45**	**0:00:21**	**0:00:00**	**0:01:31**	**0:00:46**	**0:01:31**	**0:00:00**
CV(%)	**26.00**	**9.89**	**0.00**	**23.06**	**4.50**	**0.00**	**21.09**	**9.07**	**23.40**	**0.00**

Ventilation significantly affects the multi-sensor detector placed outside the apartment as that detector mostly depends on the exhaust air from the aspiration unit. As most of the toxic gases were exhausted by the ventilation system, the detector only detected fire in two of the tests, and the response time was significantly higher than other detectors. Due to extreme weather 201_3 test produced significant irregular data. Photoelectric detectors are observed to be most efficient in such conditions.

5.3.6 Fire Scenario 6: Slow Smoldering Cotton Fire (With ventilation System)

In this fire scenario, the smoldering fire developed slowly. Thus, the detection time for all the detectors is much longer than in any other scenario. During these tests, the ventilation system was ON (during tests 202_1 and 202_4). As the inlet of the ventilation system was towards the air inlet of the aspiration detection unit, this is observed to have a significant impact on the detection time of this detector. As produced gas was much colder than the gases during the flaming fire and the bedroom door was kept open, toxic gas spread to the apartment. Thus, multi-sensor detectors were activated in all the rooms. Therefore, the activation of CO sensor from the multi-sensor detector outside the apartment was significantly faster than in the aspiration detection unit(as aspiration detection air inlets drew gases from different rooms, accumulated CO concentration in the detection chamber was much higher compared to another fire scenario).

Table 5.7: Timeline of Smoke Detection & Fire Extinguishing System Activation for *"Slow Smoldering Cotton Fire (With ventilation System)"*

	Activated Detectors Name							
S/L	Pre-Alarm Aspiration	Aspiration Detector	Multi-sensor (Outside) CO Detection	Multi-sensor (Bedroom) Optical Detection	Multi-sensor (Bedroom) CO Detection	Multi-sensor (Living Room) Optical Detection	Multi-sensor (Living Room) CO Detection	Photoelectric Detector (Living Room
202_1	0:31:23		0:36:02		0:37:12	0:37:14	0:30:56	0:06:53
202_2	0:19:38	0:25:45	0:16:41	0:26:57	0:13:55	0:25:38	0:15:02	0:16:36
202_3	0:20:40	0:23:27	0:15:23	0:25:43	0:11:36	0:24:04	0:12:58	0:19:27
202_4	0:22:07	0:25:07	0:14:30	0:27:57	0:11:24	0:26:03	0:11:56	0:19:45
Mean	**0:23:27**	**0:24:46**	**0:20:39**	**0:26:52**	**0:18:32**	**0:28:15**	**0:17:43**	**0:15:40**
SD	**0:04:40**	**0:00:58**	**0:08:55**	**0:00:55**	**0:10:49**	**0:05:14**	**0:07:43**	**0:05:13**
CV(%)	**19.89**	**3.92**	**43.17**	**3.40**	**58.42**	**18.56**	**43.53**	**33.31**

5.3.7 Fire Scenario 7: Burning Polyurethane (With ventilation system)

This is a similar fire scenario to fire scenario 3 with a location in the bedroom and ventilation during the tests 203_2 and 203_3. As this scenario took place in a much-confined place, the ventilation system seems to have an insignificant impact on detectors. Though almost all the sensors responded efficiently multi-sensor detector of the bedroom responded earlier in this scenario.

Table 5.8: Timeline of Smoke Detection & Fire Extinguishing System Activation for *"Slow Smoldering Cotton Fire (With ventilation System)"*

Activated Detectors Name										
S/L	Pre-Alarm Aspiration	Aspiration Detector	Multi-sensor (Outside) CO Detection	Multi-sensor (Bedroom) Optical Detection	Multi-sensor (Bedroom) CO Detection	Multi-sensor (Bedroom) Heat Detection	Multi-sensor (Living Room) Optical Detection	Multi-sensor (Living Room) CO Detection	Multi-sensor (Living Room) Heat Detection	Photoelectric Detector (Bedroom)
203_1	0:01:10	0:01:21	0:02:39	0:01:13	0:01:23	0:01:23	0:01:34	0:01:54	0:02:04	0:01:45
203_2	0:01:09	0:01:14	0:02:31	0:01:00	0:01:00	0:01:15	0:01:52	0:02:02	0:02:02	0:01:47
203_3	0:01:27	0:01:37	0:02:46	0:01:11	0:01:21	0:01:31	0:02:03	0:02:13	0:02:13	0:02:00
203_4	0:01:16	0:01:25	0:02:41	0:00:51	0:00:51	0:01:01	0:01:08	0:01:38	0:02:08	0:01:04
Mean	**0:01:15**	**0:01:24**	**0:02:39**	**0:01:04**	**0:01:09**	**0:01:17**	**0:01:39**	**0:01:57**	**0:02:07**	**0:01:39**
SD	**0:00:07**	**0:00:08**	**0:00:05**	**0:00:09**	**0:00:14**	**0:00:11**	**0:00:21**	**0:00:13**	**0:00:04**	**0:00:21**
CV(%)	**9.48**	**9.91**	**3.39**	**13.91**	**19.85**	**14.30**	**20.96**	**10.92**	**3.32**	**21.22**

5.3.8 Fire Scenario 8: Burning Heptane Fire (With ventilation System and extended spread of Fire)

In this scenario, similar tests as fire scenario 4 were conducted with the ventilation system ON (for the whole time of test 204_2). Ventilation was kept off during the test 204_1 and 204_4. In test 204_3, initially, the ventilation system was ON but turned off after the 23rd minute from the start of the experiment (to observe the behaviour of fire spread and detection units at low oxygen levels). Fire spread was conducted during the test 203_4 and 204_4 approximately 11th minutes from the start of the experiment. During Fire scenario 4, the extinguishing system was not activated in such a fire. Similar behaviour was observed during the first two tests, but as the fire spread occurred, the multi-sensor detector outside the apartment detected the fire's growth and activated the alarm. Thus, the extinguishing system was activated (approximately 7-10 minutes of fire spread).

Table 5.9: Timeline of Smoke Detection & Fire Extinguishing System Activation for *"Burning Heptane Fire (With ventilation System and extended spread of Fire)"*

S/L	Pre-Alarm Aspiration	Aspiration Detector	Multi-sensor (Outside) CO Detection	Multi-sensor (Bedroom) Optical Detection	Multi-sensor (Bedroom) CO Detection	Multi-sensor (Living Room) Optical Detection	Multi-sensor (Living Room) CO Detection	Multi-sensor (Living Room) Heat Detection	Photo electric Detector (Living Room	Photo electric Detector (Bedroom)
204_1	0:00:49	0:01:16		0:03:09	0:03:39	0:00:49	0:01:09	0:01:24	0:00:35	
204_2	0:00:51	0:01:07		0:03:09	0:06:10	0:00:34	0:00:59	0:00:59	0:00:48	
204_3	0:00:54	0:01:04	0:21:01	0:03:37	0:12:57	0:01:02	0:01:58	0:12:43	0:00:54	
204_4	0:01:07	0:01:59	0:11:07	0:02:28	0:02:48	0:00:39	0:00:59	0:01:19	0:00:37	0:01:47
Mean	**0:00:55**	**0:01:21**	**0:16:04**	**0:03:06**	**0:06:23**	**0:00:46**	**0:01:16**	**0:04:06**	**0:00:44**	**0:01:47**
SD	**0:00:07**	**0:00:22**	**0:04:57**	**0:00:25**	**0:03:59**	**0:00:11**	**0:00:24**	**0:04:58**	**0:00:08**	**0:00:00**
CV(%)	**12.69**	**27.11**	**30.81**	**13.25**	**62.33**	**23.26**	**32.06**	**121.22**	**17.99**	**0.00**

5.3.9 Fire Scenario 9: Smoking in the apartment

During this experiment, the Photoelectric detector of the living room activated the alarm at 5 minutes and 4 seconds from the experiment's start. All other detectors did not activate the alarm. At 21 minutes and 40 seconds, continuous smoking conditions inside the apartment aspiration detection system activated the pre-alarm. Thus, the multi-sensor detector and aspiration detection unit were less responsive to such smoke.

5.4 Scenario-Based Early Detection Time Overview

General consideration:

In this section, similar fire scenarios (differed by location and status of ventilation system) have been compared. Thus, the term "***Activation of Fire Extinguishing System"*** in the diagram represents the ***activation of the multi-sensor detection unit*** placed outside the apartment on the detection chamber made with a box. The detector's CO sensor's sensitivity has adjusted to respond to 40 ppm CO particle in its surrounding environment. Then the system will activate the extinguishing system if both the aspiration detection unit and that multi-sensor detector detect fire. This adjustment of the CO sensor was conducted after 1st trial (Fire Scenario 1-4). Therefore, on the 2nd trial of experiment, the multi-sensor detector was more responsive than earlier.

While calculating the Mean activation Time of Detectors and Mean Activation Time of Fire Extinguisher, two separate calculations have been presented (As the smoldering fire scenarios with an active ventilation system shows significant irregular data compared to the other six designs). One with six fire scenarios, including Fire Scenario: 1,3,4,5,7,8, and another including Fire scenarios 1 to 8.

But while assessing detectors' performance criteria with regards to tenability condition in case of Fire Scenario 2 & 6, the earliest time to activate smoke detection and fire extinguisher has been considered to assess; "*whether the solution tested can activate both detection and extinguishing system within tenability limit?"*

5.4.1 Fire Scenario 1 & 5: Smoldering (Pyrolysis) Wood Fire

Figure 5.5 and 5.6 shows the overview of activation time for Smoldering (Pyrolysis) Wood Fire with no ventilation and with ventilation consecutively. Here Aspiration detection system responded earlier in each of the four tests from scenario 1. But with ventilation, photoelectric smoke detectors responded earlier in each test of scenario 5. Thus, the mean early activation time of the aspiration detection system for scenario 1 is 2:53 seconds with a standard deviation of 13 seconds, having a coefficient of variation of 7.54%.

On the other hand, in terms of Mean Activation Time, even in scenario 5, the photoelectric detector system was earlier than any other system having a Mean Activation Time of 5 minutes 39 seconds with a standard deviation of 26 seconds, having a coefficient of variation of 7.54%. And aspiration detection unit has a Mean Activation Time of 6 minutes 25 seconds with a standard deviation of 38 seconds, having a coefficient of variation of 7.54 %

FIGURE 5.5 SMOLDERING (PYROLYSIS) WOOD FIRE (WITHOUT VENTILATION)

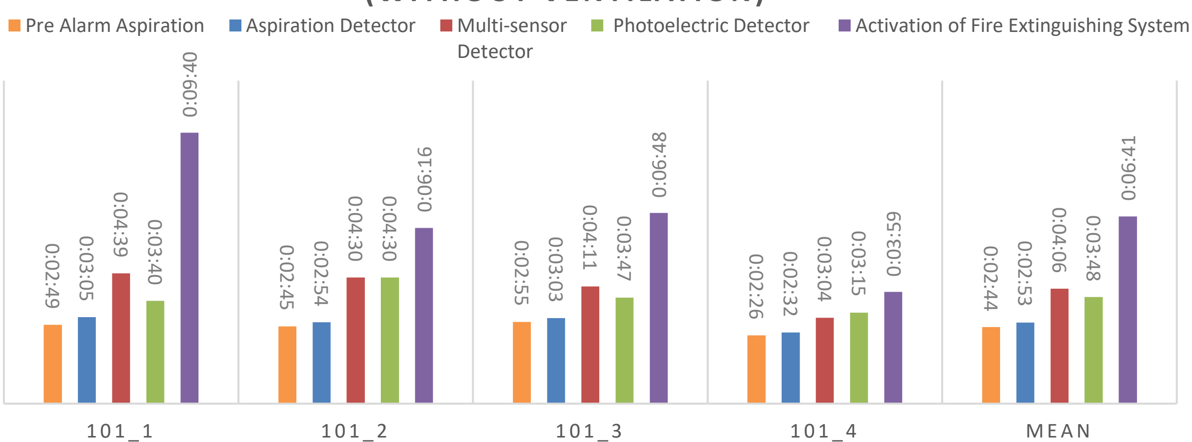
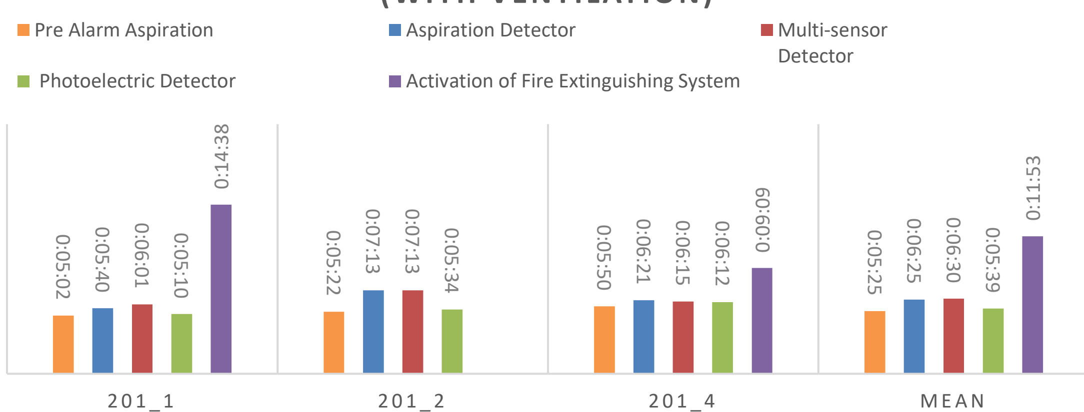


FIGURE5.6: SMOLDERING (PYROLYSIS) WOOD FIRE (WITH VENTILATION)



Activation of the fire extinguishing system was also observed to be increased with the presence of a ventilation system.

5.4.2 Fire Scenario 2 and 6: Glowing Smoldering cotton Fire with no ventilation and slow smoldering cotton fire

Figure 5.7 shows the overview of activation time for Glowing Smoldering cotton Fire with no ventilation where the aspiration detection system responded earlier in each of four tests. Thus, the mean early activation time of the aspiration detection system for this scenario is 1:27 seconds with a standard deviation of 1:14 seconds, having a coefficient of variation of 84.82%. During this scenario, the aspiration detection system responded while initial smoke was generated while igniting the cotton.

On the other hand, in Figure 5.8, it is observable that the ventilation system significantly affected the performance of detection systems in scenario 6. As the rate of ventilation was much higher [20] than the regular ventilation rate, it is expected from the detection system to perform better in normal conditions. During test 202_1 it is observed a large portion of smoke was driven at the corner (entrance side) of the apartment which caused the aspiration system not to be activated. Otherwise, a multi-criteria detector is found to be most efficient in such a scenario (if the data from test 201_1 is ignored). Thus, the Mean Activation Time for this scenario is 15:40 seconds from the photoelectric detector with a standard deviation of 5:40 seconds (coefficient of variation: 33.31%). But aspiration detection system was more consistent in activation time with a Mean Activation Time of 24:46 seconds with a standard deviation of only 58 seconds (coefficient of variation: 3.92% only)

FIGURE 5.7: GLOWING SMOLDERING COTTON FIRE (WITHOUT VENTILATION)

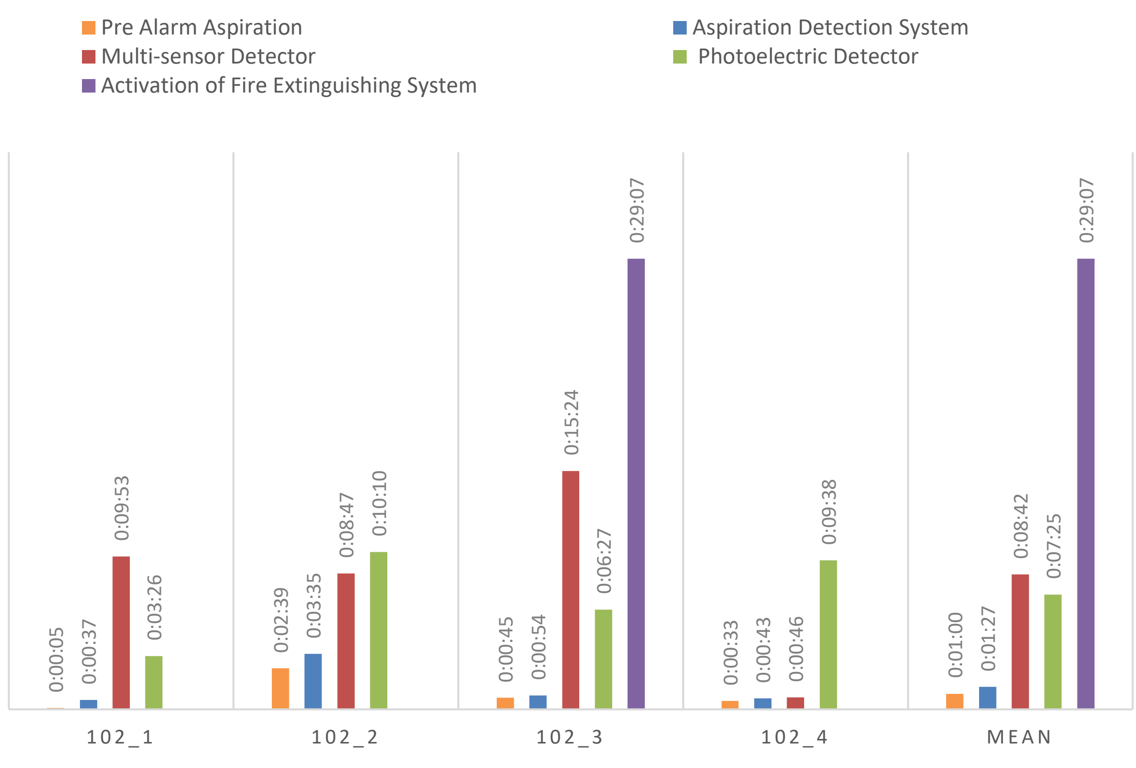
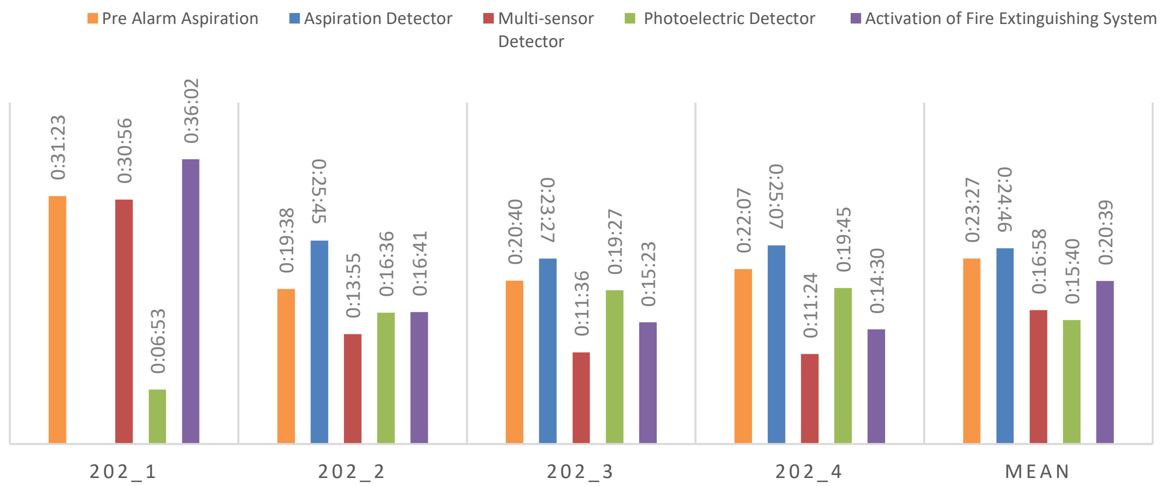


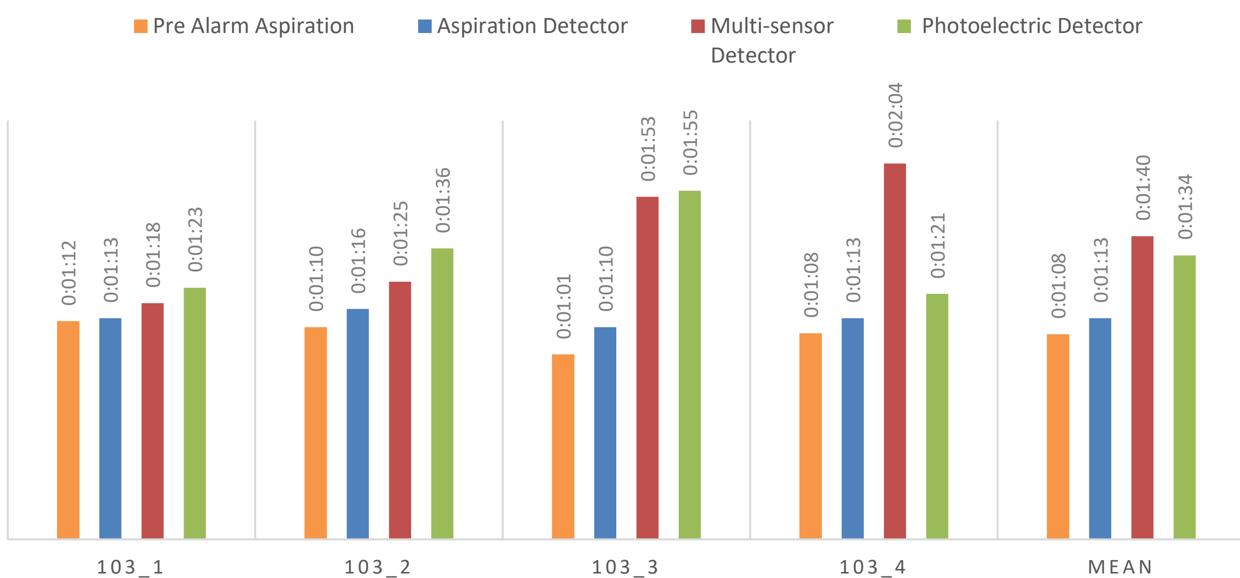
FIGURE 5.8: SLOW SMOLDERING COTTON FIRE (WITH VENTILATION)



5.4.3 Fire Scenario 3 and 7: Burning Polyurethane with no ventilation in the living room and with ventilation

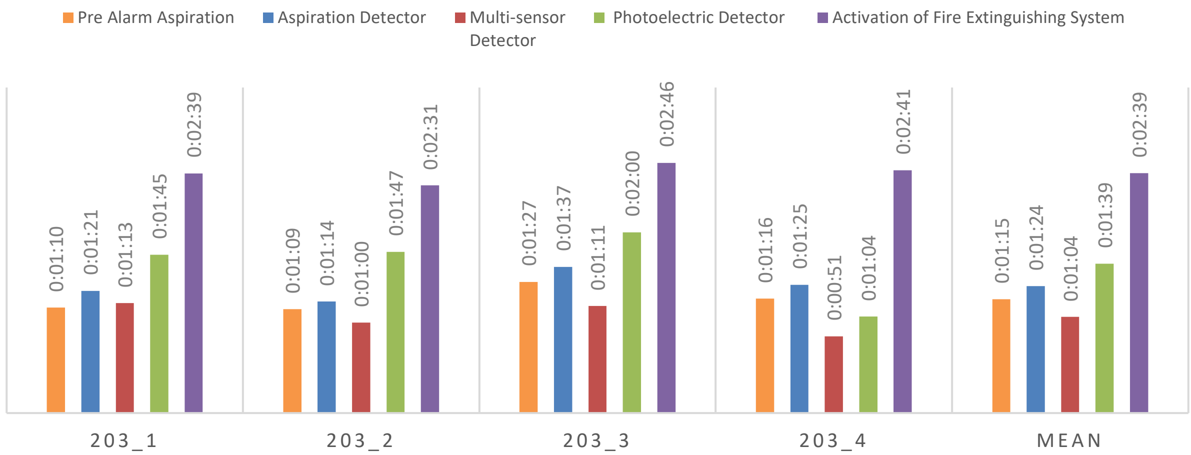
Figure 5.9 shows the overview of activation time for Burning Polyurethane with no ventilation (Fire scenario 3) where the aspiration detection system was found to respond earlier in each of four tests. Thus, the mean early activation time of the aspiration detection system for this scenario is 1:13 seconds with a standard deviation of 2 seconds having a coefficient of variation of 2.91%.

FIGURE 5.9: BURNING POLYURETHANE IN LIVING ROOM (WITHOUT VENTILATION)



But in Fire scenario 7(Figure 5.10), with the ventilation system ON, multi-sensor detectors were found relatively faster than the aspiration detection system. The Mean Activation Time of multi-sensor detectors was 1:04 seconds with a standard deviation of 9 seconds (coefficient of variation 13:91%) where the aspiration detection system activated with a Mean Activation Time of 1:24 seconds with a standard deviation of 8 seconds (coefficient of variation 9.91%). If we combine both the fire scenario it shows in terms of Mean Activation Time; the aspiration detection system responds earlier than other systems (within 1:19 seconds) and the mean time to activate the extinguishing system is 2:39 seconds with a standard deviation of just 5 seconds (Coefficient of variation 3.39%)

FIGURE 5.10: BURNING POLYURETHANE IN LIVING ROOM (WITH VENTILATION)



5.4.4 Fire Scenario 4 & 8: Burning Heptane with no ventilation and with ventilation (with the extended spread of fire)

Figure 5.11 shows the overview of activation time for Burning Heptane with no ventilation (Fire scenario 4) where the aspiration detection system was found to respond earlier in three tests. Thus, the Mean Earliest Activation time of the aspiration detection system is 40 seconds with a standard deviation of 1 second having a coefficient of variation of 1.77 %.

On the other hand, with the ventilation system turned ON; on fire scenario 8 (Figure 5.12) on three tests, photoelectric detectors were the earliest to respond (Mean Activation Time 44 seconds). The aspiration detection system was relatively slower (Mean Activation Time 1:21 seconds). But the ventilation system seems to affect the activation of the extinguishing system significantly. Thus, in tests 204_3 and 204_4 extended fire spread has been tested by adding wood blocks with fuel from the 8th minute of starting the test. Then the extinguishing system was soon activated. If we consider the Mean Activation Time of activating the extinguishing system; it took 16:04 seconds to activate. Thus, we can expect that, even with a much higher ventilation rate, soon as the fire starts to spread, the extinguishing system will be activated.

FIGURE 5.11: BURNING HEPTANE (WITHOUT VENTILATION)

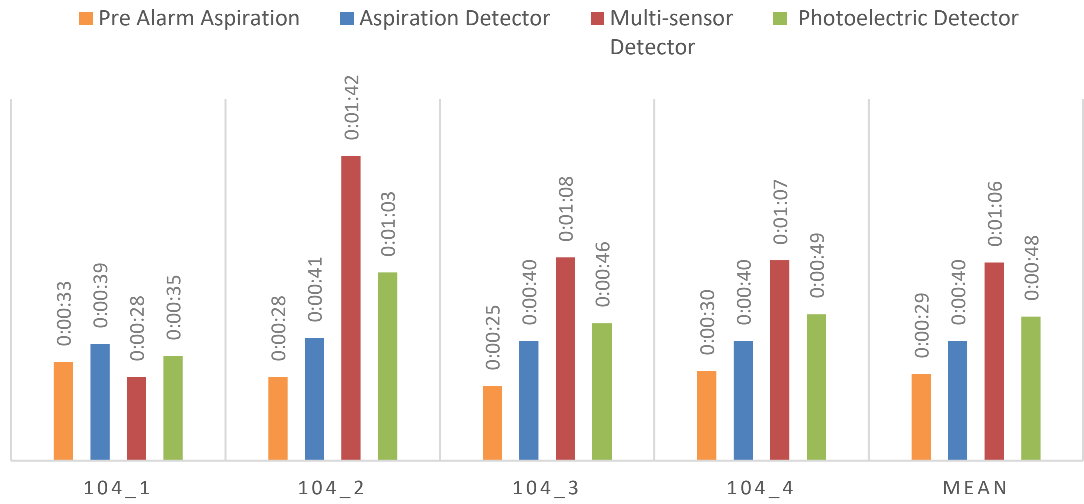
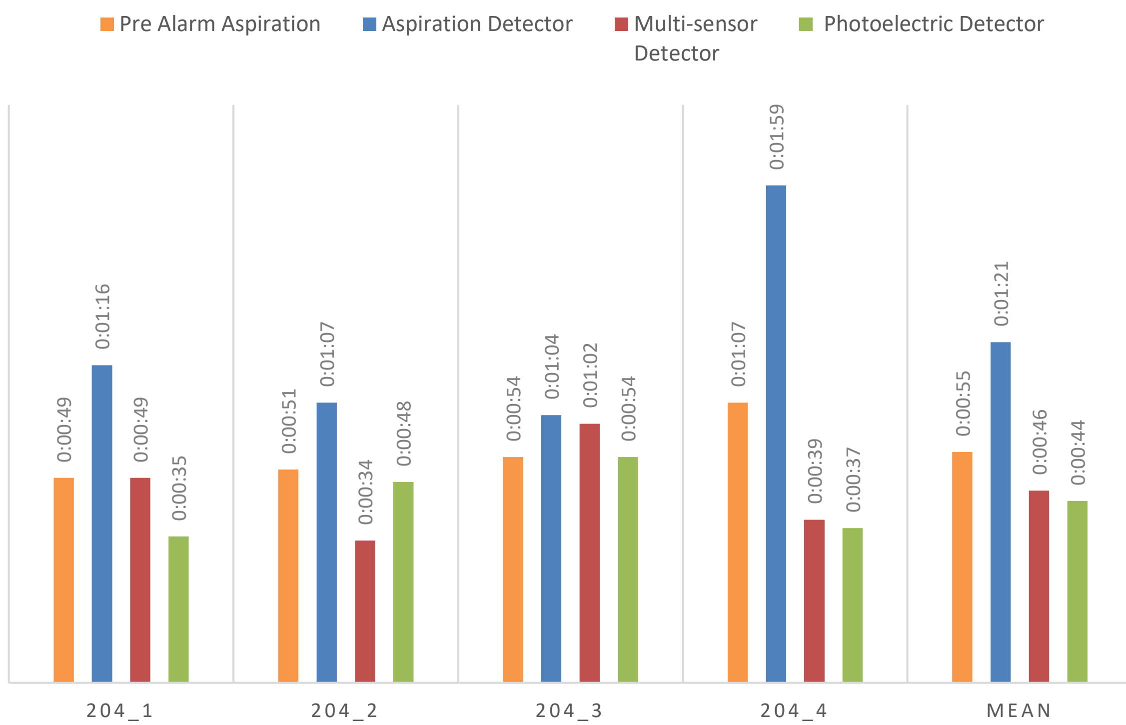


FIGURE 5.12:BURNING HEPTANE FIRE WITH VENTILATION (203 AND 204 WITH EXTENDED SPREAD OF FIRE)



5.4.5 Summary

Figure 5:13 shows; that if all the scenario is considered then the Photoelectric smoke detector has the earliest Mean Activation Time of 4:46 seconds with a coefficient of variation of 21.79%. But in most of the scenarios aspiration detection system was the earliest detection system to respond. As smoldering fire scenarios (especially Fire Scenario 6) took much time just to start ignition, for those tests naturally the average detection time of the aspiration detection system increased significantly. Thus, Figure: 5.14 shows the Mean Activation Times of the detectors without considering glowing cotton fire and slow smoldering cotton fire gives, the earliest detection system to respond in six fire scenario is the aspiration detection system having a Mean Activation Time of 2.19 seconds

FIGURE: 5.13: OVERVIEW OF MEAN ACTIVATION TIME OF DETECTION AND ACTIVATING FIRE EXTINGUISHING SYSTEM

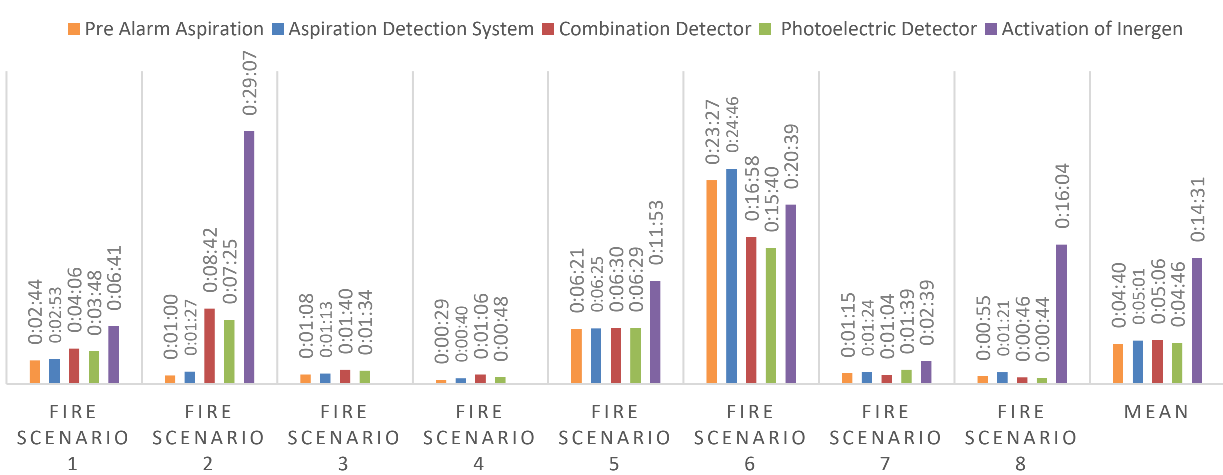
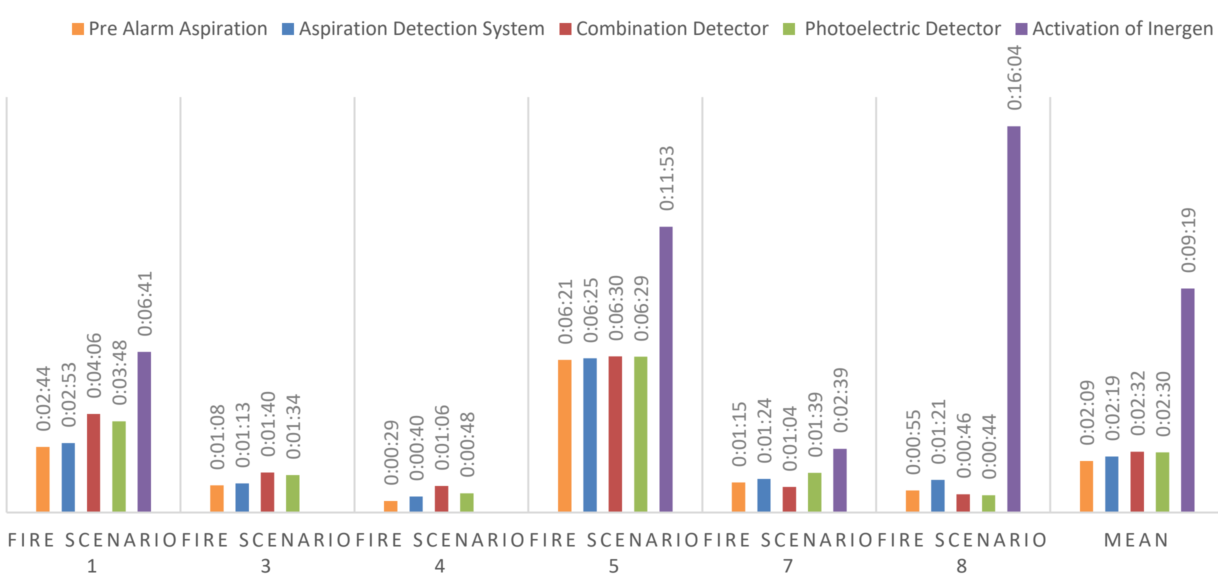


FIGURE: 5.14:OVERVIEW OF MEAN ACTIVATION TIME OF DETECTION AND ACTIVATING FIRE EXTINGUISHING SYSTEM



5.5 Gas concentration overview

The concentration of gas in the living room and bedroom was measured to identify the concentrations; an ROP resident can be exposed to during different fire scenarios. Thus, three toxic gas measurements (CO, CO_2 & low O_2 concentration) are represented in table 5.1.

Table 5-1 lists results from measurements of gas. Values marked in red lie above the limit for ID50. Here CO dose is calculated as the integral of the CO concentration from test start to time for Mean Activation Time (as the activation time for each fire scenario is much lower than the Mean Activation Time) of the alarm and Mean Activation Time extinguishing unit. But for the smoldering fires, the earliest activation time of the smoldering fire has been considered. (102_1 to 102_4 and 202_1 to 202_4). Data shows only in the slow smoldering fire tenability limit exceed duting activation of Smoke and Fire detection unit.

Table 5.10: Measured gas concentrations at 1.7m high from the ground and in boxed detection chamber

Smoldering (Pyrolysis) Wood Fire (With no ventilation)						
	S/L	CO(At the height of (2m)	CO dose [ppm min]	CO dose [ppm min] Aspiration Chamber	Min O2 level(Vol%)	Max CO2 level (Vol%)
At Mean Earliest Activation Time of Detector	101_1	0.00	0.00	0.00	20.90	0.065
	101_2	0.00	0.00	0.00	20.90	0.060
	101_3	0.00	0.00	0.00	20.90	0.060
	101_4	0.00	0.00	0.00	20.90	0.055
During Mean Activation Time of Fire Extinguishing Unit	101_1	30.00	3141.00	1929.00	20.90	0.225
	101_2	42.00	8882.00	3780.00	20.90	0.175
	101_3	24.00	6698.00	3603.00	20.90	0.250
	101_4	100.00	44434.00	13260.00	20.10	0.305
Glowing Smoldering cotton Fire(With no ventilation)						
	S/L	CO(At the height of (2m)	CO dose [ppm min]	CO dose [ppm min] Aspiration Chamber	Min O2 level(Vol%)	Max CO2 level (Vol%)
At Mean Earliest Activation Time of Detector (Considering All Scenario) 00:05:01	102_1	30	6680	374	20.9	0.06
	102_2	24.00	5152.00	129	20.90	0.060
	102_3	20.00	4612.00	1215	20.90	0.085
	102_4	28.00	5951.00	1489	20.90	0.085
During Mean Activation Time of Fire Suppression unit (Considering All Scenario) 00:12:41	102_1	76.00	32740.00	1601	20.90	0.065
	102_2	63.00	21270.00	4718	20.90	0.095
	102_3	31.00	15867.00	4753	20.90	0.075
	102_4	61.00	22375.00	5191	20.90	0.100

Burning Polyurethane(With no ventilation)						
	Test No	CO(At the height of (2m)	CO dose [ppm min]	CO dose [ppm min] Aspiration Chamber	Min O2 level(Vol%)	Max CO2 level (Vol%)
At Mean Earliest Activation Time of Detector	103_1	34.00	1032.00	164.00	20.40	0.440
	103_2	17.00	819.00	196.00	20.90	0.290
	103_3	9.00	250.00	78.00	20.90	0.195
	103_4	8.00	165.00	63.00	20.90	0.170
During Mean Activation Time of Fire Extinguishing Unit	103_1	8.00	9927.00	3850.00	20.90	0.235
	103_2	3.00	3851.00	1485.00	20.90	0.125
	103_3	11.00	5346.00	2410.00	20.90	0.295
	103_4	7.00	3721.00	1312.00	20.90	0.265

Burning Heptane(With no ventilation)						
	Test No	CO(At the height of (2m)	CO dose [ppm min]	CO dose [ppm min] Aspiration Chamber	Min O2 level(Vol%)	Max CO2 level (Vol%)
At Mean Earliest Activation Time of Detector	104_1	19.00	1226.00	286.00	20.40	0.425
	104_2	4.00	223.00	188.00	20.90	0.165
	104_3	4.00	270.00	226.00	20.90	0.155
	104_4	8.00	594.00	250.00	20.90	0.230
During Mean Activation Time of Fire Extinguishing Unit	104_1	15.00	8657.00	4244.00	20.50	0.360
	104_2	13.00	3855.00	2269.00	20.90	0.340
	104_3	13.00	3218.00	2314.00	20.90	0.335
	104_4	13.00	4948.00	4149.00	20.90	0.295

Smoldering Wood Fire with ventilation System								
	Test No	CO(ppm) Bedroom	CO(ppm) Living Room	CO dose [ppm min] Bedroom	CO dose [ppm min] Living Room	CO dose [ppm min] Aspiration Chamber	O_2(Vol%)	CO_2(Vol%)
At Mean Earliest Activation Time of Detector	201_1	0	2	0	147	0	20.90	0.055
	201_2	0	1	0	1	0	20.90	0.055
	201_3	0	1	0	25	0	20.90	0.055
	201_4	0	0	0	0	1	20.90	0.050
During Mean Activation Time of Fire Extinguishing Unit	201_1	2	13	1366	3464	2984	20.90	0.055
	201_2	3	3	528	596	622	20.90	0.055
	201_3	0	2	0	304	0	20.90	0.055
	201_4	7	26	547	1403	5347	20.90	0.050

Slow Smoldering Cotton Fire with Ventilation System

	Test No	CO(ppm) Bedroom	CO(ppm) Living Room	CO dose [ppm min] Bedroom	CO dose [ppm min] Living Room	CO dose [ppm min] Aspiration Chamber	O_2(Vol%)	CO_2(Vol%)
At Mean Earliest Activation Time of Detector	202_1	13.00	18.00	5697.00	6385.00	3	20.90	0.060
	202_2	39.00	146.00	9640.00	42648.00	0	20.90	0.060
	202_3	51.00	214	15967.00	79031	0	209.00	0.065
	202_4	63.00	296.00	23558.00	113348.00	0	20.90	0.060
During Mean Activation Time of Fire Extinguishing Unit	202_1	14.00	18.00	9879.00	11710.00	3219	20.90	0.060
	202_2	64.00	240.00	25470.00	114769.00	2510	20.90	0.050
	202_3	71.00	200.00	34440.00	151342.00	7424	20.90	0.070
	202_4	84.00	344.00	45822.00	203116.00	7526	20.90	0.065

Burning Polyurethane at Bedroom

	Test No	CO(ppm) Bedroom	CO(ppm) Living Room	CO dose [ppm min] Bedroom	CO dose [ppm min] Living Room	CO dose [ppm min] Aspiration Chamber	O_2(Vol%)	CO_2(Vol%)
At Mean Earliest Activation Time of Detector	203_1	56.00	21.00	2226.00	360.00	543.00	19.80	0.950
	203_2	84.00	12.00	3425.00	169.00	1281.00	19.20	1.440
	203_3	82.00	8.00	3356.00	68.00	574.00	19.30	1.420
	203_4	73.00	24.00	3760.00	752.00	204.00	19.60	1.100
During Mean Activation Time of Fire Extinguishing Unit	203_1	54.00	43.00	11268.00	7154.00	6790.00	20.20	0.610
	203_2	3.00	4.00	12837.00	4799.00	4587.00	20.90	0.100
	203_3	4.00	10.00	9928.00	3604.00	5464.00	20.90	0.205
	203_4	7.00	11.00	13151.00	10344.00	11479.00	20.90	0.250

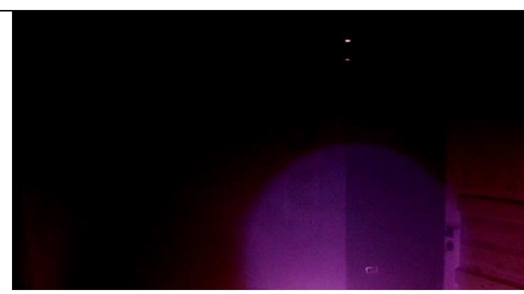
Burning Heptane Fire (203 and 204 with extended spread of Fire)

	Test No	CO(ppm) Bedroom	CO(ppm) Living Room	CO dose [ppm min] Bedroom	CO dose [ppm min] Living Room	CO dose [ppm min] Aspiration Chamber	O_2(Vol%)	CO_2(Vol%)
At Mean Earliest Activation Time of Detector	204_1	8.00	20.00	337.00	1093.00	418.00	20.90	0.390
	204_2	7.00	9.00	342.00	550.00	0.00	20.90	0.215
	204_3	7.00	9.00	276.00	474.00	540.00	20.90	0.220
	204_4	0.00	2.00	0.00	89.00	634.00	20.90	0.050
During Mean Activation Time of Fire Extinguishing Unit	204_1	30.00	38.00	10062.00	14853.00	9851.00	20.00	0.740
	204_2	17.00	16.00	3122.00	4779.00	3273.00	20.40	0.415
	204_3	14.00	13.00	5237.00	5542.00	7540.00	20.90	0.130
	204_4	23.00	31.00	9832.00	14487.00	11040.00	20.10	0.650

5.6 Visibility overview

Table 5.11: Visibility overview during Mean Activation Time of smoke detector and extinguishing unit.

Fire Scenario	Mean Detection time of Smoke Alarm	Mean Detection time of Extinguishing Unit
Smoldering (Pyrolysis) Wood Fire (With no ventilation)		
Glowing Smoldering cotton Fire (With no ventilation)		
Burning Polyurethane (With no ventilation)		
Burning Heptane (With no ventilation)		

Fire Scenario	Mean Detection time of Smoke Alarm	Mean Detection time of Extinguishing Unit
Smoldering Wood Fire with ventilation System		
Slow Smoldering Cotton Fire with Ventilation System		
Burning Polyurethane at Bedroom		
B Burning Heptane Fire (203 and 204 with extended spread of Fire)		

Notes: Images and video by the camera used in second trial of experiment (Fire Scenario 5-8) were much darker than the camera used in first trial. Visually the room were brighter than it seems.

6 Discussion

6.1 Testing of hypotheses

6.1.1 Hypothesis A

The Aspiration detection system equipped with a multi-sensor and a Photoelectric detector will be able to efficiently detect a broad spectrum of fire or smoke with an early time to activation than other smoke detectors. Thereby will give a person a better chance of escaping or being rescued.

The main objective of this study is to find an alternative to the traditional smoke detection system, fulfilling the particular need of ROP residents and overcoming the challenges. It is observed that the aspiration detection system requires few air inlets inside the apartment with minimal visibility. Also, the resident cannot tear it down/damage it.

It is observed to detect a broad spectrum of fire/smoke efficiently. During the first experiment trial (when the ventilation system was not installed), out of 16 tests, 15 tests detected fire earlier than any other detector. During the second trial of the experiment with excessive vent flow, its performance was observed to be significantly affected in terms of early detection. But its detection time was consistent compared to photoelectric and multi-sensor detectors. Thus, out of eight fire scenarios, the average detection time of the aspiration detection system was earlier in six. As shown in Figure 5.13 aspiration detection unit has the lowest mean activation time of 2 minutes 19 seconds, with a coefficient of variation of 18.48%. Even considering all the scenarios aspiration detection unit takes 15 seconds more than the photoelectric detector to detect any fire with minor variation and consistent performance.

Under the condition "Ventilation ON," detecting slow smoldering fire required a much longer time by the aspiration detection system, multi-sensor detector, and photoelectric detector. A possible reason for that may be the position of the test-fire was precisely in front of the ventilation inlet, which may drove relatively cold smoke (due to slow smoldering) to the whole apartment.

Thus, it can be concluded aspiration detection unit provides consistence performance in terms of early and efficient detection (having minimal deviation and variation for each scenario)

6.1.2 Hypothesis B

The multi-sensor detector placed outside the apartment (at the exhaust of the aspiration detection unit) can detect the fire or smoke simultaneously with other detectors.

It is observed from all the tests that; this specific multi-sensor detector activated 17 times out of 33. As it is placed outside the apartment and depends on the exhaust air of the aspiration detection unit, therefore, out of the three-detection sensor it contains, it mainly detects fire based on the CO sensor and merely by the optical sensor.

As the aspiration unit draws air from all the rooms of the apartment, naturally, the density of CO and smoke particles necessary to detect fire by such a multi-sensor detector reduces significantly (as the CO and smoke particles from the origin of fire dilute with the fresh air from the other part of the apartment). This amount may be sufficient for the highly sensitive optical sensor of aspiration detection, but it fails to activate this multi-sensor detector simultaneously. Thus, a large portion of fire remains undetected by this setup.

But interestingly, as the sensitivity of the detector was enabled to react with CO when the concentration reached 40 PPM in the boxed chamber, activation of this multi-sensor detector provided a unique and sensible pattern of activating the extinguishing system.

Because of the fire's growth, smoke particles are evenly distributed throughout the apartment. And fire growth naturally produces more incomplete burns, thus a high concentration of CO. As a result, the exhaust air of the boxed chamber soon reaches the threshold point when this multi-sensor detector activates. And from table 5.10, it is observable that during the mean time of starting the fire extinguishing system, the indoor air quality remains tenable for the occupant but reasonably hazardous. Thus, with the further growth of the fire, this multi-sensor detector activates and simultaneously activates the extinguishing system. But if the fire is controlled or the amount of fuel reduces, the exhaust air in the boxed chamber starts to normalize, and the detector does not trigger. So, ultimately it provides a simple and sensible activation of the extinguishing system based on the indoor concentration of toxic gases and smoke particles.

Thus, it can be concluded that placing a multi-sensor detector outside the apartment to detect fire by avoiding challenges from ROP residents may not be a good and sustainable solution for such housing facilities as it cannot detect almost half of the fire scenario. But placing it in series with aspiration detection units exhaust provides an opportunity to develop intelligent and sensible activation of fire extinguishing system. Thus, it also partially fulfils the goal of Hypothesis C.

As in such an apartment, it is proposed to use an inegen gas extinguishing system, such expensive system (considering cost of gas agent and aftermath of each release) a sensible activation of such system is required. As ROP residents threaten any sensor or detection unit, such remote and reasonable activation can be a possible solution to address this challenge.

6.1.3 Hypothesis C

Before The Aspiration detection system responds to smoke from the fire, the tenability limits for incapacitation from toxic gases and other means shall not exceed. Also, the activation of the fire extinguishing system shall be efficient.

In section 5.5 of this document in Table 5.10, the concentration of toxic gases was measured in the mean avg—time of smoke detection and activation time of the extinguishing system. But in most fire scenarios, the fire was detected much earlier. Thus, to make a "worst-case scenario" assumption, gas concentration was measured for the living room, bedroom, and the boxed chamber for 2 minutes 19 seconds and 9 minutes 21 seconds from the beginning of each experiment. It shows that in six cases, the gas concentration was within the tenability limit (far below the untenable condition).

During a glowing smoldering fire with no ventilation aspiration detector activated within 1:27 seconds, but in the slow smoldering fire with ventilation, avg activation time was 24:46 seconds which indicates a severe threat to the resident. But a series of tests with a proper ventilation system may suggest how the aspiration detection unit performs under such conditions. Elsewise this can detect and provide a person a better chance to egress from the toxic gases.

In table 5.2, for each fire scenario, an overview of visibility has been shown in "Mean detection time of smoke" and "Mean Activation Time of Extinguishing unit." It is observed that during the detection time of smoke, visibility inside the apartment remains within tenability limits. In most cases, detection and activation of the fire extinguishing unit occurred much earlier. Thus, visibility remains within the tenability limit during activation of the aspiration detection unit. Also, when the ventilation system is ON (especially kitchen exhaust), mostly visibility remains within the tenability limit.

But if the fire's origin is in the bedroom or kitchen, the apartment gets much darker and thus exceeds the visibility limit. Also, the tenability limit of visibility rapidly exceeds in cases of extended fire spread. Therefore, it is expected that ROP residents will be able to egress by this detection interval to activate the extinguishing system/spread of fire.

Figure 6.1: Visibility during experiment 204_4 (with an extended spread of fire)

As described in 6.1.2, with the setup of the multi-sensor unit in series with the exhaust of the aspiration detection unit, a sensible and efficient activation of the fire extinguishing system may be possible. Regulation on organizing and dimensioning Norwegian Fire and Rescue Services on section § 4-8 states the requirement of response time, which shall be within 10 minutes for densely populated areas, and 20 minutes for urban settlements. The Mean activation time of this experiment shows the setup may activate the gas extinguishing system in 9 minutes 21 seconds. This provides fire and rescue service a standard frame of time to respond. Otherwise, the inergen system will be activated. Therefore, the fire is expected to be controlled or extinguished even if the response is delayed.

3.7.5 Hypothesis D

The Aspiration detection system shall not be sensitive to cigarette smoke or trigger a false alarm.

Test 205 was dedicatedly conducted to find whether the aspiration detection system is over-sensitive to smoke produced by smoking. In most such dwellings, indoor smoking is one of the main reasons for false alarms. Thus, it also annoys ROP residents, and out of annoyance, they often get rid of detection units. During the experiment, the photoelectric smoke detector was triggered at 5 minutes 4 seconds. But both the aspiration detection unit and multi-sensor detector were observed to be non-responsive to such smoke. After 25 minutes of continuous smoking inside the apartment, aspiration detection units activated the pre-alarm. Thus, in this experiment aspiration detection unit was observed to overcome one of the challenges in such dwellings.

Additionally, excessive smoke during cooking is another cause of false alarms. A similar condition was raised during fire scenario 5 with the ventilation system on. But it is observed that the aspiration detection unit responded only when the indoor air condition worsened by toxic gases. With the small number of gases that cannot be extracted by the exhausted, it remained stable and only activated the pre-alarm.

6.2 Relevant Observation & Suggestion

While performing the test of multiple fire scenarios under different condition

Pre-alarm from Aspiration detection Unit:

Aspiration detection units' pre-alarm feature was far more effective in every test. Thus, it shows the mean time of activating the pre-alarm system for all the tests is only 2:09 seconds. As it is found in some smoldering fires, the fire develops slowly, and in most cases, victims perish even before it becomes flaming. Thus, this pre-alarm system can notify emergency services or voluntary organizations, neighbors, or their relatives; therefore, they can make a short visit or inspection to assess whether there is any chance of real danger in such dwellings.

Detection Principle of Aspiration detection Unit:

Though the aspiration detection unit can detect a broad spectrum of fire, in the case of a slow smoldering fire, it is observed that the system struggles to detect the hazard, especially with the ventilation system on. The data in Table 5.10 shows that during the activation of the aspiration detection system toxicity of apartments air was far above tenability conditions. In those cases, even the multi-sensor detector was activated outside the apartment, but the aspiration detection system was not. So extinguishing system was not activated subsequently. Thus, it shows within the aspiration detection system there is a necessity for up-gradation in terms of sensing fire by measuring CO. It will also ease the logical setup for activating the extinguishing system.

Tenability condition/Toxicity in the Origin of Fire and surroundings:

It is observed that the tenability condition in the origin of the fire or the room the of incident develops dramatically compared to the other room. The data from table 5.9 shows CO concentration in the boxed chamber of the detection unit and other rooms varies significantly compared to the fire's origin but has a good correlation. But this situation fluctuates dramatically by a slight variation in ventilation, openings, and open door/ window condition, significantly affecting the activation of smoke detector and fire extinguishing systems.

6.3 Benchmarking Tested detection system

Considering the ability to overcome the challenges of ROP residents and based on the test result and observation conducted with the aspiration detection unit, multi-sensor detectors, and photoelectric detectors, a simple qualitative and performance-based benchmarking of the following system can be represented as follows.

Here detection efficiency is calculated based on detection ability on tested 32 tests (excluding the smoking scenario). For the false alarm test, 205 was considered. Green marking on the cell represents the best performance against the specific performance criteria, yellow is moderate, and Red is not satisfactory.

Table 6.1: Benchmarking tested detection system based on test performance, features, and ability to meet the particular need of ROP residents.

Performance Criteria	Aspiration Detection	Multi-sensor Detector	Photoelectric Detector
Detection Efficiency	95%	96.87%	100%
Early Detection Rate	43.87%	28.12%	28.12%
Co-efficient of variance (CV%) of overall detection time	18.69%	27.69%	22.38%
Adjustability of sensitivity Range	Yes	No	No
Standard Deviation (mm:sec)	00:00:27	00:01:56	00:01:21
Mean Activation time (Flaming Fire) (mm:sec)	2:19	2:32	2:30
Mean Activation time (Smoldering) (mm: sec)	24:46	12:18	18:24
Early activation counts out of eight fire scenario	4	1	3
False alarm	0	0	1
Remote Maintenance	Yes	No	No
Low visibility to ROP residents	Yes	No	No
Sensible Activation of the Extinguishing system	Yes	Yes	No

Thus, from the performance during this experiment, comparing the features that different smoke detection systems provide (by which challenges, and particular needs of ROP residents shall be addressed), this simple benchmarking shows that, for people at-risk group/ROP residents' aspiration detection system can be a better solution compared to other solution available.

6.4 Outcome of the Studies

Result of the thesis indicates aspiration detection system; which by the features of its installation can overcome several challenges of ROP residents; also can meet their particular needs to fulfil life safety by its early and reliable detection. This study also suggest an alternative way to sensibly activate extinguishing system and also providing fire and rescue service(FRS) a standard frame of time to respond. If response is delays and fire keep developing the extinguishing system will be activated if required. The pre alarm of aspiration unit also can be used to inform care service or neighbous or relevant personnel prior to inform FRS. So this solution may provide a reliable smoke detection solution for ROP resident, thus can be implemented in The ROP project Karmøy.

7 Further Scope of Work

- As this solution is proposed for the ROP residents in Karmøy, whether it is fulfilling the particular needs of ROP residents can be assessed. Also, how they may react to such a system and what new challenges and threats may arise to such a solution by the at-risk group can be studied in the future.
- In this study, a single aspiration detection unit has been tested with a multi-sensor and photoelectric detector. Further study can be carried out by using multiple aspiration detection units from different manufacturers by placing air inlets in other places on apartments' ceilings to quantify their performance. Thus, the effect of ventilation on the aspiration system can be assessed by such a study.
- Detecting slowly increasing concentrations of CO and other toxic gases under ventilation was a challenging part of this work. Further development in such detection systems can be done with an integrated and dedicated sensory system for CO detection. Then it will be more viable and accessible to activate the fire extinguishing system sensibly.
- How the aspiration detection system can address the fire from the control panel can be studied.
- Performance of aspiration detection system for various smoldering fires can be studied further to find the best possible solution to detect smoldering fire by this detector at an early stage.

8 Conclusion

- Aspiration detection unit can detect a broad range of fire and smoke scenarios reliably and efficiently compared to multi-sensor and photoelectric detectors. The aspiration system's detection time is more consistent and has the slightest variation for similar fire scenarios compared to other detectors.
- In terms of early detection, the aspiration detection system, in most cases (Almost 50%), detected fire earlier than multi-sensor and photoelectric detectors. The sensitivity range can be adjusted for further early activation in most cases.
- Aspiration detection system can detect smoke and assist activation of fire extinguishing system before the tenability limit exceeds in most flaming and smoldering fire scenarios.
- Aspiration detection system can be installed with minimum visibility in the dwellings, thus fulfilling the particular need of at-risk group/ ROP residents. Also, it requires less maintenance inside the apartment.
- Both aspiration detection systems and multi-sensor detectors are less sensitive to cigarette and excessive cooking smoke. Therefore, it may create fewer False alarms than traditionally used photoelectric detectors.
- Fire detection by installing a multi-sensor detector outside the apartment by feeding with air from the apartment does not provide a satisfactory outcome. But connecting it with an aspiration detection unit can sensibly activate the fire extinguishing system. Also, it provides Fire and Rescue services a standard frame of time to respond for ensuring life safety of victim.
- In case of fire spread extinguishing system is activated within shortest required time by the combination of multi-sensor and aspiration detection unit.
- Ventilation system significantly affects aspiration detection system and delays its detection time. But still, it can detect within the tenability limit.
- In the case of a slow smoldering fire, the aspiration detection units' performance is less satisfactory compared to multi-sensor and photoelectric detectors.
- Pre-alarm feature of the aspiration detection system can initiate precautionary measurement by people in at-risk groups or by the neighbour, relatives, care services, voluntary organizations, security and emergency services.

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10 Appendix

This appendix gives the pictorial overview of the experimental setup

Figure A1: Overview of Apartment

Figure A2: Aspiration detection air inlet and Smoke Detectors in Livingroom

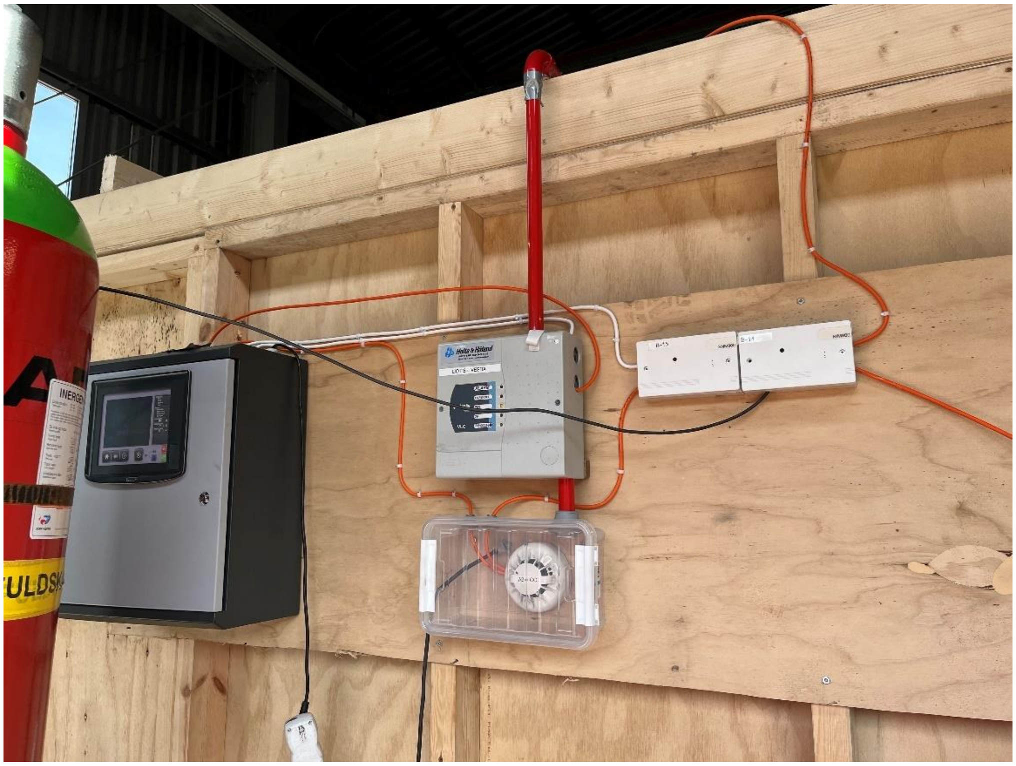

Figure A3: Boxed chamber of multi-sensor detector at the exhaust of aspiration detection Unit

Figure A4:Indoor setup showing visibility marking posters

Figure A5: Bedroom of apartment showing thermocouple stack-3, smoke detectors and volunteer participant during test with activation of inergen gas extinguishing system

Figure A6: Testing further development of fire (Test Number 204_4)

Figure A7: Inergen gas extinguishing system with Alarm control panel, Aspiration detection unit and Boxed chamber for multi-sensor detector

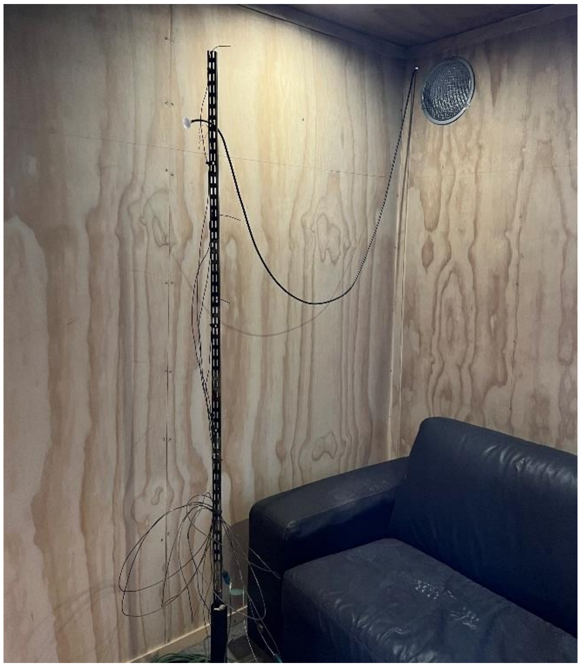

Figure A8: Thermocouple Stack (Living Room)

Figure A9: Aspiration Detection Unit and control panel

Figure A10: Ventilation System of test apartment

A11: Dräger X-am 8000 gas Detector and air sample inlet inside apartment