RESPIRATORY HEALTH EFFECTS OF
OCCUPATIONAL EXPOSURE TO BUSHFIRE SMOKE
IN WESTERN AUSTRALIA

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MPH, RN, IC Cert.

This thesis is presented for the degree of Doctor of Philosophy of
The University of Western Australia
School of Population Health

2008
DECLARATION FOR THESE CONTAINING PUBLISHED WORK
AND/OR WORK PREPARED FOR PUBLICATION

This thesis contains published work and/or work prepared for publication, some of which has been co-authored. The bibliographical details of the work and where it appears in the thesis are outlined below.


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The full paper is attached in Appendix 6. Some sections of the paper have been adapted and included in Chapter 4 of the thesis. All the adapted material from the paper included in the thesis was originally written by me.

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Summary

Bushfires are an integral part of the Australian environment, and consequently Australian fire fighters are regularly confronted with the challenge of bushfire fighting activities. Bushfires can be extensive and long-lasting, and as a result fire fighters can be exposed to bushfire smoke for long periods without respite.

Anecdotal evidence suggests that bushfire smoke exposure can lead to respiratory symptoms such as coughing, wheezing, and shortness of breath. In an optimal environment, fire fighters are equipped with respirators and protective filters to prevent the inhalation of the air toxics in bushfire smoke. Yet, reports from the fire ground indicate that the protective filters are not effective in preventing the inhalation of bushfire smoke. As a result, fire fighters have increasingly expressed concern about the ineffective equipment and the resultant respiratory symptoms during and after bushfire fighting.

This research aims to establish a scientific data base to support the anecdotal evidence. The objectives of the research were: (1) to identify and quantify the air toxics in Western Australian bushfire smoke; (2) to profile the acute respiratory health effects associated with bushfire smoke exposure; (3) to assess the effectiveness of three different types of filters under controlled conditions in a smoke chamber, and in the field during fuel reduction burn-off; (4) to formulate recommendations for reducing fire fighters’ exposure to bushfire smoke; and (5) to inform policy decision makers about the most effective form of respiratory protective equipment for bushfire fighting.

Exposure trials were conducted in an experimental setting utilising bushfire smoke conditions in a smoke chamber and during prescribed burn-offs. Repeated measurements of respiratory symptoms, pulmonary function and oximetry were undertaken before and after bushfire smoke exposure. In addition, personal air sampling inside the respirators was undertaken to quantify and compare the levels of filtered air toxics. The analysis of the collected data demonstrated that, of those compared, the particulate/organic vapour formaldehyde filter was most effective in protecting fire fighters’ respiratory health during the smoke exposure period of maximally 120 minutes. Further research would be useful to determine the
effectiveness of the filters under more realistic conditions during bushfire fighting activities.

The findings of this research have resulted in a policy review in Western Australia. In 2006, the Fire and Emergency Services Authority of Western Australia (FESA) reviewed its *Bush Fire Smoke Exposure Standard Operational Procedures S1*, and now issues the recommended particulate/organic vapour/formaldehyde filters to the 1,000 FESA career fire fighters.

The use of protective equipment for bushfire fighters is inadequately regulated worldwide and the recommendation implemented by FESA can be seen as proactive and in advance of national and international best practice.

In conclusion, this project was instrumental in the translation of public health research into best practice that protects occupational health, without the need for the lengthy process of legislative reform. Fire fighter organisations in other countries with high frequencies of bushfires could learn from this example, and move to review their policies and introduce adequate personal protection for fire fighters.
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Acknowledgements

In 2004 I rang Professor Philip Weinstein to ask him ‘what the options were for PhD research’ in the School of Population Health at The University of Western Australia. This phone call would be the start of a remarkable journey. Following Phil’s advice I embarked on the PhD project, not sure whether I had the capacity and the discipline to fulfil the requirements of this enterprise.

Throughout these four years I managed the research project and became more comfortable with my role as a PhD candidate. The exposure trials in the smoke chamber in Forrestfield and in the field near Yanchep during some scorching hot days in 2004 and 2005 were a memorable experience. This and various other challenges along the way have now resulted in the completion of this PhD thesis.

I wish to thank my supervisors Professor Philip Weinstein, Dr Angus Cook and Mr Brian Devine for their support, encouragement, and feedback throughout the course of the project. Particular thanks to Phil for his wise thoughts, enthusiasm, and encouragement; to Angus for his invaluable statistical and epidemiological expertise; and last but not least to Brian for helping me with his boundless energy during the exposure trials in the smoke chamber and during the prescribed burns. It was an unforgettable and rewarding experience in many ways.

I would also like to thank the following staff and students of the School of Population Health for their support and friendship: Sarah Joyce, Yih Pyng Lee, Kim Chisholm, Andrew Jardine, Clemencia Rodriguez, Fiona Maley, and Karin Ljung.

I am grateful for the contribution of the Fire and Emergency Services Authority of Western Australia. In particular, I would like to thank Russell Stevens, Ralph Smith, Dave Wright, Leah Parlour, Barry Jenkins and John Chatfield for their invaluable support and feedback during the numerous meetings we had. I also want to acknowledge the 131 FESA career fire fighters, who served with distinction as volunteer subjects in the exposure trials at Forrestfield and Yanchep.

Thanks to the staff of the Department of Environment and Conservation Western Australia, in particular Rick Sneeuwjagt, who challenged me on many occasions with his view on the project. Also thanks to Mike Cantelo and Brian Inglis, who
scheduled the prescribed burns to facilitate the field validation trials. I am also thankful to Leigh Sage for providing comprehensive data about vegetation types, predicted weather conditions, and fire behaviour.

I would like to acknowledge the contribution to the project from the Chemistry Centre Western Australia, in particular Steve Wilkinson, Dave Fleming, John Genovese, and Lincoln Morton.

Thanks to the Bushfire Cooperative Research Centre, Melbourne for their support during the last four years. I am also grateful for providing me the opportunity to attend the annual Bushfire CRC/AFAC conferences, and present the progress of the project.

Special thanks to Robyn and Marty Melican who let me stay in their house in Bullsbrook by way of a writing retreat. In this week I managed to finish the last chapter of the thesis. I also wish to thank the following family and friends for their encouragement, love and support along the way: Janny and Cees Vandenberg, Willemina Curtis, Sandra Hayward, Jane Hamilton, Kathy Johnson and Wietske Bouma.

And finally I would like to thank Anne and Sara for putting up with a mother who was determined to undertake a PhD. You are the sunshine of my life……
Abbreviations and Acronyms

AARI  Asthma and Allergy Research Institute

ACGIH  American Conference of Governmental Industrial Hygienists

APR  Air-purifying respirator

AS  Australian Standards

ASCC  Australian Safety and Compensation Council

AS/NZS  Australian Standards/New Zealand Standards

ATS  American Thoracic Society

BTPS  Body temperature and barometric pressure

CALM  Department of Conservation and Land Management

CCWA  Chemistry Centre Western Australia

CFR  Code of Federal Regulations

CFS  Country Fire Service

CIIT  Chemical Industry Institute of Toxicology

CO  Carbon monoxide

CRC  Cooperative Research Centre

CSIRO  Commonwealth Scientific and Industrial Research Organisation

DEC  Department of Environment and Conservation

DSE  Department of Sustainability and Environment

EEC  European Economic Community

ESLI  End-of-service-life indicator

FDI  Fire danger index

FEF_{25-75}  Forced expired flow over the middle half of the FVC manoeuvre

FESA  Fire and Emergency Services Authority of Western Australia

FEV\textsubscript{1}  Forced expiratory volume in one second

FVC  Forced vital capacity

HPLC  High performance liquid chromatography

IARC  International Agency for Research on Cancer

ISO  International Organization for Standardization

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1 In 2006 renamed in Lung Institute of Western Australia (LIWA).

2 In 2006 renamed in Department of Environment and Conservation (DEC).
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<td>LIWA</td>
<td>Lung Institute of Western Australia</td>
</tr>
<tr>
<td>Mg/m³</td>
<td>Milligrams per cubic metre</td>
</tr>
<tr>
<td>NATA</td>
<td>National Association of Testing Authorities</td>
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<td>NFPA</td>
<td>National Fire Protection Association</td>
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<td>NICNAS</td>
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<td>NIST</td>
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<td>National Occupational Health and Safety Commission</td>
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<tr>
<td>NSWFB</td>
<td>New South Wales Fire Brigades</td>
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<tr>
<td>OHS</td>
<td>Occupational Health and Safety</td>
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<tr>
<td>OSHA</td>
<td>Occupational Safety and Health Administration</td>
</tr>
<tr>
<td>OR</td>
<td>Odds ratio</td>
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<tr>
<td>PM</td>
<td>Particulate matter</td>
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<td>PPE</td>
<td>Personal protective equipment</td>
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<td>PPM</td>
<td>Parts per million, equivalent to mg/kg in water</td>
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<tr>
<td>PAH</td>
<td>Polycyclic aromatic hydrocarbon</td>
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<tr>
<td>SaO₂</td>
<td>Arterial oxygen saturation</td>
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<td>SCBA</td>
<td>Self-contained breathing apparatus</td>
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<tr>
<td>SMC</td>
<td>Surface moisture content</td>
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<tr>
<td>SOP</td>
<td>Standard operational procedures</td>
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<tr>
<td>SPSS</td>
<td>Statistical Package for Social Sciences</td>
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<tr>
<td>STEL</td>
<td>Short term exposure limit</td>
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<tr>
<td>TLV</td>
<td>Threshold limit value</td>
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<tr>
<td>TWA</td>
<td>Time weighted average</td>
</tr>
<tr>
<td>USA</td>
<td>United States of America</td>
</tr>
<tr>
<td>USDAFS</td>
<td>United States of America Department of Agriculture and Forest Service</td>
</tr>
<tr>
<td>UWA</td>
<td>The University of Western Australia</td>
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<tr>
<td>VOC</td>
<td>Volatile organic compound</td>
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<td>µg</td>
<td>Microgram</td>
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<td>µm</td>
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Glossary

**Acute effects:** Effects that occur rapidly after exposure and are of short duration.

**Air purifying respirator:** Respirator with an air purifying element to remove specific air contaminants.

**Air supplying respirator:** A respirator that supplies the user with air from a source independent of the ambient atmosphere, and includes the self-contained breathing apparatus.

**Breakthrough:** Penetration of challenge material(s) through a gas or a vapour air-purifying element. The quantity or extent of breakthrough during service life testing is often referred to as the percentage of the input concentration.

**Carcinogen:** An agent - physical, chemical or biological - that can act on living tissue to cause cancer.

**Cartridge:** Small container filled with air-purifying media.

**Chronic effects:** Effects that develop slowly and have long duration. They are often, but not always, irreversible. Some chronic effects appear a long time (several years) after exposure.

**Dust:** Mechanically produced solid particle.

**End-of-service-life indicator:** A system that warns the wearer of a respirator of the end of adequate protection (e.g. the sorbent is approaching saturation or is no longer effective).

**Face piece:** Portion of a respirator that covers the wearer’s nose, mouth, and/or eyes. Designed to make a gas-tight or dust-tight fit with the face, it includes the headbands, exhalation valve(s), and connections for an air-purifying device.

**Filter:** A medium used in respirators to remove solid or liquid particles from the air stream entering the respiratory enclosure.

**Fit-test:** The use of a protocol to qualitatively or quantitatively evaluate the fit of a respirator on an individual.

**Forced expiratory volume in one second (FEV_{1}):** Volume of air that can be forcibly expelled during the first second of expiration.

**Forced vital capacity (FVC):** Maximal volume of air that can be exhaled forcefully after a maximal inspiration.

**Fume:** Solid airborne particles generated by condensation from the gaseous state, generally after volatilisation from a melted substance (e.g. welding).
Gas: A substance that is in the gaseous state at room temperature and pressure.

Initial attack wildfires: Fires that were successfully controlled by initial attack forces.

Mop-up: Fire fighting technique, which consists of the use of hand tools, chain saws, soil, and water to completely extinguish the fire. Mop-up activities include digging up smouldering stumps, roots, mineral soil, and felling burning dead trees or branches.

Overhaul: Fire fighting stage in which the suppression is complete and fire fighters are searching the structure for hidden fires or embers.

Oxygen deficiency: A sea-level (partial pressure of less than 148 millimetres of mercury) concentration of oxygen in the ambient air of less than 19.5 percent by volume.

Particulate matter: A suspension of fine solid or liquid particles in air, such as dust, fog, fume, mist, smoke or sprays. Particulate matter suspended in air is commonly known as an aerosol.

Project wildland fires: Eight multi-day wildland fires (United States).

Pulmonary function test: Tests requiring use of an approved spirometer including FVC and FEV₁.

Respirator: A device designed to protect the wearer from inhalation of harmful atmospheres.

Self-contained breathing apparatus: A respirator designed to provide the wearer with clean air independent of the contaminated surrounding air. The wearer carries a supply of approved compressed air contained in a gas cylinder.

Service Life: The length of time during which, a respirator, filter, sorbent, or other respiratory equipment provides adequate protection to the wearer.

Smoke: Aerosols, gases, and vapours resulting from incomplete combustion.

Sorbent: A material contained in air-purifying respirators that removes toxic gases and vapours from the inhaled air.

Threshold limit value: A list published yearly by the American Conference of Governmental Industrial Hygienists as a guide for exposure concentrations that a healthy individual normally can tolerate for eight hours a day, five days a week, without harmful effects.

Short term exposure limit: Concentration to which workers can be exposed continuously for a short period without suffering from adverse effects. Exposures
should not be longer than 15 minutes and should not occur more than four times per day. There should be at least 60 minutes between successive exposures in this range.

**Time weighted average:** The concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.

**Vapour:** Gaseous state of a substance that is solid or liquid at room temperature and pressure.
Chapter 1 Introduction

1.1 Background

For the past ten years, career fire fighters in Western Australia have expressed their concern about respiratory health effects after inhaling smoke during bushfire fighting. Anecdotal evidence of this problem was supported by a report presented to the Fire and Emergency Services Authority of Western Australia (FESA) (2001). Although fire fighters were issued with respiratory protective equipment for use during bushfire fighting, it was noted that respiratory health symptoms, including coughing and wheezing were common during and sometimes even weeks after bushfire fighting activities.

The overarching aims of this research are to systematically assess and report on the respiratory health effects in fire fighters during and after bushfire smoke exposure. Investigating this issue is vital, given that a scientific database is necessary to assist in the development of policies regarding the use of the most appropriate and effective respiratory protective equipment during bushfire fighting. The objectives of the research are:

- To identify and quantify the air toxics in Western Australian bushfire smoke;
- To profile the acute respiratory health effects associated with bushfire smoke exposure;
- To assess the effectiveness of three different types of filters under controlled conditions in a smoke chamber, and in the field during fuel reduction burn-off;
- To formulate recommendations for reducing fire fighters’ exposure to bushfire smoke; and
- To inform policy decision makers about the most effective form of respiratory protective equipment for bushfire fighting.

In 2004, the Bushfire Cooperative Research Centre (CRC) commissioned the School of Population Health, The University of Western Australia to conduct the project ‘Respiratory Health of Fire Fighters’. In collaboration with FESA and the then Asthma and Allergy Research Institute (AARI), the project was undertaken in 2004
- 2006. The findings and recommendations were presented in a report ‘Respiratory Health of Fire Fighters - Bushfire CRC Project D4 – Final Report’ (De Vos et al. 2006) to FESA and the Bushfire CRC.

Figure 1.1 outlines the framework for the research.

**Figure 1.1 Research Framework**

- **Occupational health problem**
  - Concerns/outrage amongst Western Australian career fire fighters about respiratory health symptoms after bushfire fighting

- **Lack of scientific evidence base**

- **2004 Collaboration between:**
  - Bushfire Cooperative Research Centre
  - Fire and Emergency Services of Western Australia
  - Asthma and Allergy Research Institute
  - School of Population Health - The University of Western Australia

- **PhD Research:**
  - Literature Review
  - Proposal Writing
  - Proposal Presentation
  - **Thesis Writing:**
    - Literature Review
    - Air Toxics
    - Filter Study
    - Evaluation
    - Legislation/Policy Development
  - Thesis Completion/Submission

- **Bushfire CRC Project D4 Respiratory Health of Fire Fighters**
  - 2004 Filter Study - Exposure trials in smoke chamber
  - 2005 Based on preliminary findings FESA provides the option for career fire fighters to using the P/OV/F filter pending finalisation of the study
  - 2005 Filter Study - Exposure trials during prescribed burns (Field Validation)
  - 2006 Presentation of ‘Respiratory Health of Fire Fighters - Bushfire CRC Project D4 – Final Report’

- **Post bushfire season 2006-2007**
  - Cross-sectional survey evaluating the perceived performance of the P/OV/F filters

- **Bushfire season 2006-2007**
  - FESA adopts the recommendation of the report and amend the Standard Operational Procedures 51. As a result FESA’s 1,000 career fire fighters are now issued with the recommended P/OV/F filters for use during bushfire fighting
1.2 Dissertation Overview

This research dissertation is organised in seven chapters. The following chapters each deal with a key component of this research.

Chapter 2 introduces the domain and the scope of the research. It highlights the significance of the research problem in terms of its relevance to increasing trends in bushfire frequency and intensity, and subsequent potential health problems for fire fighters. The chapter builds upon a review of the literature and discusses the research that has been undertaken in this field, predominantly in the United States. The apparent lack of Australian occupational health data in regard to bushfire smoke exposure indicates the importance of this research.

Chapter 3 presents the major air toxics in bushfire smoke and the associated health effects in the occupational context. Although bushfire smoke contains hundreds of individual compounds, formaldehyde, acrolein, particulate matter (PM) and carbon monoxide (CO) are the main health hazards for fire fighters. The chapter describes the experimental burns and air toxics sampling from bushfire smoke in a smoke chamber and in field experiments. The sampling was undertaken to identify and quantify bushfire smoke components in a systematic way for the first time in Western Australia.

Chapter 4 outlines the ‘Filter Study’. This study was undertaken to investigate the effectiveness of the commonly issued Class 2 particulate filters for use during bushfire fighting. The study compared this Class 2 particulate filter to two other types of filters during bushfire smoke exposure trials in a smoke chamber and in the field during prescribed burn-offs. The measured end-points were respiratory symptoms and pulmonary function. In August 2006, the findings and recommendations of this study were presented in a report to FESA. Following the recommendations, FESA amended its Bush Fire Smoke Exposure Standard Operational Procedures 51 (SOP 51), and issued the P/OV/F filters to the 1,000 FESA career fire fighters.

Chapter 5 presents the evaluation of the use and effectiveness of the recommended P/OV/F filter after the filters had been deployed for use by the fire fighters for one
bushfire season. The methodology and findings of this small-scale cross-sectional survey are presented in this chapter.

Chapter 6 reviews legislation and policy frameworks, which form the base for occupational health and safety decisions and recommendations. The review focuses on national and international legislation and policy, particularly in countries that frequently encounter bushfires. Recommendations for best practice are formulated, aimed at appropriate and effective use of respirators and minimisation of exposure to air toxics in bushfire smoke.

From a public health perspective it is rewarding to note that the recommendations from scientific research are readily translated into policy changes. One of the reasons for this success is likely to be the strong collaboration between the Respiratory Health Steering Committee, comprising of FESA managers, Occupational Health and Safety Officer, and FESA career fire fighters, and the researchers during the project.
Chapter 2 Literature Review

2.1 Introduction

Bushfires are naturally occurring events across the Australian continent. Due to climatic variation across the nation’s vast land mass, at any time of the year some part of Australia experiences bushfire events. The likelihood of a significant increase in fire risk in Australia resulting from future climate change is very high (Pitman, Narisma & McAneney 2007). As a consequence, Australia’s fire fighters will be more frequently and intensively exposed to bushfire smoke in the future.

Within the fire fighting community, concerns have been raised about the inhalation of bushfire smoke, and the associated effects on the respiratory health of fire fighters. Anecdotal evidence suggested that the current respiratory equipment issued to the FESA career fire fighters in Western Australia could be improved. A scientific base was needed to provide recommendations for the improvement of best practice procedures.

This chapter provides the conceptual perspective for this thesis, and introduces and explores the scope of the issues, which will be presented later. The emphasis of the literature review is on the significance of bushfires in Australia, fire fighters’ exposure to air toxics in bushfire smoke, respiratory health effects resulting from such exposures, as well as the preventative measures to reduce the expanding resultant morbidity.

2.2 Historical Perspective

For more than 40,000 years, Aboriginal people have used fire for a variety of purposes, including signalling, game hunting, cooking, tree felling, illumination, and clearing the land to stimulate re-growth of native grasses (Singh & Geissler 1985). The journals of early navigators contain many references to the sighting of smoke along the Australian coastline. In the Geelvinck, a ship’s log from Willem De Vlamingh’s Dutch expedition to Terra Australis (1696-1697), Rottnest Island is referred to as Mist Eiland (Fog Island). It is suggested that the island came into view through a haze of smoke blown from the mainland, where many bushfires, lit by the Aborigines, were then burning (Playford 1998). In 1699, William Dampier recorded similar observations in his journals (Figure 2.1).
The consistent observation of the first explorers was of open forests and woodlands with grassy understorey, with an impression of an annual conflagration during the fire season. In May 1770, Captain James Cook described the vegetation and country on Botany Bay’s southern shore as:

"The moors looked like our moors in England and as no trees grew upon it but everything is covered with a thin brush of plants about as high as the knees" (Banks 1770).

This description fits with vegetation which is burnt annually, or in the case of heathlands, every two or three years (Cheney 1995). These observations were repeated by
other explorers, who referred frequently to fires smouldering or raging, according to the nature of the season or the fuel conditions.

During the 19th century, Australia underwent a process of sparse settlement, largely through use of axes and fire sticks to carve small farms out of the bush. Despite the general view that European settlement increased the frequency of bushfires in Australia, it is clear from historical evidence that as settlement increased, fire frequency decreased. However, as fire frequency decreased, the fuels built up, and thus fires that did occur they were more intense than those under the Aboriginal annual burning regime. Environmental conditions for widespread bushfires become more common (Luke & McArthur 1978).

### 2.3 Occurrence and Extent of Bushfires in Australia

Bushfires occur throughout Australia, although they may be very infrequent in some climatic zones, such as those dominated by rainforest or wet eucalypt forest ecosystems. In any given year the greatest extent of bushfires is in the savannas of northern Australia, and in the south-eastern corner of the continent, south of a line from Sydney to Adelaide. This is partially caused by the fact that the most severe fire weather conditions generally occurs in this part of the country. In addition to this climatic influence, the south eastern areas of mainland Australia, Tasmania, and the south western corner of Western Australia produce the tallest forests and heavy fuel loads. These fuel loads can produce the most intense and devastating bushfires, when these usually wet forests dry out.

Given the climatic variation across the continent, the seasons, in which bushfires are most likely to occur, vary in different parts of Australia (Figure 2.2). In south-eastern Australia (including Tasmania) the major fire season is summer and early autumn; in coastal New South Wales and southern Queensland, spring and early summer; and in much of northern Australia, winter and spring. In the arid zones of Australia large fires most commonly occur in the months following an abnormally wet season, when there is enough vegetation to provide fuel.
Since the middle of the 19th century, the Australian Bureau of Statistics, Emergency Management Australia, and various other government departments have recorded bushfire events. A number of data sets have been generated with different parameters, such as areas burnt, stock lost, and fatalities. Table 2.1 has been compiled to provide an overview of the major bushfires in Australia from 1851 to 2007. The data shows the impact on the Australian people, not only because of damage to native vegetation, but the huge loss of property and significant loss of life at a bushfire event.
Table 2.1 Major Bushfires in Australia

<table>
<thead>
<tr>
<th>Year</th>
<th>State</th>
<th>Location</th>
<th>Areas burnt (ha)</th>
<th>Stock lost (n)</th>
<th>Houses destroyed (n)</th>
<th>Property damaged ($)</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1851</td>
<td>Victoria</td>
<td>Throughout Victoria – ‘Black Thursday’</td>
<td>5,000,000</td>
<td>1,000,000</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>1898</td>
<td>Victoria</td>
<td>Throughout Victoria – ‘Red Tuesday’</td>
<td>260,000</td>
<td></td>
<td>2,000</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>1919</td>
<td>Victoria</td>
<td>Otway Ranges</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>1926</td>
<td>Victoria</td>
<td>Gippsland, Dandenong</td>
<td></td>
<td></td>
<td>Widespread damage to farms, homes, and forest</td>
<td></td>
<td>91</td>
</tr>
<tr>
<td>1939</td>
<td>Victoria</td>
<td>Throughout Victoria – ‘Black Friday’</td>
<td>Up to 2,000,000</td>
<td></td>
<td>1,000</td>
<td></td>
<td>71</td>
</tr>
<tr>
<td>1939</td>
<td>New South Wales</td>
<td>Multiple regions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>1943</td>
<td>Victoria</td>
<td>Multiple regions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>51</td>
</tr>
<tr>
<td>1961</td>
<td>Western Australia</td>
<td>Dwellingup</td>
<td>145,000</td>
<td>0</td>
<td>132</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>1964</td>
<td>Victoria</td>
<td>Dandenong Ranges</td>
<td>2,000</td>
<td></td>
<td>454</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>1967</td>
<td>Tasmania</td>
<td>Around Hobart – ‘Black Tuesday’</td>
<td>264,000</td>
<td>0</td>
<td>1,700</td>
<td>$101,000,000</td>
<td>61</td>
</tr>
<tr>
<td>1968</td>
<td>New South Wales</td>
<td>Sydney, Blue Mountains, Illawarra</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>1974-</td>
<td>Northern Territory</td>
<td>Central Australia</td>
<td>117,000,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>Victoria</td>
<td>Throughout Victoria – ‘Ash Wednesday’</td>
<td>210,000</td>
<td>27,000</td>
<td>2,080</td>
<td></td>
<td>47</td>
</tr>
<tr>
<td>1983</td>
<td>South Australia</td>
<td>Throughout South Australia – ‘Ash Wednesday’</td>
<td>160,000</td>
<td></td>
<td>383</td>
<td>$200,000,000</td>
<td>28</td>
</tr>
<tr>
<td>1984-</td>
<td>New South Wales</td>
<td>Throughout New South Wales</td>
<td>3,500,000</td>
<td>40,000</td>
<td></td>
<td>$40,000,000</td>
<td>4</td>
</tr>
<tr>
<td>1985</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1993-</td>
<td>New South Wales</td>
<td>Throughout New South Wales</td>
<td>800,000</td>
<td></td>
<td>287</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>1994</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>South Australia</td>
<td>Adelaide Hills</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>1997</td>
<td>Victoria</td>
<td>Dandenong and Wilson’s Promontory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>Victoria</td>
<td>Alpine National Park/Carey River State Forest, Victoria</td>
<td>32,000</td>
<td>0</td>
<td>0</td>
<td>$0</td>
<td>0</td>
</tr>
<tr>
<td>2002</td>
<td>Victoria</td>
<td>Big Desert Wilderness Park/Wyperfield National Park, Victoria</td>
<td>181,400</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2001-</td>
<td>New South Wales</td>
<td>Multiple regions</td>
<td>1,465,000</td>
<td>3,400</td>
<td>86</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>2002</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>Northern Territory</td>
<td>Throughout the State</td>
<td>15,000,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>Victoria</td>
<td>Mt Buffalo, Bright, Dinner Plain,</td>
<td>1,300,000</td>
<td>11,000</td>
<td>41</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Year</td>
<td>Location</td>
<td>Area</td>
<td>Incidence</td>
<td>Severity</td>
<td>Notes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------</td>
<td>-------------------------------</td>
<td>-----------</td>
<td>----------</td>
<td>-------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>Tasmania</td>
<td>Benambra and Omeo, Victoria</td>
<td>52,000</td>
<td>0</td>
<td>Minor</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2002-2003</td>
<td>Western Australia</td>
<td>Southern half of Western Australia</td>
<td>20,000</td>
<td>3,000</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>Australian Capital Territory</td>
<td>Canberra</td>
<td>1,000,000</td>
<td>400</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>South Australia</td>
<td>Eyre Peninsula</td>
<td></td>
<td></td>
<td></td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>2005-2006</td>
<td>Victoria</td>
<td>Melbourne, Mount Gambier,</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Warmambool, Wilson's Promontory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Victoria/New South Wales</td>
<td>Multiple regions</td>
<td>&gt; 1,000,000</td>
<td>40</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Western Australia</td>
<td>Dwellingup, Coolup</td>
<td>13,000</td>
<td>14</td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
In 1960 - 1961, Western Australia experienced serious bushfires near Dwellingup during which 145,000 hectares of forest were burnt. There were no fatalities, but 800 people were left homeless (Luke & McArthur 1978). The 2002-2003 bushfire season in the southern half of Western Australia has been described as the one of the most severe since the Dwellingup fires. A total of 656 wildfires burnt 2.11 million hectares of land managed by the Department of Conservation and Land Management (CALM) (Department of Conservation and Land Management 2005; Department of Conservation and Land Management 2003). More recently, for two weeks in January and February 2007, intense bushfires burnt 13,000 hectares of forest between Dwellingup and Coolup and south of the Murray River in Western Australia. Over 700 staff from the Department of Environment and Conservation (DEC) and the Forest Products Commission were involved in containing the fires. Although 14 homes were destroyed and three were damaged, fire crews saved many more homes and properties than were lost (Higgs 2007).

Victoria has experienced the most devastating fires in Australian history. In 1851, the 'Black Thursday' fires burnt approximately five million hectares and killed more than one million sheep, thousands of cattle as well as taking the lives of 12 people. The greatest devastation occurred on ‘Black Friday’ in 1939, when fires burned in almost every part of the State. Townships were destroyed and others badly damaged, and it has been reported that so much ash and smoke was generated that ash fell as far away as New Zealand (Department of Primary Industries 2004). The ‘Ash Wednesday’ fires of 16 February 1983 are Australia’s most well-known bushfire event of recent times. These fires caused severe damage in Victoria and South Australia, and resulted in 75 fatalities. Nearly 400,000 hectares of land were burnt, and property damage was estimated approximately $200 million (Department of Sustainability and Environment 2006a).

The 2002-2003 fire season, extending from May 2002 in northern Australia to April 2003 in southern and western Australia, was the most severe fire season in all states and territories for the past 20 to 40 years. There were major fires in all jurisdictions, affecting in excess of 54 million hectares, with vast areas being affected in central and northern Australia. In total these fires claimed 10 lives, destroyed over 1,200 structures, killed over 21,000 head of livestock, and resulted in great environmental
damage and estimated insurance losses in excess of $400 million (Ellis, Kanowski & Whelan 2004).

In January 2007, Victoria and parts of New South Wales experienced one of the worst bushfire episodes. The fires burnt more than one million hectares of land in these two states. Australia’s fire fighters received assistance from more than a hundred Canadian, New Zealand and United States fire fighters and fire behaviour specialists.

Given the high frequency and severity of bushfires in Australia, and the impact on both the environment and the population, it is evident that bushfires play a key role in the lives of many Australians. Whether it is through the destruction of land and structures, the devastating effects on flora and fauna, or the injuries and loss of human life, the impacts of bushfires are dramatic, extensive and may have long term consequences.

2.3.1 Causes of Bushfires

Bushfires are caused by natural processes, human activities, or a combination of both. Lightning strikes are the cause of virtually all naturally occurring bushfires, and account for approximately 26% of all bushfires on public land in Victoria (Table 2.2). Most other bushfires start as a result of human activity, and include both deliberate and accidental ignitions.

<table>
<thead>
<tr>
<th>Cause</th>
<th>Fires n</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning strikes</td>
<td>3,042</td>
<td>25.9</td>
</tr>
<tr>
<td>Deliberate lighting</td>
<td>2,499</td>
<td>21.4</td>
</tr>
<tr>
<td>Escapes - burning</td>
<td>2,098</td>
<td>18.0</td>
</tr>
<tr>
<td>Escapes - campfire, BBQ</td>
<td>1,109</td>
<td>9.5</td>
</tr>
<tr>
<td>Departmental burns</td>
<td>232</td>
<td>2.0</td>
</tr>
<tr>
<td>Public utilities</td>
<td>224</td>
<td>1.9</td>
</tr>
<tr>
<td>Machines</td>
<td>296</td>
<td>2.5</td>
</tr>
<tr>
<td>Pipe, cigarette, match</td>
<td>913</td>
<td>7.8</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>596</td>
<td>5.1</td>
</tr>
<tr>
<td>Unspecified</td>
<td>685</td>
<td>5.9</td>
</tr>
<tr>
<td>Total</td>
<td>11,676</td>
<td>100.0</td>
</tr>
</tbody>
</table>
On average, campfires cause approximately 10 percent of the bushfires that start on public land. Most of these fires start when the campfire is left unattended or not properly extinguished. Farmers may burn vegetation on their properties for a variety of reasons including weed control, burning of crop debris and the removal of rubbish. Agricultural burns can accidentally spark fires on public land. On average, these fires account for over 18 percent of bushfires each year. Unattended burns are most likely to 'escape' and become bushfires. Any equipment or machinery that generates heat or sparks is a potential cause of bushfires. Examples of such machinery include chainsaws, slashers, welders, grinders, and exhaust from vehicles. Fires, which are purposely lit, may also potentially develop into bushfires on public land. Examples include children experimenting with fire or farmers deliberately lighting fires without necessary permits. Another category of purposely lit fires is arson, i.e. fires lit with the intention of damaging or destroying property (Davies 1997).

FESA commenced concerted arson reduction activities in December 2001. The program aimed to develop an arson information network, in collaboration with the Western Australian Police and CALM. Over the program’s lifetime of five years, the number of fire fighter responses to the same categories of fires declined from 13,245 to 6,567, a total reduction of 6,678 incidents (Figure 2.3). Although FESA suggests that the annual number of bushfires may be affected by weather-related ignitions (particularly by lightning), it is highly unlikely that a decrease in lightning strikes and other weather-caused fires would alone account for the magnitude of the reduction in bushfire incidents (Fire and Emergency Services Authority of Western Australia 2006).
Occupational lung disease is as old as human civilisation. Concerns about adverse health effects of hazardous occupational exposures date back to Hippocrates’ warnings to physicians to explore patients’ environmental, lifestyle, and vocational backgrounds as determinants of aetiology and treatment (Lilienfeld 1994).

In the late seventeenth century, Bernardino Ramazzini (Figure 2.4) was the first physician, who systematically studied diseases related to occupation. His contribution to medicine was his work on occupational diseases called *De Morbis Artificum Diatriba* (Ramazzini 1703), which outlined the health hazards of chemicals, dust, metals, and other agents encountered by workers in 52 occupations. Among them were miners, potters, masons, wrestlers, farmers, nurses, and soldiers. (He even discussed the topic of overtaxed minds among ‘learned men’: “The maladies that affect the clerks arise from three causes: first, constant sitting; secondly, incessant movement of the hand and always in the same direction; and thirdly, the strain on the mind . . .” (Ramazzini 1703)).
In discussing the aetiology, treatment, and prevention of these diseases Ramazzini often refers back to earlier authorities such as Hippocrates, Celsius, and Galen, and, after summarising their observations, relates his own experience with the various diseases:

"The mortality of those who dig minerals is very great, and women who marry men of this sort marry again and again. According to Agricola, at the mines in the Carpathian Mountains, women have been known to marry seven times".

And

"Those who work standing - carpenters, sawyers, carvers, blacksmiths, and masons - are liable to varicose veins, because the strain on the muscles is such, that the circulation of the blood is retarded. Standing even for a short time proves exhausting compared with walking and running though it be for a long time......... Nature delights and is restored by alternating and varied actions" (Ramazzini 1703).

The De Morbis Artificum Diatriba was one of the founding and seminal works of occupational medicine and played a substantial role in the development of this discipline. Published in 1703, it is the first comprehensive work on occupational diseases, and a milestone in the history of occupational medicine. Yet, even in modern industrialised nations, many of the occupational diseases described in the
1700s continue to have a debilitating impact on workers. Unless discovered very early in their course, many work-related respiratory diseases are not curable. It is for this reason that the identification and prevention of occupational disease is of paramount importance.

### 2.4.1 Bushfire Smoke and Respiratory Health Effects

For decades fire fighters and fire managers have provided anecdotal evidence of the health effects of inhaling bushfire smoke. Since the mid 1970s these health effects have been systematically investigated, reported, and consequently recognised. Toxic exposures are generally higher in structural fire fighting, and declines in FEV₁, FVC, and FEF_{25-75} have been well documented in urban and structural fire fighters (Brandt-Rauf et al. 1988; Guidotti & Clough 1992; Musk et al. 1979; Musk et al. 1982; Musk, Peters & Wegman 1977a; Musk, Peters & Wegman 1977b; Sheppard et al. 1986; Peters et al. 1974; Large, Owens & Hoffman 1990; Sherman et al. 1989; Unger et al. 1980). Yet, in comparison, bushfire fighters tend to have longer periods of smoke exposure, which can range from hours to several days with limited respite periods (Betchley et al. 1997). In addition, situational factors beyond the bushfire fighters’ control, such as the wind speed, the terrain, the type of fuel, the fire behaviour, and the urgency of the work task, determine the intensity and the time period of the smoke exposure. Bushfire scenes produce a diverse mix of chemicals that are not easily characterized. Published health effects are not available for many of these chemical contaminants, and there is a lack of evidence on the impact of multiple low level exposures. Adverse health effects may occur from a mixture of toxic compounds even if the individual levels of airborne agents do not exceed occupational exposure limits.

Research conducted in the United States in the 1960s and 1970s on the health effects of smoke exposure was largely inconclusive, and a 1985 survey of the fire community indicated that studying the health effects of smoke was not a high priority of fire managers (Sharkey 1997a). This position changed dramatically with the 1987 fires in California and the 1988 fires in Yellowstone, when thousands of fire fighters experienced respiratory problems. A comprehensive study plan of seven years was developed aimed at determining the immediate and long-term effects of exposure to wildland fire smoke (Sharkey 1997a).
Since the 1980s, a limited number of exposure studies suggest that bushfire smoke leads to both acute and chronic lung function impairment in fire fighters. The following section provides an overview of bushfire smoke exposure studies and the associated respiratory symptoms and pulmonary effects in fire fighters.

2.4.2 Previous Studies of Respiratory Health Effects from Bushfire Smoke

Immediate effects of bushfire smoke exposure include symptoms of sore eyes, cough, and running nose. A study of 94 wildland fire fighters engaged in the Klamath National Forest fires in California in 1987 found that 76% reported at least three respiratory symptoms, i.e. cough, wheezing, and shortness of breath. During the 1988 Yellowstone fires, 40% of the approximately 30,000 medical visits made by wildland fire fighters were for respiratory problems (National Institute for Occupational Safety and Health 2004). This information suggests that wildland fire fighters experience significant rates of acute smoke inhalation. In addition, studies in the United States on wildland fire fighters have shown significant acute declines in measures of respiratory function associated with increasing exposure both over work shifts and fire seasons.

Cross-seasonal effects in pulmonary function and respiratory symptoms were studied in 52 wildland fire fighters in Northern California (Rothman et al. 1991) (Table 2.3). Spirometry was performed on crews from six California Department of Forestry and Fire Protection fire stations early in the 1988 fire season and again eight weeks later. Significant cross-season increases in symptoms of eye irritation, nasal irritation, cough, phlegm production, and wheezing were reported, with eye irritation and wheezing most strongly correlated with fire fighting activity in the two weeks immediately preceding the study. Mean cross-season decreases in FEV$_1$ (-1.2%) and FVC (-0.3%) were observed, with cumulative hours of fire fighting associated with a decline in FEV$_1$. Although the decreases are well within the repeatability of measurements, the data suggest that multiple-day exposures may lead to greater changes in lung function than single day exposures.

Sixty-three wildland fire fighters from five U.S. Department of Agriculture and Forest Service (USDAFS) crews in Northern California and Montana were studied across the 1989 fire season (Liu et al. 1992) (Table 2.3). Crew members underwent spirometry and methacholine testing to assess the degree of airway responsiveness.
There were significant individual declines of 0.09L, 0.15L, and 0.44L/s in post-season values of FVC, FEV\textsubscript{1}, and FEF\textsubscript{25-75} respectively. No consistent relationship was found between declines of FVC or FEV\textsubscript{1} and any of the covariates investigated, including smoking status, history of asthma or allergies, full-time or seasonal employment status, or history of respiratory tract symptoms. There was a significant increase in post-season airway responsiveness, measured by the methacholine testing, which was not associated with any of the covariates mentioned.

In a cross-sectional study in Sardinia, 92 firemen showed a significant reduction in lung function compared to the carabinieri (policemen) (Serra, Mocci & Sanna Randaccio 1996). No significant correlation was found among years of service, numbers of fires extinguished, and respiratory data. In addition, there was no significant correlation between respiratory changes and hobbies or previous professional experience, or involvement in non-rural fire fighting (Table 2.3).

Betchley et al. (1997) evaluated both the cross-shift and cross-season respiratory effects in wildland fire fighters exposed to high concentrations of smoke during their work. The cross-shift analysis identified significant individual declines in mean values for FVC, FEV\textsubscript{1}, and FEF\textsubscript{25-75} (0.065 L, 0.150 L, and 0.496 L/s respectively). Individual declines in mean values for FVC, FEV\textsubscript{1}, and FEF\textsubscript{25-75} (0.083 L, 0.104 L, and 0.275 L/s respectively) were also found in the cross-season analysis. Interestingly, the use of wood fires in the home was also found to be associated with the declines in FEV\textsubscript{1} (Table 2.3).

In another study, 53 wildland fire fighters from USDAFS and Bureau of Land Management Crews in Washington and Oregon underwent pre-season and post-season spirometry across the 1992 fire season (Betchley et al. 1997) (Table 2.3). In addition, cross-shift spirometry was obtained on 76 individuals during both prescribed burns and wildfires. Significant cross-shift declines in FVC (0.065L), FEV\textsubscript{1} (0.150L), and FEF\textsubscript{25-75} (0.496L/s) were seen and remained significant after adjustment for covariates (recent respiratory infection, smoking status, history of asthma or allergies). A significant cross-season decline was observed for FEV\textsubscript{1} and FEF\textsubscript{25-75} (0.104L and 0.275L/s respectively) but not for FVC. A group of ten fire fighters were retested more than eight months later and showed increases in all spirometric indices compared with previous post-season testing, which suggests
some degree of reversibility of the effect after an extended period of little or no occupational smoke exposure.

Slaughter et al. (2004) measured the short-term effects of smoke exposures on lung function in a group of fire fighters performing prescribed burns (Table 2.3). The study also measured several inhalable compounds, such as respirable PM, CO, formaldehyde, and acrolein. Spirometric measurements were made at the beginning, mid-point, and at the end of the work shift, while exposure was measured over the entire day. The cross-shift analysis showed a significant decline in FEV$_1$ (0.125L), a decline in FVC (0.067L), and a decline in FEF$_{25-75}$ (0.451L/s). The investigators could not establish a link between the individual toxic components and any of the changes in lung function.

Many studies have been limited by the absence of either quantitative or validated qualitative exposure estimates, often caused by difficulties in evaluating hazards at the scene of the fire, the lack of a coherent sampling strategy or verified sampling methods. In addition, the reported declines in lung function may have been caused by spirometry technique, the type of spirometer used, and the study design. Bushfire fighters are often difficult to engage in testing throughout the season, since they are called to fires on an emergency basis, often in remote locations that are relatively inaccessible to investigators. Testing on a uniform schedule is practically impossible due to variable crew shifts, and obtaining post-season test before dispersal of seasonal fire fighters may be difficult. Cross-shift pulmonary testing is hampered by crew accessibility, cooperation of fatigued individuals, and difficult conditions.
Table 2.3 Studies of Bushfire Smoke Exposures and Respiratory Health Impacts on Fire Fighters

<table>
<thead>
<tr>
<th>Author</th>
<th>Subjects</th>
<th>Location</th>
<th>Exposure Period</th>
<th>Measured Endpoints</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rothman et al. 1991</td>
<td>52</td>
<td>North California</td>
<td>Season</td>
<td>Spirometry, Pulmonary symptoms</td>
<td>Significant increases in symptoms of nose irritation, cough, phlegm production, and wheezing Declines in FEV$_1$ -1.2%, FVC -0.3%</td>
</tr>
<tr>
<td>Liu et al. 1992</td>
<td>63</td>
<td>Northern California Montana</td>
<td>Season</td>
<td>Spirometry, Airway responsiveness</td>
<td>Significant declines in FVC 0.09L, FEV1 0.15L, FEF$_{25-75}$ 0.44L/s</td>
</tr>
<tr>
<td>Serra et al. 1996</td>
<td>92</td>
<td>Sardinia</td>
<td>Cross-sectional study</td>
<td>Spirometry, Pulmonary symptoms</td>
<td>Significant reduction in FEV$_1$ 0.5L vs. 0.44L Significant reduction in FEV$_1$/FVC relationship 5.89 vs. 1.67</td>
</tr>
<tr>
<td>Betchley et al. 1997</td>
<td>76</td>
<td>Washington’s and Oregon’s Cascade Mountains</td>
<td>Shift Season</td>
<td>Spirometry, Respiratory symptoms</td>
<td>Cross-shift: Significant declines in FVC 0.065L, FEV$<em>1$ 0.150L, FEF$</em>{25-75}$ 0.496L/s Increase of respiratory symptoms (cough, phlegm, sore throat, chest tightness, chest pain, wheezing) Cross-season: Declines in FVC 0.083L, FEV$<em>1$ 0.104L, FEF$</em>{25-75}$ 0.275L/s No significant changes in respiratory symptoms</td>
</tr>
<tr>
<td>Slaughter et al. 2004</td>
<td>65</td>
<td>Western United States</td>
<td>Shift</td>
<td>Spirometry</td>
<td>Significant decrease in FEV$<em>1$ 0.125L Decrease in FVC 0.067L Decrease in FEF$</em>{25-75}$ 0.451L/s</td>
</tr>
</tbody>
</table>
There is conflicting evidence about the contribution of other confounders, such as cigarette smoking, to symptoms of airways obstruction in fire fighters. In the 1980s, one Australian study reported that the respiratory health effects of smoking in Sydney fire fighters far outweighed any contribution from occupational exposure to bushfire smoke (Young, Jackson & West 1980). In contrast, Liu et al. (1992) and Slaughter et al. (2004) could not establish a relationship between cross-seasonal and cross-shift declines in lung function and smoking status.

The relationship between bushfire smoke and health impacts in the Australian context has not been clearly established, even though bushfire smoke by virtue of its composition is likely to present a health risk. Although anecdotal evidence is available, there remains a lack of reliable occupational disease data examining the impact of bushfire smoke in the Australian environment (Australian Safety and Compensation Council 2005).

Community studies of Australian bushfire smoke and asthma incidence have been undertaken, but show conflicting results. Four in six studies support a link between bushfire smoke exposure and asthma incidence (Cooper et al. 1994; Johnston et al. 2002; Smith et al. 1996; Churches & Corbett 1991; Bowman & Johnston 2005; Chen, Verrall & Tong 2006). The study by Churches and Corbett (1991) showed a weak link between particulate air pollution and asthma attendances for a short period (a month) in Sydney during the 1991 bushfire. Subsequently, three studies were conducted in Sydney during the 1994 bushfire. Among these, a study by Cooper et al. (1994) did not find any increase in asthma presentations after the bushfire event, compared with those before the bushfire. Another study by Smith et al. (1996) used a more detailed and complex analysis strategy and concluded that particulate air pollution generated from bushfires did not increase asthma presentations to the emergency departments in Western Sydney. A further study by Jalaludin et al. (2000) does not demonstrate any clinically significant reduction in peak expiratory flow rates in children with wheeze during a severe bushfire episode. However, a time series study, conducted by Johnston et al. (2002) in Darwin showed a significant increase in asthma with each 10 µg/m³ increase in PM₁₀ over 7 months with almost continuous bushfire activity. More recently, Chen et al. (2006) also showed a statistically significant association between the presence of bushfire
smoke and the increased risk of asthma hospital admissions in Brisbane. Although some of the previous community studies do not report statistically significant findings, it is likely that bushfire smoke poses some degree of increased risk of respiratory disease in the community.

In summary, there is limited and conflicting information about the respiratory health effects of occupational exposure to Australian bushfire smoke, particularly for fire fighters in Western Australian conditions.

### 2.5 Economic Implications of Inhalation Injuries

Fire fighting agencies may face high injury-related costs for fire fighters. The National Institute of Standards and Technology (NIST) investigated the economic losses caused by fire fighter injuries in the United States. The purpose of the study was to quantify and compare the costs of injury prevention versus mitigation. In the year 2002 alone there were an estimated 80,800 injuries (Table 2.4) and 100 deaths among fire fighters in the United States.

<table>
<thead>
<tr>
<th>Nature of Injury</th>
<th>Injuries</th>
<th>Percentage of Injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprain, strain, muscular pain</td>
<td>39,390</td>
<td>48.8</td>
</tr>
<tr>
<td>Wound, cut, bleeding, bruise</td>
<td>16,220</td>
<td>20.1</td>
</tr>
<tr>
<td>Other</td>
<td>9,650</td>
<td>11.9</td>
</tr>
<tr>
<td>Burns (fire or chemical)</td>
<td>3,855</td>
<td>4.8</td>
</tr>
<tr>
<td>Thermal stress</td>
<td>3,225</td>
<td>4.0</td>
</tr>
<tr>
<td>Smoke or gas inhalation</td>
<td>2,575</td>
<td>3.2</td>
</tr>
<tr>
<td>Dislocation, fracture</td>
<td>2,340</td>
<td>2.9</td>
</tr>
<tr>
<td>Other respiratory distress</td>
<td>1,360</td>
<td>1.7</td>
</tr>
<tr>
<td>Burns and smoke inhalation</td>
<td>1,165</td>
<td>1.4</td>
</tr>
<tr>
<td>Heart attack or stroke</td>
<td>1,020</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>80,800</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

*Totals may not add due to rounding

The cost of addressing fire fighter injuries and of efforts to prevent them is estimated between US $2.8 billion to US $7.8 billion per year. These costs include workers' compensation payments and other insured medical expenses, including long-term care; lost productivity and administrative costs of insurance. The estimates do not include many indirect costs, such as labour spent investigating fire
fighter injuries, the cost of training fire fighters, physical fitness and wellness programs, or medical insurance (TriData Corporation 2005).

FESA reported 307 injuries in the year 2005-2006 (Figure 2.5). These injuries are not specified and financial data regarding economic losses, due to workers’ compensation claims and insured medical expenses for FESA career fire fighters, are not available. In the time period July 2003 to April 2007, one worker compensation claim was submitted with an injury cause of inhalation of bushfire smoke. The claim involved one day lost time and the reported cost for FESA was $262 (Parlour, L., pers. comm. 2007).

Figure 2.5 Reported Injuries and Hazards among FESA Career Fire Fighters
(Fire and Emergency Services Authority of Western Australia 2006)

It is difficult to obtain reliable workers’ compensation data, since the published data only show cases that result in five or more days off work (Australian Safety and Compensation Council 2005). Since not all work-related symptoms or disease result in a period off work, it is likely that the actual number of workers’ compensation claims is significantly higher than the published data. In addition, a sizeable, but unknown proportion of workers with work-related respiratory disease may not be diagnosed, or may be diagnosed after leaving the job. In these cases, the connection to previous employment is unlikely to be established and a workers’ compensation claim is unlikely to be made (Feyer & Williamson 1998).
2.6 Air Toxics in Bushfire Smoke

Bushfire smoke is a complex mixture of toxic air contaminants that may pose an occupational hazard for fire fighters. The air toxics generated by combustion of biomass fuels can be present as particles, gases, and vapours. Although it is now well established that these toxics can be health damaging, it is still not uncommon to hear the view expressed that bushfire smoke, being a natural substance, must be benign to humans.

This section provides an overview of the major air toxics in bushfire smoke, and the associated health effects in the occupational context. Smoke is the most obvious product of bushfires and at the same time the most complex. It contains an array of organic and inorganic compounds original to the combusted material or formed during the combustion process (Lees 1995; Gill, Groves & Noble 1981). Combustion, in essence, is a chemical physical process in which the fuel properties affect the type and amount of the combustion products present in the smoke. Other key factors affecting the combustion process include the temperature, the concentration of oxygen present, and the efficiency of the combustion, which in turn is determined by meteorological conditions, such as the presence of clearing winds or inversions (Terrill, Montgomery & Reinhardt 1978; Brandt-Rauf et al. 1988; Gill, Groves & Noble 1981; Beer & Meyer 1999).

2.6.1 Key Air Toxics

In the presence of sufficient oxygen, bushfire smoke is primarily composed of carbon dioxide and water vapour. In natural fires, however, the oxygen supply is by no means sufficient, which results in incomplete combustion, producing a complex mixture of air contaminants. Approximately 200 distinct organic compounds have been identified in wood smoke aerosol, which are present in both the particles and gaseous phases, and include respirable and inspirable PM, CO, nitrogen and sulphur based compounds, aldehydes, volatile and semi-volatile organic compounds, polycyclic aromatic hydrocarbons, dioxins, organic acids, free radicals, and ozone (Ward 1999; Ward 1997; Reisen & Brown 2006; Malilay 1999; Dost 1991). These studies indicate that emissions vary with fuel type, combustion conditions, and behaviour of combustion products in the atmosphere. Consequently, the chemical basis for acute smoke toxicity is not adequately known. Moreover, the majority of
the findings are based on analyses from United States wildland fire smoke, and it is not clear whether these findings are applicable in the Australian environment, as vegetation types and weather conditions differ substantially.

Analyses of smoke components pertaining to Australian bushfires are scarce. Hinwood et al. (2002) suggest that obtaining the relevant data appears to be difficult and costly, complicated by the broad range of burn scenarios, the composition and the variation of the vegetation type, and other varying factors such as weather conditions. Vines et al. (1971) estimated pollution concentrations in smoke from bushfires, and concluded that smoke consists mainly of tar, soot particles and ash. Cheney et al. (1980) reported that the annual release of carbon from burning vegetation was greater than the annual release of carbon from burning fossil fuels in Australia. Much of the carbon is converted into carbon dioxide and CO during combustion (Vines et al. 1971).

Reisen et al. (2006) conducted a method evaluation for the burning of forest fuels selected from across Australia. The fuel types were Cheltenham Park pine litter, Darwin sorghum grass, Mt Dandenong eucalyptus litter, Wombat State Forest eucalyptus litter, and Western Australian coastal scrub. Under controlled conditions, set amounts of these fuels were burnt in a burn chamber (3.3m x 4.2m x 2.4m), and air toxic sampling was undertaken. The main identified toxic compounds were respirable particles, aldehydes (formaldehyde, acetaldehyde, acrolein, 3 furaldehyde), volatile organic compounds (benzene, toluene, xylene, phenol), and CO. For Western Australian coastal scrub, respirable particles, CO, and acrolein exceeded occupational exposure guidelines (Table 2.5). However, the authors indicated that the comparison was only made as a preliminary evaluation for the air toxics of interest, and concentrations in the burn chamber could not be directly related to actual concentrations in real bushfires.
Table 2.5 Air Toxics Concentrations generated in Burn Chamber
(Reisen et al. 2006; National Occupational Health and Safety Commission 1995; American Conference of Governmental Industrial Hygienists 2003)

<table>
<thead>
<tr>
<th>Air toxics from 125 gram WA coastal scrub</th>
<th>Reisen et al. 2006b</th>
<th>TWA*</th>
<th>STEL*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respirable particles</td>
<td>35 mg/m³</td>
<td>3.0 mg/m³</td>
<td>-</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>170 ppm</td>
<td>30 ppm</td>
<td>200 ppm</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>0.32 mg/m³</td>
<td>1.2 mg/m³</td>
<td>2.5 mg/m³</td>
</tr>
<tr>
<td></td>
<td>(1.0 ppm)</td>
<td>(2.0 ppm)</td>
<td></td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>1.2 mg/m³</td>
<td>180 mg/m³</td>
<td>270 mg/m³</td>
</tr>
<tr>
<td>Acrolein</td>
<td>0.42 mg/m³</td>
<td>0.23 mg/m³</td>
<td>0.69 mg/m³</td>
</tr>
<tr>
<td></td>
<td>(0.1 ppm)</td>
<td>(0.3 ppm)</td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>0.72 mg/m³</td>
<td>16 mg/m³</td>
<td>-</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.42 mg/m³</td>
<td>190 mg/m³</td>
<td>565 mg/m³</td>
</tr>
<tr>
<td>Xylenes</td>
<td>0.15 mg/m³</td>
<td>350 mg/m³</td>
<td>655 mg/m³</td>
</tr>
<tr>
<td>Phenol</td>
<td>0.4 mg/m³</td>
<td>4 mg/m³</td>
<td>-</td>
</tr>
</tbody>
</table>

°Time Weighted Average: Concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.

*Short Term Exposure Limit: Concentration to which workers can be exposed continuously for a short period without suffering from adverse effects. Exposures should not be longer than 15 minutes and should not occur more than four times per day. There should be at least 60 minutes between successive exposures in this range.

These findings of toxic compounds were confirmed in a later study of personal exposure measurements during prescribed and experimental burns across Australia (Reisen, Brown & Cheng 2006). The major air toxics identified in fire fighter personal sampling devices included CO, respirable particles, formaldehyde, acrolein, benzene, and toluene. Exposure standards were exceeded for CO and respirable particles. It was noted that smoke exposure levels were determined by a number of factors, including work activities, burn locations, fuel types, meteorological variables.

Detailed data on the composition of Australian bushfire smoke, and in particular Western Australian bushfire smoke, are relatively limited. There is ongoing uncertainty about the degree of overall toxicity of smoke from bushfires or how the toxicity varies from fire to fire. However, there is some consistency in the identification of particular respiratory irritants, including acrolein, formaldehyde, respirable particles, and CO, as the major smoke hazards to fire fighters (Reinhardt & Ottmar 2000; Reisen et al. 2006; Sharkey 1997a). These compounds will therefore be discussed in more detail in the following sections.
2.6.2 Formaldehyde

Formaldehyde is a colourless, strong-smelling, highly flammable gas that occurs naturally in the atmosphere and biosphere, where it is released through a variety of biological and chemical processes. The most important process responsible for natural background concentrations of formaldehyde in the environment is the photochemical oxidation of atmospheric methane. Formaldehyde occurs naturally in plants and is released through biomass combustion during bushfires (Reinhardt & Ottmar 2000).

The most important man-made source of formaldehyde is automotive exhaust from engines not fitted with catalytic converters. Other anthropogenic sources include direct emissions from the production and use of formaldehyde (World Health Organization 2001). Formaldehyde is used in the manufacture of building materials, particleboard, furniture, hardwood plywood wall panels, and insulation. In addition, formaldehyde is used in glues, wood products, permanent press fabrics, and paper product coatings (Australian Government - Department of Health and Ageing 2005). Formaldehyde is also utilized as a disinfectant and preservative (formalin) in a number of industries, including those involving medical procedures and products, embalming in funeral homes, film processing, textile treatments, leather tanning, and manufacture of a wide range of personal care and consumer products (Australian Government - Department of Health and Ageing 2005).

2.6.2.1 Occupational Exposure to Formaldehyde

Occupational exposure to formaldehyde occurs on a large scale and in a wide variety of occupations and industries. Hauptmann (2004) estimates that approximately 1.5 million workers are exposed to formaldehyde in the USA, and about one million in the European Union. Short-term exposures to high levels have been reported for embalmers, pathologists, wood and paper workers (Vaughan et al. 2000; World Health Organization 2002b). Lower levels (less than 0.2 ppm during 8 to 12 hour shifts) have usually been encountered with the manufacture of man-made vitreous fibres, abrasives, and rubber, and in formaldehyde production industries. A wide range of exposure levels has been observed in the production of resins and plastic products (0.2 to 0.5 ppm) (Australian Government - Department of Health and Ageing 2005).
Monitoring data during wildland fires in the United States indicates that firefighters can be exposed to formaldehyde levels up to 0.34 ppm while controlling wildland fires. Exposure levels for formaldehyde in this context were found to depend on the work activity being undertaken (Reinhardt & Ottmar 2000). Average formaldehyde levels varied from 0.015 ppm for ‘holding’ (i.e. holding back the fire) compared to 0.098 ppm for ‘mop-up’. These variations in formaldehyde exposure levels were confirmed in a smoke exposure study during prescribed burns by Reinhardt, Ottmar and Hanneman (2000). Mean pollutant concentrations of formaldehyde were highest for firefighters involved in work activities such as ‘attack’ (0.464 ppm), ‘sawyer’ (the person using a chain saw) (0.346 ppm), and ‘attack/lighting’ (0.197 ppm). Similarly, in Australia, Reisen, Brown and Cheng (2006) measured different personal exposure levels of formaldehyde depending on work activities. Exposure levels for formaldehyde were highest for firefighters who were ‘patrolling/suppressing with a hose and/or a rake hoe’ (up to 0.6 ppm) compared to firefighters who were ‘lighting’ and ‘supervising’ (both up to 0.2 ppm). These variations in exposure levels may be explained by different weather conditions, the variety and density of fuel loads, and different ways of fire fighting management and tactics.

Exposure standards for formaldehyde in the occupational environment in Australia are provided by the National Occupational Health and Safety Commission (Table 2.6). Based on the hazard assessment for formaldehyde, the National Industrial Chemicals Notification and Assessment Scheme (NICNAS) recommends lowering the current TWA occupational exposure standard for formaldehyde from 1 ppm to 0.3 ppm, and the STEL occupational exposure standard from 2.0 ppm to 0.6 ppm (Australian Government - Department of Health and Ageing 2005). In the United States, the National Institute for Occupational Safety and Health recommends lowering occupational standards for formaldehyde from 0.75 ppm to 0.016 ppm (TWA), and from 2.0 ppm to 0.1 ppm (STEL).
Table 2.6 Exposure Standards for Formaldehyde in the Occupational Environment

<table>
<thead>
<tr>
<th></th>
<th>TWA*</th>
<th>STEL*</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOHSC (Australia)</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>NICNAS Recommendation (Australia)</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>OSHA (USA)</td>
<td>0.75</td>
<td>2.0</td>
</tr>
<tr>
<td>NIOSH Recommendation (USA)</td>
<td>0.016</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*Time Weighted Average
*Short Term Exposure Limit

2.6.2.2 Health Effects of Formaldehyde Exposure

The human health effects of inhalation of formaldehyde have been extensively reviewed (International Agency for Research on Cancer 2004b; Australian Government - Department of Health and Ageing 2005; National Environment Protection Council 2003; Hauptmann 2004; World Health Organization 2002b). Although the principal route of exposure is by inhalation, there is consistent evidence of respiratory irritation, as well as skin and eye effects after exposure to formaldehyde (Witek et al. 1987; Kulle 1987; Day et al. 1984; Andersen & Molhave 1983). Reported symptoms are rare below levels of 0.5 ppm, but become increasingly prevalent in exposure chamber studies as concentrations increase (International Agency for Research on Cancer 2004b; Australian Government - Department of Health and Ageing 2005).

There is epidemiological evidence of associations between occupational exposure to formaldehyde and nasopharyngeal and sinonasal cancers (Partanen 1993; McLaughlin 1994; Vaughan et al. 2000). In a review of seven studies of professional workers, including embalmers, funeral parlour workers, pathologists and anatomists, the International Agency for Research on Cancer (IARC) reported that excess mortality from leukaemia was seen relatively consistently, i.e. in six of the seven studies (International Agency for Research on Cancer 2004b). Although it has been speculated in the past that these findings may be explained by exposures to viruses experienced by these workers, there is little evidence that these occupations have higher incidence of viral infections than the general population.

Based on the above, the IARC concluded in 2004 that there was sufficient evidence to change the classification of formaldehyde from ‘probably carcinogenic’ (Class 2A) to ‘carcinogenic for humans’ (Class 1) (International Agency for Research on
Cancer 2004a; International Agency for Research on Cancer 2004b). The Australian National Occupational Health and Safety Commission takes a more conservative approach and classifies formaldehyde as a Category 2 carcinogen, based on the Approved Criteria for Classifying Hazardous Substances (National Occupational Health and Safety Commission 2004). This implies that formaldehyde is regarded as a probable human carcinogen for which there is sufficient evidence to provide a strong presumption that human exposure might result in the development of cancer.

2.6.3 Acrolein

Acrolein is a clear, colourless to straw-coloured liquid with a pungent, suffocating odour. Although the specific odour of acrolein may be an indicator for exposure, it does not provide adequate warning of hazardous concentrations. Acrolein is highly flammable and at room temperature has the capacity to produce toxic concentrations of gases, such as peroxides and oxides of carbon. In smoke from cigarettes, acrolein is about 10 times more plentiful than formaldehyde. Emissions from gas and diesel motors are considered to be the major sources of acrolein in the ambient air, although acrolein emissions are also associated with waste incinerators, furnaces, and power plants. Acrolein is emitted by burning of wood in open fireplaces, and similarly in forest fires as a product of incomplete combustion (Lipari, Dasch & Scruggs 1984; Dost 1991; Sharkey 1997a).

2.6.3.1 Occupational Exposure to Acrolein

Exposure to acrolein occurs in a wide variety of industrial settings, including manufacturing plants of plastic products, restaurants, and bakeries (World Health Organization 2002a). Data on airborne levels suggest a wide range of concentrations depending on the work environment conditions and the type of material that is being used or burned. Chamber studies have demonstrated that acrolein concentrations can vary by a factor of 35 depending on the material that is burnt (Terrill, Montgomery & Reinhardt 1978).

Studies of exposure patterns during structural fire fighting suggest that acrolein levels may exceed occupational standards. Treitman et al. (1980) determined acrolein levels during structural fire fighting and reported that 50% of the analysed samples had concentrations greater than the STEL value of 0.3 ppm, and 10% were
in excess of 3 ppm, a concentration considered to be immediately dangerous to health (Table 2.7). The single highest sample was 98 ppm, which would represent a rapidly fatal exposure for an unprotected fire fighter. Bolstad-Johnson et al. (2000) found maximum acrolein levels of 0.3 ppm during overhaul (Table 2.7), which is the fire fighting stage in which the suppression is complete and fire fighters are searching the structure for hidden fires or embers, which may be found above ceilings, or in between walls.

Studies of wildland fire exposures indicate lower concentrations of acrolein than those typically found in structural fires. A single sample analysed for acrolein in a wildland fire study showed a concentration of 0.023 ppm (Materna et al. 1992). During prescribed burns, Reinhardt et al. (2000) found shift averages for acrolein of 0.009 ppm for fire fighters with the highest exposure averaging 0.06 ppm during the work shift (compared to TWA 0.1 ppm). During the time on the fire line, the fire fighters’ exposure to acrolein averaged 0.015 ppm, ranging up to 0.098 ppm. In another study, Reinhardt and Ottmar (2000) found average acrolein exposures of 0.005 ppm during initial attack operation, and 0.001 ppm over a work shift (compared to TWA 0.1 ppm). In a study investigating the short-term health effects of exposures to smoke from prescribed burns, Slaughter et al. (2004) found mean levels of acrolein at 0.01 ppm (Table 2.7). These findings show that acrolein is present in bushfire smoke, but in levels that do not exceed occupational exposure standards. However, this was debated by Sharkey (1997a), who stated that acrolein concentration in smoke can reach levels as high as 0.1 to 10 ppm near wildland fires.

2.6.3.2 Health Effects of Acrolein Exposure

Acrolein is an upper respiratory tract irritant, causing increased airway resistance and a decreased respiratory rate (World Health Organization 2002a). Severe respiratory symptoms, including bronchitis or pulmonary oedema occur at concentrations of 10-20 ppm (Bolstad-Johnson et al. 2000). Eye irritation can occur at concentrations of 0.01-2.0 ppm, irritation of the nose and throat at 1.0-3.0 ppm (World Health Organization 2002a). Systemic effects may occur after exposure by any route.
Table 2.7 Acrolein Exposure Levels during Fire Fighting

<table>
<thead>
<tr>
<th></th>
<th>TWA°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1 ppm</td>
</tr>
<tr>
<td><strong>Structural Fire Fighting</strong></td>
<td></td>
</tr>
<tr>
<td>Treitman et al. (1980)</td>
<td>50% &gt; 0.3</td>
</tr>
<tr>
<td>Bolstad-Johnson et al. (2000)</td>
<td>10% &gt; 3</td>
</tr>
<tr>
<td><strong>Bushfire Fighting</strong></td>
<td></td>
</tr>
<tr>
<td>Materna et al. 1992</td>
<td>0.023</td>
</tr>
<tr>
<td>Reinhardt et al. (2000)</td>
<td>0.009</td>
</tr>
<tr>
<td>Reinhardt and Ottmar (2000)</td>
<td>0.001</td>
</tr>
<tr>
<td>Slaughter, Koenig &amp; Reinhardt (2004)</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*Time Weighted Average
*Short Term Exposure Limit

2.6.4 Carbon Monoxide

Carbon monoxide (CO) is a colourless, odourless, tasteless, non-corrosive, highly toxic gas of the same density as air. It is extremely flammable, burning in air with a bright blue flame, and is present in virtually all fire environments (Lees 1995). It is produced abundantly through the incomplete combustion of biomass fuels, particularly in the smouldering phase.

2.6.4.1 Occupational Exposure to Carbon Monoxide

Carbon monoxide is present in all fire environments, and fire fighters’ exposure to this asphyxiant has been a concern for fire fighters for many years. Treitman et al. (1980) described CO as the most common and serious acute hazards for fire fighters. Although fire fighters rarely encounter CO levels that are capable of causing coma and death within minutes, they are frequently exposed to levels that can compromise their judgement and psychomotor efficiency, visual vigilance, mental functions, performance, and safety (Matticks et al. 1992; Hathaway & Proctor 2004; Burgess, Treitman & Gold 1979). Radford and Levine (1976) demonstrated that the level of carboxyhaemoglobin correlated with neither the length of the exposure nor the fire fighter’s own evaluation of the degree of exposure.

Current occupational exposure limits set by the National Occupational Health and Safety Commission (1995) are a TWA of 30 ppm for an eight hour work day, a STEL of 200 ppm for 15 minutes, and a peak limit of 400 ppm, which should not be
exceeded at any time. During structural fire fighting, Treitman et al. (1980) found a wide range of CO exposures ranging from 0.4 - 800 ppm. The average exposure was 320 ppm, but one fire reached the short-term lethal concentration of 5,000 ppm. The STEL of 200 ppm was exceeded in approximately 15 of the fires investigated. Bolstad-Johnson et al. (2000) found maximum TWA levels of CO levels of 26.9 ppm and peak levels of 260 ppm during overhaul.

Studies of fire fighters’ exposures during forest and wildland fires reveal lower levels of CO, possibly due to the lack of confinement. Brotherhood et al. (1990) calculated environmental CO concentrations from carboxyhaemoglobin concentrations. For fire fighters extinguishing bushfires in Australia, average CO levels were estimated at 17 ppm for non-smokers and 31 ppm for smokers. These findings suggest that fire fighters who were smokers were exposed to as much CO from their cigarettes as from the bushfire smoke. Carbon monoxide concentrations ranged from 1.4 - 38 ppm in 46 samples during fire line mop-up and a prescribed burn (Materna et al. 1992). The average concentration was 14.4 ppm, and the average sampling period was 3.5 hours. The highest exposures, up to 300 ppm on an instantaneous basis, were associated with operators of gasoline-powered pumping engines (Table 2.8).

During a three year evaluation program of full-face air-purifying respirators, the highest peak exposure during wildland fire fighting was recorded at 703 ppm (Beason et al. 1996). However, the majority of the exposure levels fell below the (United States) 25 ppm TWA limit. In a study measuring exposure levels during prescribed burns, TWA levels were within occupational exposure limits, i.e. shift average was 38 ppm, and at the fire line a TWA of 58 ppm was measured (Reinhardt, Ottmar & Hanneman 2000). Smoke exposure measurements among fire fighters at wildland fires undertaken between 1992 and 1995 showed that CO levels occasionally exceeded full-shift permissible exposure limits (Reinhardt & Ottmar 2000). The average exposures to CO at project wildland fires (i.e. eight multi-day wildland fires) averaged 2.8 ppm over the work shift, with a maximum TWA exposure to CO of 30.5 ppm over the work shift. During initial attack wildland fires (i.e. fires that were successfully controlled by initial attack forces) CO levels averaged 1.6 ppm, with a maximum of 13.1 ppm, during the work shift (Table 2.8).
Similar levels of CO were found in a study investigating the association between lung function and exposure to prescribed burn smoke (Slaughter, Koenig & Reinhardt 2004).

### Table 2.8 Carbon Monoxide Levels during Fire Fighting

<table>
<thead>
<tr>
<th></th>
<th>TWA° 30 ppm</th>
<th>STEL* 200 ppm</th>
<th>Peak Limit# 400 ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural Fire Fighting</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treitman et al. (1980)</td>
<td>320</td>
<td>&gt; 200</td>
<td></td>
</tr>
<tr>
<td>Bolstad-Johnson et al. (2000)</td>
<td>26.9</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td><strong>Bushfire Fighting</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brotherhood et al. (1990)</td>
<td>17/31±</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Materna et al. (1992)</td>
<td>14.4</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Beason et al. (1996)</td>
<td>&lt;25</td>
<td>703</td>
<td></td>
</tr>
<tr>
<td>Reinhardt et al. (2000)</td>
<td>38</td>
<td>179</td>
<td></td>
</tr>
<tr>
<td>• Shift average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Fire line</td>
<td>58</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Reinhard and Ottmar (2000)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project wildland fires</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Shift average</td>
<td>2.8 (max 30.5)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>• Fire line</td>
<td>4.0 (max 38.8)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Initial attack wildland fires</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Shift average</td>
<td>1.6 (max 13.1)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>• Fire line</td>
<td>7.4 (max 28.2)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Slaughter, Koenig &amp; Reinhardt (2004)</td>
<td>7.19</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

°Time Weighted Average
*Short Term Exposure Limit
#Peak limit should not be exceeded at any time
±Non-smokers/smokers

### 2.6.4.2 Health Effects of Carbon Monoxide Exposure

Carbon monoxide causes asphyxiation by decreasing the oxygen-carrying capacity of the blood. It binds to haemoglobin with more than 200 times the affinity of oxygen, and as a consequence prevents the release of oxygen to the tissue (Ellenhorn 1997; Malilay 1999; Bizovi & Leikin 1995).

The primary targets of CO are the nervous and the cardiovascular system, and health effects vary with the physical condition, the breathing rate, and the pulmonary volume of the individual (Hamilton & Hardy 1974). At a concentration of 200 ppm, a healthy individual starts experiencing mild headaches after two or three hours. At 400 ppm exposure, the individual can experience nausea, headache, and dizziness after one or two hours. Carbon monoxide is also recognized to impair judgment,
visual acuity, and decision making (Treitman, Burgess & Gold 1980). With an exposure concentration of 800 ppm and higher, confusion, ataxia, coma and seizures may develop. After an exposure of 1,600 ppm death may occur within two hours (Beason et al. 1996).

In people with existing coronary heart disease, inhalation of slightly elevated concentrations of CO may cause palpitations, chest pain, shortness of breath, dyspnoea on exertion, tachypnoea, and tachycardia. Moreover, symptoms of ischemia and electrocardiogram changes may occur. Severe cardio toxicity may occur with decreased oxygen delivery to the heart and is manifested by hypotension (Bizovi & Leikin 1995).

2.6.5 Particulate Matter
Particulate matter (PM) represents a complex mixture of organic and inorganic substances, and consists primarily of condensed hydrocarbon, tar materials, and fragments of vegetation and ash (Ward & Hardy 1991). PM is abundantly produced during bushfires, is highly visible, and affects ambient air quality. Mass and composition of PM is usually classified into two principal groups: (1) coarse particles mostly larger than 2.5 µm in diameter, and (2) fine particles mostly smaller than 2.5 µm in aerodynamic diameter (PM$_{2.5}$). Size distribution of PM is schematically shown in Figure 2.6. The chemical composition and size of the PM depends on the weather conditions, the amount and type of biomass fuels. For example, a smouldering fire yields considerably more fine PM than a high intensity fire, and incomplete combustion, due to a lack of oxygen, produces more toxic PM compared to complete combustion. The fine particles (PM$_{2.5}$) account for up to 90 to nearly 100% of the mass of particulate matter (Ward 1997).
Currently there is no occupational exposure limit available for toxic PM. In the USA, exposure levels are generally assessed against the occupational exposure levels for “nuisance” dust, i.e. 5 mg/m$^3$ for the respirable fraction, and 15 mg/m$^3$ for the total dust fraction. In Australia, the recommended occupational exposure level for inspirable non-toxic dust is 10 mg/m$^3$ (National Occupational Health and Safety Commission 1995). However, this general exposure standard should only be applied where the particulate material contains no substances which may themselves be toxic or cause physiological impairment at lower concentrations. For example, where a dust contains asbestos, the exposure to these materials should not exceed the appropriate value for these substances. For specific dusts, the occupational exposure levels for specific respirable particles vary from 1 – 6 mg/m$^3$ (Table 2.9).
Table 2.9 TWA for Specific Respirable Particulate Matter

<table>
<thead>
<tr>
<th>Dust/Particulate Matter</th>
<th>TWA* mg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal dust</td>
<td>3</td>
</tr>
<tr>
<td>Graphite dust</td>
<td>3</td>
</tr>
<tr>
<td>Hardwood dust</td>
<td>1</td>
</tr>
<tr>
<td>Softwood dust</td>
<td>5</td>
</tr>
<tr>
<td>Fumed silica</td>
<td>2</td>
</tr>
<tr>
<td>Fume (thermally generated)</td>
<td>2</td>
</tr>
<tr>
<td>Soapstone</td>
<td>6</td>
</tr>
</tbody>
</table>

*Time Weighted Average

During bushfire fighting, fire fighters are exposed to considerable levels of particles produced by the combustion of biomass. Reinhardt and Ottmar (Reinhardt & Ottmar 2000) found maximum PM$_3$ levels of 2.3 mg/m$^3$ on the fire line (compared to TWA 5 mg/m$^3$).

There are a number of limitations with the occupational limits for PMs as given. They fail to account for complex mixtures of the toxic compounds, which are adhered to the surface of the PM, and associated health effects are largely unknown, and differ in every work environment. Moreover, exposure levels may vary with the specific tasks within a job. Reinhardt and Ottmar (2000) found that PM$_{3.5}$ concentration was highest for fire fighters during holding and mop-up (Figure 2.7). These results were expected, as this task involves digging and stirring of ashes and dirt, which causes particles to become airborne.

![Figure 2.7 Distribution of Respirable PM$_{3.5}$ Concentration among Fire Fighters by Job Task at Wildland Fires](Reinhardt & Ottmar 2000)
Reisen et al. (2006) reported similar findings in particulate sampling during prescribed burns. The average work shift concentrations of particles ranged from 0.2 to 9 mg/m$^3$, and particles reached levels above 20 mg/m$^3$ during periods of rake hoeing.

2.6.5.2 Health Effects of Particulate Matter Exposure

Although PM is the most visible manifestation of combustion, the health effects of smoke particles are not entirely clear. Inhalation is the most important route of exposure during bushfires, and when particles are in the ambient air, there is a significant likelihood that fire fighters will inhale them. Smoke particles largely consist of condensed volatile organics, which serve as surfaces of attachment for any compound in the atmosphere. As a consequence, it is extremely complex to establish the health effects of particulate matter in smoke, as the damage causing properties of particles not only depend on chemical and toxic characteristics, but also on their size, shape and density (Schwela 2001; Dost 1991; Naeher et al. 2007). Occupational hygiene specialists therefore use aerodynamic diameters to compare particles of different sizes, shapes and densities in terms of how they settle out of the air flow stream. Figure 2.8 illustrates the different types of PM and their typical size.

The American Conference of Governmental Industrial Hygienists (ACGIH) classifies PM into three categories:

1. Inspirable PM (0 – 100 µm) is hazardous when deposited anywhere in the respiratory tract;

2. Thoracic PM (0 - 25 µm) is hazardous when deposited within the lung airways and the gas-exchange region; and

3. Respirable PM (0 - 10 µm) is hazardous when deposited in the gas-exchange region (Rajhans & Pathak 2002).
The respirable PM mass represent over 90% of the total PM in bushfire smoke, and is considered to present a higher risk than the inspirable PM. The respirable fraction of the total suspended PM is defined by the size and the settling velocity of the PM. The deposition fraction of PM which is able to penetrate deeper into the respiratory system decreases with the increasing size and the deposition rate of the PM (Checkoway, Pearce & Crawford-Brown 1989).

The respiratory system can be divided into three distinct subregions, which are characterised by separate retention functions and amounts of deposited material (Figure 2.9). These subregions are the nasopharyngeal, the tracheo-bronchial, and the alveolar regions. Table 2.10 presents an overview of the various factors influencing the PM deposition in the respiratory system.
Table 2.10 Factors Influencing PM Deposition in the Respiratory System
(American Conference of Governmental Industrial Hygienists 2003; Standards Australia 1994)

<table>
<thead>
<tr>
<th>PM µm</th>
<th>Air Velocity</th>
<th>Area of Respiratory System most likely to be deposited</th>
<th>Method of Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1</td>
<td>↑ to 0</td>
<td>Alveolar region</td>
<td>Diffusion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(smaller branches of lung and the air exchange area)</td>
<td></td>
</tr>
<tr>
<td>1 - 5</td>
<td>↑↑↑ to ↑↑</td>
<td>Trachea, bronchial and bronchiolar region</td>
<td>Sedimentation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(windpipe and larger branches of the lungs)</td>
<td></td>
</tr>
<tr>
<td>5 - 10</td>
<td>↑↑↑↑</td>
<td>Nasopharyngeal region</td>
<td>Impaction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(upper airway passages - nose and throat)</td>
<td></td>
</tr>
</tbody>
</table>

PM having an aerodynamic diameter of 5 to 10 µm is deposited in the nasopharyngeal region largely by impaction. This mechanism predominates because of the high air velocity and the many turns in the nasopharyngeal air way. Changes in airflow direction cause many particles to strike the walls of the air passage and consequently the particles deposit in this region. Smaller particles with an aerodynamic diameter of about 1 to 5 µm are deposited in the tracheo-bronchial region and upper bronchial tubes. Sedimentation is the most common method, because at this point the air flow has reduced enough for particles to settle. When the air enters the alveolar region it has slowed even more, and particles smaller than 1 µm deposit on the lung walls relatively randomly. Diffusion is the most important mechanism for deposition in the alveolar region (Figure 2.9).

Figure 2.9 Respiratory System
(Canadian Centre for Occupational Health and Safety 2004)
The ACGIH recommends the concept of particulate size-selective limits be incorporated in the occupational exposure limits. However, this has not been implemented in the United States or in Australia.

### 2.6.6 Occupational Exposure Standards

The exposure standards are presented in terms of:

- **Time-weighted average (TWA):** the concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.
- **Short-term exposure limit (STEL):** the concentration to which workers can be exposed continuously for a short period without suffering from adverse effects. Exposures should not be longer than 15 minutes and should not occur more than four times per day. There should be at least 60 minutes between successive exposures in this range.

The national standard relevant to the bushfire air toxics research is *Exposure Standards for Atmospheric Contaminants in the Occupational Environment* (National Occupational Health and Safety Commission 1995). These standards ensure that air inhaled at work should not contain chemical agents at concentrations that produce adverse effects on health, safety or wellbeing. The occupational standards have an advisory character only, and do not represent no-effect levels, but are best used to assess the quality of the working environment and identify areas of unacceptable risks for which control measures would be required.

The exposure limits provided in these Standards may need to be adjusted to take into account the different working environment of bushfire fighting, such as:

- The wide variety of environmental conditions of bushfire fighting, such as elevations that range from sea level to over 2000 meters; steep, uneven ground, and high ambient air temperatures that often exceed 35°C;
- The long work shifts. Bushfire fighters may employ a 24-hour shift on the first day of a 7-day assignment. They work 24 hours (including travel time), followed by 8 hours of rest. They may work up to 16 hours a day for the rest of the 7-day assignment (Sharkey 2002);
• The extremely heavy workloads. Heavy or strenuous work increases lung ventilation, thereby increasing the uptake of airborne contaminants; and

• The complex nature of bushfire smoke. There is no current standard available that is specific to bushfire smoke particles, which addresses the potential for adverse health effects arising from interactions between these air toxics.

2.7 Respiratory Protective Equipment

Respiratory protective equipment refers to the equipment needed when adequate control of airborne contaminants in the workplace is not feasible, or when an individual is at increased risk of adverse effects from exposure to toxic agents (Boehlecke 1996). Not only are fire fighters frequently exposed to uncontrollable amounts of airborne contaminants, the health effects of the complex mixture of compounds in bushfire smoke are often impossible to determine. Bushfire fighters often spend long periods in the smoke, including the breaks and travelling time, and have only limited options for minimising their exposure to smoke constituents, particularly in emergency fire situations. Individuals can step back from the flames and smoke, or they can be rotated through the tasks by the fire managers to minimise long-lasting exposure to the dense smoke (Smith, R. pers. comm. 2005; Sneeuwjagt, R., pers. comm. 2005). However, opportunities to rotate crews may be limited during bushfire emergencies in rural urban interface locations, where fire fighters need to remain in smoke-filled conditions to protect properties and buildings from fire impact (Stevens, R., pers. comm. 2006).

Considering this high-risk working environment, the need for respiratory protection for fire fighters would appear compelling, yet studies are unclear about the need for respirators for bushfire fighters. According to Sharkey (1997a) fewer than 5% of the past case studies concluded that devices would only be required. Yet, this percentage is based on a comparison of 8-hr TWA and Permitted Exposure Levels (PELs), and measured in light smoke conditions only. Failure to use a respirator is influenced by psychological factors (Morgan 1983) and by the additional burden on the respiratory system caused by the use of such devices (Raven, Dodson & Davis 1979). In the fire fighting community, it has been suggested that the provision of respiratory protection may present the fire fighters with a false sense of protection, thereby leading fire fighters to make incorrect decisions about their safety. For
example, the fire fighters may decide to remain in the smoke for a longer period as they do not notice the smoke odour through the more superior filters. One potentially serious result is carbon monoxide poisoning, as this asphyxiant is not filtered out by any of the protective filters.

2.7.1 The Development of Respiratory Protective Devices

The concept of using respiratory protective devices to reduce or eliminate hazardous exposures to airborne contaminants first came from Pliny (A.D. 23-79) who discussed the use of loose fitting animal bladders in Roman mines to protect workers from the inhalation of red oxide of lead (United States Department of Labor 2007). Later, in the 1700s, the ancestors of modern atmosphere-supplying devices, such as the self-contained breathing apparatus (SCBA) or hose mask, were developed. Although the devices themselves have become more sophisticated in design and materials, respirator performance is still based on one of two basic principles: (1) purifying the air by removing contaminants before they reach the breathing zone of the worker, or (2) providing clean air from an uncontaminated source.

In 1814, a particulate-removing filter encased in a rigid container was developed, and was in fact the predecessor of the modern filters for air-purifying respirators. In 1854, it was recognized that activated charcoal could be used as a filtering medium for vapours. The field of respiratory protection has developed continually since the First World War, when the use of gas weapons created a requirement for mass-produced respirators for use by the troops (United States Department of Labor 2007).

One of the major developments in the basic design of respirators was the resin-impregnated dust filter in 1930 (National Institute for Occupational Safety and Health 2007). This development has made available efficient, inexpensive filters that have good dust-loading characteristics and low breathing resistance. More recently, ultrahigh efficiency filters have emerged and are made from paper that contains very fine glass fibres. These extremely efficient filters are used for very small airborne particulates and produce little breathing resistance.
2.7.2 Selection of Respirators for Bushfire Fighting

There are many different types of respirators available, each with their own specific features. It is important to consider a number of factors when selecting a suitable respirator for a particular situation. The physical characteristics of the contaminants need to be known, i.e. whether it is a particulate, a gas, or a combination. Where the type or extent of atmospheric contamination (gaseous or particulate) remains unknown and a safe level of oxygen cannot be assured, then devices which are designed to give protection against all three types of hazards should be used. To provide effective protection, the respirator must be worn whenever the person is exposed to the contaminant. In selecting the most appropriate form of respiratory protection, reference should be made to Australian/New Zealand Standard 1715:1994 (AS/NZS 1715) (Standards Australia 1994) and Australian/New Zealand Standard 1716:2003 (AS/NZS 1716) (Standards Australia 2003b).

There are two basic ways of providing personal respiratory protection against atmospheric contaminants:

1. Purifying the air that a person breathes with the air purifying respirator. Air-purifying respirators are designed to remove toxic contaminants in the form of particulates, gases, and vapours or combinations by filtering the contaminants from the inhaled air before they enter the breathing zone.

2. Supplying the person with respirable air. The air supplying respirator is a device that provides clean breathing air from an uncontaminated source, independent of the surrounding atmosphere.

The selection of the most appropriate respirator for specific hazards for fire fighters is outlined in Figure 2.10.
2.7.3 Air Purifying Respirators

Bushfire fighters are usually provided with an air purifying respirator (Figure 2.11). The various combinations of filters, cartridges and canisters allow the user to match the respirator to the particular work situation. However, it is important to ensure that air purifying respirators should not be used in atmospheres containing less than 19.5 percent oxygen, since they do not provide respirable air. The following sections outline the main types of filters and cartridges used by fire fighters to prevent the inhalation of air toxics during bushfire fighting.
2.7.3.1 Particulate Filters

Particulate filters are mechanical filters used for protection against dusts, fumes, and/or mists. A dust is a solid, mechanically-produced particle. A fume is a solid condensation particulate, usually of a vaporised metal. A mist is a liquid condensation particle (Bollinger & Schutz 1987). Filters are made of fibrous material (Figure 2.12) which traps the particles. The efficiency of the entrapment depends on the particle relative to the filter size, particle velocity, and, to some extent, the composition and shape of the particle and the fibre. Small densely packed fibres in the filter material increase the efficiency of the filter, but also increase resistance to airflow. As the entrapped particle load on the filter increases, deposition efficiency and resistance increase. The higher the ambient concentration of particles, and the greater the volume of inhaled air per minute through the respirator, the more quickly the filter becomes heavily loaded and hence requires replacement (Rajhans & Pathak 2002).
The particulate filters are classified according to their use, which facilitates selection of the most appropriate filter for specific situations or jobs (Table 2.11). With current filter media, any filter designed to be 100 percent efficient in removing particles would be unacceptably difficult to breathe through. Standards Australia (2003b) classifies the efficiency of the filters as part of their certification testing.

### Table 2.11 Classification of Particulate Filters*
(Standards Australia 2003b)

<table>
<thead>
<tr>
<th>Class</th>
<th>Use</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Against mechanically generated particles, e.g. silica, asbestos</td>
<td>Penetration lower than 20%</td>
</tr>
<tr>
<td>P2</td>
<td>Against both mechanically and thermally generated particulates, e.g. metal fumes</td>
<td>Penetration lower than 6%</td>
</tr>
<tr>
<td>P3</td>
<td>Against all particles including highly toxic materials, e.g. beryllium</td>
<td>Penetration lower than 0.05%</td>
</tr>
</tbody>
</table>

*These classes do not take into account the size of the particles.

#### 2.7.3.2 Gas Filters

Gas filters (or chemical cartridges) are sorbent elements, usually containing activated charcoal, which adsorb the vapours or gases from the contaminated air before they can enter the breathing zone of the worker. Other materials may be added to increase removal of contaminants with specific properties. The basic types of gas filters are presented in Table 2.12.

### Table 2.12 Types of Gas Filters
(Standards Australia 2003b)

<table>
<thead>
<tr>
<th>Type</th>
<th>For Use against</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Certain organic gases and vapours</td>
</tr>
<tr>
<td>B</td>
<td>Certain inorganic gases and vapours</td>
</tr>
<tr>
<td>E</td>
<td>Sulphur dioxide and other acid gases and vapours</td>
</tr>
<tr>
<td>G</td>
<td>Low vapour pressure chemicals, e.g. agricultural chemicals</td>
</tr>
<tr>
<td>K</td>
<td>Ammonia and ammonia derivates</td>
</tr>
<tr>
<td>MB</td>
<td>Methyl bromide</td>
</tr>
<tr>
<td>AX</td>
<td>Certain groups of low boiling point organic compounds</td>
</tr>
<tr>
<td>Hg</td>
<td>Mercury vapour</td>
</tr>
<tr>
<td>NO</td>
<td>Oxides of nitrogen</td>
</tr>
<tr>
<td>Specific chemical type</td>
<td>One or more specific chemicals not falling into any of the above type descriptions. The filter is identified by the name of that chemical</td>
</tr>
</tbody>
</table>

Each gas filter is available in one of four classes, which are arranged in order of increasing capacity. The higher the number, the longer the filter will last for a given concentration of gas where other factors remain constant. These classes are:
• Class AUS\textsuperscript{3}: low capacity filter with a shorter life than Class 1;
• Class 1\textsuperscript{4}: low absorption capacity filter;
• Class 2: medium absorption capacity filter; and
• Class 3\textsuperscript{5}: high absorption capacity filter.

Combination filters are available to protect against particulates, as well as vapours and gases (Figure 2.13). The ability of sorbents to remove gases and vapours decreases as the sorbent becomes saturated with the contaminant, allowing additional chemicals to pass without being absorbed. If the sorbent is not replaced, ‘breakthrough’ occurs, and protection is diminished. The wearer may sense an odour, taste, or irritation from the contaminants penetrating the sorbents, but this warning may not occur for some substances until undesirable concentrations have been reached in the inhaled air.

\textbf{Figure 2.13 Air Purifying Respirator with Combination Gas/Particulate Filter}

It is widely acknowledged that a reliable indicator to signal the breakthrough of the toxic gases and vapours would be extremely useful for fire fighters. Although various studies have developed predictive mathematical models to calculate breakthrough times for individual contaminants (Yoon, Nelson & Lara 1996; Foote 1994; Wood 1994; Wood 2005), it is extremely difficult to estimate accurate breakthrough times for complex mixtures (Yoon, Nelson & Lara 1996). This is complicated by numerous external factors, such as: (i) a particular contaminant's chemical properties and concentration; (ii) surrounding humidity and temperature; (iii) the breathing rate of the respirator user, and (iv) the variability of respirator

\textsuperscript{3} Also referred to as ‘cartridge’.
\textsuperscript{4} Also referred to as ‘cartridge’.
\textsuperscript{5} Also referred to as ‘canister’.
filters between manufacturers. As a result, the service life of gas filters is largely unknown, and as a ‘rule of thumb’, filters are replaced when the user senses an odour, taste, or irritation from the contaminants penetrating the filter.

It should be noted that currently no available filter can protect fire fighters from all hazards of bushfire smoke. In particular, removing carbon monoxide from the respirable air is currently not practicable, since this would require converting the carbon monoxide to carbon dioxide in an exothermic reaction. This process adds additional breathing resistance, increases the respiratory effort triggered by the respiratory stimulus of carbon dioxide, and increases the heat stress with the inhalation of hot air (Sharkey 1997b; Budd et al. 1997; Barnes 1999).

2.7.3.3 Air Supplying Respirators

These self-contained breathing apparatus (SCBA) is an air supplied respirator with air or oxygen carried in a cylinder on the person’s back (Figure 2.14). Although the air supplying respirators act to simultaneously control for particulates, vapours, gases, and carbon monoxide, its use is considered unsuitable for bushfire fighting. The cylinders are too heavy for use in high temperatures for long periods with a heavy workload. Moreover, the air in the cylinders lasts for approximately 30 minutes, which is too short to effectively fight bushfires. Supply and transport of hundreds of air cylinders to the fire scene, when staff workloads are stretched, would be logistically impossible (Gorman 2004; Melius 2001). For these reasons, the SCBA is not typically being used during bushfire fighting, and therefore, will not be further discussed in this thesis.

Figure 2.14 Scott Air-Pack® Fifty™ Self Contained Breathing Apparatus
2.7.4 Bandana: Respiratory Protection or Myth?

The bandana has been, and is still used by fire fighters and the general public in order to prevent the inhalation of air toxics from bushfire smoke (Figure 2.15). The bandana, similar to a handkerchief, has the ability to absorb and neutralize the penetrating odours from bushfire smoke. However, it has no filtering properties, and does nothing to prevent smaller PM, gases and vapours from entering the respiratory tract.

Figure 2.15 Carbon Shield™ Bandana

A study by the National Institute of Occupational Safety and Health (Reh, Letts & Deitchman 1994) showed that the pore size of a new unwashed bandana is approximately 200µm x 200µm (Figure 2.16). This is approximately 100 larger than the size of the fine particles (PM$_{2.5}$), which measure 2.5µm, and account for nearly 100% of the mass of PM in bushfire smoke (Ward 1997). Gases, vapours, and respirable and inspirable PM would readily pass through the fabric, and there was no indication that frequent washing and hot air drying significantly reduced the pore size of the fabric.
The findings of this study demonstrated that the bandana has no filtering capacity, and thus, does not protect the fire fighters from inhaling the air toxics from bushfire smoke. Moreover, wearing the bandanas may give the fire fighters a false sense of protection. Considering the above, Reh et al. (1994) recommended that the use of bandanas for forest fire fighters should be prohibited.

2.8 Summary

The preceding review of the literature has highlighted the extent of bushfires in Australia. Due to climatic variation and the vastness of the land area, bushfires occur somewhere in the country throughout the year, and the fire danger may continue for long periods. As a result, Australian fire fighters may be at risk of bushfire smoke exposure essentially in any season and for variable durations.

There is growing concern among Australian fire fighters about their respiratory health during and even weeks after bushfire fighting. In addition, the literature supports the anecdotal evidence, and demonstrates that occupational exposure to bushfire smoke may cause declines in pulmonary function and an increase in respiratory symptoms. Therefore, it is vital that fire fighters are issued with
appropriate respiratory protection to be used when bushfire smoke exposure is unavoidable.

The aim of this research is to develop a scientific database for policy development on the regulation of protective respiratory equipment for bushfire fighting. It is expected that transparent policies with regard to respiratory protection will provide guidelines for both fire agencies and fire fighters. As a result, informed decisions can be made with regard to the selection of the most appropriate respiratory protection for the specific task and situation.

The next chapter discusses the experimental burns, which were undertaken to identify and quantify the individual compounds in bushfire smoke. For years, the general assumption was that inhalation of bushfire smoke was relatively harmless. Given the complex mixture of identified toxic compounds in bushfire smoke, this perspective should be reviewed, and in particular exposure in the occupational context needs to be addressed to reduce the expanding resultant morbidity in Australian fire fighters.
Chapter 3 Analysis of Bushfire Smoke in Western Australian Conditions

3.1 Introduction

This chapter describes the sampling and analysis of bushfire smoke from native vegetation in Western Australia. The sampling was undertaken to identify and quantify bushfire smoke components in a systematic way for the first time in Western Australia. This study was undertaken as part of the Filter Study, which will be further discussed in Chapter 4.

3.2 Test Site and Conditions

Experimental smoke trials were undertaken in two situations: in a smoke chamber and during prescribed burns. The aim of these trials was to identify the chemical composition of bushfire smoke in a Western Australian context. The emphasis of the sampling was on the toxic compounds already reported in overseas studies. Also personal sampling in the breathing zone of the participating fire fighters was undertaken as part of the Filter Study (Chapter 4). The following section describes the test sites and the smoke conditions during the experimental trials.

3.2.1 Study Site 1: Smoke Chamber

The smoke chamber used for the study was a modified sea container (12.2m x 2.4m x 2.4m), which is commonly used by FESA for education and training purposes. The container had two doors which could be opened to regulate the smoke behaviour and density inside (Figure 3.1).
A light smoke situation was produced, determined as a density of smoke producing a white to light grey colour with reasonable visibility of at least 15 metres (Fire and Emergency Services Authority Western Australia 2007). Visual assessment of the smoke was undertaken by one single observer, using the visual smoke exposure classification as described by Reinhardt and Ottmar (2000). It is acknowledged that the visual assessment of smoke density may be complicated by confounding factors such as type of biomass fuel, combustion properties, and light conditions (e.g. day vs. night, sunny vs. cloudy day). Five white circles were therefore spray-painted on the rear panel of the smoke chamber to provide a consistent indicator for the visibility (Figure 3.2).
The smoke was generated from a small incinerator (Figure 3.7), which was located outside, and was connected into the smoke chamber. The environment inside the smoke chamber was controlled as far as practicable to ensure an even distribution and density of the smoke at all times.

The vegetation used in the smoke chamber trials was a mixture of banksia and coastal heath (Figure 3.4) collected in the Gingin and Eglington area in Western Australia. This material was typical of the material fire fighters would encounter in Western Australian bushfire situation. These vegetation types were also selected because, based on workplace reports, they are known to create substantial smoke levels during bushfires. The collected vegetation was stockpiled at the FESA Training Centre, Forrestfield. The moisture content of the vegetation was analysed and recorded at 9.4 percent during period of the smoke chamber trials (Wilkinson, S., pers. comm. 2004).
3.2.2 Study Site 2: Prescribed Burns

Prescribed burns are low intensity fires used to reduce the build up of leaves and twigs on the forest floor. This procedure has proven to be an effective and environmentally sound way of reducing the future risks of destructive, high intensity bushfires. The frequency of prescribed burns in a given area is variable, with intervals between burns typically ranging from five to 15 years. The preferred seasons are usually during spring and autumn months. Only 60 to 80 percent of each target burn area is actually burnt and many areas remain unburnt for several decades. Fire is also used to promote the biological diversity of the forest, to regenerate habitat for native fauna and to restore areas cut for timber.

The Department of Environment and Conservation (DEC) in Western Australia undertakes the prescribed burns as part of the ‘Indicative Prescribed Burning Plan South-West Western Australia, Spring 2005 to Autumn 2008’. These prescribed burns are designed to meet either a primary purpose, or a combination of purposes that include:

- Biodiversity conservation, i.e. through application of scientifically based fire regimes to maintain and protect native flora and fauna communities and/or habitats;
- Community protection, including the protection of human life, property, public assets, parks, timber values and plantations; and
- Silvicultural burns for regeneration of native forests following timber harvesting.
The Phase 2 trials were conducted during four prescribed burns in the Yanchep and Two Rocks area, which is on the outer fringe of the Perth Metropolitan area (Figure 3.5).

**Figure 3.5 Location of Prescribed Burns**
(Map Courtesy Department of Environment and Conservation 2005; Map Overlay Courtesy Y. P. Lee 2006)
Chapter 3 Analysis of Bushfire Smoke in Western Australian Conditions

The prescribed burns were managed and controlled by CALM officers. Table 3.1 shows the collected field data and predicted conditions for these days.

Table 3.1 Details of the Prescribed Burns
(Sage, L., pers. comm. 2006)

<table>
<thead>
<tr>
<th></th>
<th>17 and 20 October 2005</th>
<th>10 and 24 November 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Caraban State Forest Block Prescribed Burn (415 057A) - approx. 10 km NE of Two Rocks/Yanchep (Figure 10)</td>
<td>Caraban State Forest Block Prescribed Burn (415 055) - approx. 5 km E of Yanchep</td>
</tr>
<tr>
<td>Area burnt</td>
<td>20 to 30 hectares per day were burnt to provide smoke for the trial</td>
<td>20 to 30 hectares per day were burnt to provide smoke for the trial</td>
</tr>
<tr>
<td>Total burn area</td>
<td>418 hectares</td>
<td>210 hectares</td>
</tr>
<tr>
<td>Vegetation Type</td>
<td>Predominantly Banksia Low Forest A (LAc) with small areas of Dryandra sessilis Dense Heath A (Figure 9)</td>
<td>Predominantly Banksia Dense Low Forest A (LAd) with some emergent Eucalyptus marginata and E. gomphocephala</td>
</tr>
<tr>
<td>Associated Plant Species</td>
<td>Banksia grandis, Banksia menziesii, Acacia pulchella, Xanthorrhoea preissii, Dryandra sessilis, Scaevola repens, Scaevola canescens, Conostylis aculeate, Dampiera linearis, Hakea prostrata, Hakea lissocarpha, Melaleuca spp., Eucalyptus todtiana</td>
<td>Eucalyptus marginate, E. gomphocephala, Eucalyptus todtiana, Banksia grandis, B. menziesii, Xanthorrhoea preissii, Allocasurina fraseriana, Carpobrotus sp., Conostylis aculeate, Hakea prostrata, Hakea lissocarpha, Scaevola repens, S. canescens</td>
</tr>
<tr>
<td>Fire Behaviour</td>
<td>Surface Moisture Content (SMC) 8 - 12%</td>
<td>SMC 10 - 12%</td>
</tr>
<tr>
<td></td>
<td>Rate of Spread ~ 35m/hr</td>
<td>Rate of Spread ~ 35m/hr</td>
</tr>
<tr>
<td></td>
<td>Fire intensity - low to medium</td>
<td>Fire Intensity - low to medium</td>
</tr>
<tr>
<td>Predicted Conditions</td>
<td>17 October 2005</td>
<td>10 November 2005</td>
</tr>
<tr>
<td></td>
<td>Min SMC for pine 10%</td>
<td>Min SMC for pine 8%</td>
</tr>
<tr>
<td></td>
<td>Fire Danger Index (FDI) 441m/hr and extreme</td>
<td>FDI 181m/hr and very high</td>
</tr>
<tr>
<td></td>
<td>Winds mostly SW to 35 km/hr</td>
<td>Winds W to 20 km/hr</td>
</tr>
<tr>
<td></td>
<td>Temp 21 °C and fine</td>
<td>Temp 24 °C and fine</td>
</tr>
<tr>
<td></td>
<td>20 October 2005</td>
<td>24 November 2005</td>
</tr>
<tr>
<td></td>
<td>Min SMC for pine 7%</td>
<td>Min SMC for pine 6%</td>
</tr>
<tr>
<td></td>
<td>FDI 414m/hr and extreme</td>
<td>FDI 370m/hr and extreme</td>
</tr>
<tr>
<td></td>
<td>Winds mostly W to 25 km/hr</td>
<td>Winds mostly SW to 28 km/hr</td>
</tr>
<tr>
<td></td>
<td>Temp 21 °C and fine</td>
<td>Temp 23 °C and fine</td>
</tr>
<tr>
<td></td>
<td>Windy and then showers</td>
<td>Windy and then showers</td>
</tr>
</tbody>
</table>
For the purpose of the study, a consistent light smoke situation was required comparable to the smoke produced in the smoke chamber. In order to monitor the smoke pattern during the prescribed burns, 20 fire fighters were asked to complete an observation sheet with respect to vegetation, terrain, wind, and smoke behaviour. Table 3.2 summarises these recordings.

<table>
<thead>
<tr>
<th>Smoke Behaviour Indicator</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation type</td>
<td>Scrubland, banksias, grass trees, coastal heath</td>
</tr>
<tr>
<td>Vegetation height</td>
<td>1 - 4 meter</td>
</tr>
<tr>
<td>Vegetation dryness</td>
<td>Moderate - dry - very dry</td>
</tr>
<tr>
<td>Slope terrain</td>
<td>Level - gentle slope - 5°</td>
</tr>
<tr>
<td>Wind direction</td>
<td>South - South-West</td>
</tr>
<tr>
<td>Wind speed</td>
<td>15 - 20 km/hour</td>
</tr>
<tr>
<td>Smoke density</td>
<td>Light – moderate</td>
</tr>
<tr>
<td>Smoke behaviour</td>
<td>Consistent, stable, drifting slightly, swirling</td>
</tr>
<tr>
<td>Fire fighters’ position in the smoke</td>
<td>Downwind - peripheral – central</td>
</tr>
<tr>
<td>Other observations</td>
<td>Light smoke, not from an intense hot fire, thick smoke at the end</td>
</tr>
</tbody>
</table>

### 3.3 Methodology

The Chemistry Centre Western Australia (CCWA) was commissioned to perform the monitoring and sampling of the bushfire smoke compounds of interest, including PM, formaldehyde, acrolein, CO, and volatile organic compounds (VOCs). Table 3.3 outlines the sampling methodology in the smoke chamber and in the field during the prescribed burns.

<table>
<thead>
<tr>
<th>Smoke Compound</th>
<th>Smoke Chamber (Static Sampling)</th>
<th>Prescribed Burns (Personal Sampling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>DustTrak Aerosol Monitor</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Gravimetric sampling</td>
<td></td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>Sorbent tubes</td>
<td>Sorbent tubes</td>
</tr>
<tr>
<td>Acrolein</td>
<td>Sorbent tubes</td>
<td>Sorbent tubes</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>Multi-Gas Monitor</td>
<td>n/a</td>
</tr>
<tr>
<td>VOCs</td>
<td>Multi-Gas Monitor</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Hapsite Portable GC/MS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3M™ Organic Vapour Monitors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(personal sampling)</td>
<td></td>
</tr>
</tbody>
</table>
3.3.1 Static Sampling

Particulate matter was measured using the DustTrak™ Aerosol Monitor (Figure 3.6). This is a portable, battery-operated, laser-photometer that measures and records airborne dust concentrations. The device shows real-time concentrations in mg/m$^3$, while data is simultaneously logged into the memory. A PM$_{10}$ impactor was used on the DustTrak™, which was attached to a portable stand, and placed in the smoke chamber for a sampling period of 15 minutes (Figure 3.7). In addition, gravimetric samples (PM$_{10}$) were collected onto pre-weighed 25 mm Acrylic filters (pore size 1 µm, sample rate 2 L/min).

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6 The use of trade names is for reader information only and does not imply endorsement by the author of any product.
Carbon monoxide and VOC monitoring was performed using the Multi-Gas Monitor PGM50-5P™. This is a portable monitor with Photo-Ionisation Detection, which determines the total level of VOCs (Figure 3.8).

![Figure 3.8 Multi-Gas Monitor](image)

The Hapsite™ Field-Portable Gas Chromatograph/Mass Spectrometer was used to identify and quantify the VOCs, including benzene, toluene, ethylbenzene, xylenes, styrene, benzaldehyde, benzonitrile, phenol, benzoic acid, alkanes, indene, and naphthalene (Figure 3.9).

![Figure 3.9 Hapsite™ Gas Chromatograph/Mass Spectrometer](image)

Formaldehyde and acrolein were sampled, using a sampling pump and two sectioned 2,4-Dinitrophenylhydrazine SKC® sorbent tubes.

### 3.3.2 Personal Sampling

Organic vapours were sampled using 3M™ Organic Vapour Monitors, which are devices that collect contaminants through the principle of diffusion (Figure 3.10). The purpose of the use of personal sampling devices was to measure the specific individual exposures, thereby assisting in the determination of the type of respiratory equipment appropriate to the contaminants (Chapter 4).

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7 The use of trade names is for reader information only and does not imply endorsement by the author of any product.
The passive sampling of VOCs was conducted as per Australian Standard 2986.2 - 2003 (Standards Australia 2003a). The target compounds were N-hexane, benzene, toluene, ethyl benzene, M & P xylenes, O-xylenes, and total C2 benzenes. The monitors (n=8) were attached near the participant’s breathing zone, i.e. on the lapel of the jackets (Figure 3.11). Sampling lasted for 15 minutes, the minimal required period to obtain sufficient material for analysis (Standards Australia 2003a).

During the field trial, formaldehyde was sampled using 2,4-Dinitrophenylhydrazine SKC® sorbent tubes (i.e. similar methodology as in the smoke chamber). Only formaldehyde was sampled, because of logistic limitations: due to the unstable weather conditions, the researchers only had a time window of 24 hours to prepare laboratory equipment and arrange staff to attend the trials. No measurements of CO, particles, acrolein and VOCs were conducted during the field trials.
At the completion of the sampling, CCWA sealed and labelled the cassettes, organic vapour monitors, and sampling tubes. The collected samples were stored and transported under refrigeration, until analysed, to prevent sample degradation.

### 3.3.3 Chemical Analysis

The CCWA performed the analyses of the collected samples. The CCWA is accredited for a range of chemical science tests (NATA 8) and has a Quality Management System certified to AS/NZS ISO 9001:2000 (NSCI 6712). The following established methods were applied for analysis of the samples:

- **Particulate matter (PM):** Inspirable dust samples were analysed gravimetrically as per Australian Standard 3640 - 2004 (Standards Australia 2004);

- **Formaldehyde:** analysed by High Performance Liquid Chromatography, as per National Institute for Occupational Safety and Health (NIOSH) Method No. 2016 (Schlecht & O'Connor 2003);

- **Acrolein:** analysed by Gas Chromatography, as per NIOSH Method No. 2501 (Schlecht & O'Connor 1994);

- **Volatile Organic Compounds:** analysed by Gas Chromatography/Mass Spectrometry with flame ionisation detection, as per NIOSH Method No. 1501 (Schlecht & O'Connor 2003). The target compounds were N-hexane, benzene, toluene, ethyl benzene, M & P xylenes, O-xylenes, and total C2 benzenes.

The logged electronic monitor data for oxygen, CO, sulphur dioxide, nitric oxide, nitrogen dioxide, and particulate matter were downloaded, and printed out with result summaries (Genovese 2005).

### 3.4 Results

#### 3.4.1 Static Sampling

Static sampling was undertaken to characterise and quantify levels of air pollutants in the smoke chamber and in the field during the prescribed burns. Formaldehyde, acrolein, particles, CO and VOC levels were measured for 15 minutes in the smoke chamber. As noted above, only formaldehyde was sampled in the field, due to logistic limitations.
Table 3.4 presents an overview of the results of the static sampling. Formaldehyde levels ranged from 1.16 to 2.54 mg/m$^3$ during the three trials in the smoke chamber. Although the STEL level was exceeded slightly in one sample, it must be noted that these are static samples in contrast to personal samples, and thus participants have not necessarily inhaled these levels of formaldehyde. Formaldehyde levels during the prescribed burns ranged from 0.49 to 0.75 mg/m$^3$, which is well within the occupational exposure levels of 2.5 mg/m$^3$ (STEL) and 1.2 mg/m$^3$ (TWA), but in excess of the ACGIH ceiling limit of 0.3 ppm for this known human carcinogen. The mean formaldehyde level in the smoke chamber was approximately three times higher compared to the mean level of formaldehyde during the prescribed burns (1.84 (± 0.30) vs. 0.62 (± 0.10) mg/m$^3$). This discrepancy may be explained by the confinement and the limited airflow through the smoke chamber.

Acrolein levels were measured in the smoke chamber only, and ranged from ‘not detected’ to 0.69 mg/m$^3$. The measured concentrations in the second trial reached the STEL of 0.69 mg/m$^3$, and were significantly higher compared to the levels in the first and third trial. Although the trials were set up in a standard way to ensure consistency of the measurements, the variation in these findings may be explained by uncontrollable factors, including weather conditions. This may have resulted in a decreased airflow through the smoke chamber during the October 2004 trial.

Levels of particles (PM$_{10}$) in the smoke chamber ranged from 3.9 to 13.1 mg/m$^3$, with a mean of 10 mg/m$^3$, and exceeded the TWA of 10 mg/m$^3$ for non-toxic particles on three occasions. Due to the toxic nature of bushfire smoke, it would be more appropriate to compare these results to occupational standards for toxic particles. Unfortunately, such standards are not available, and no other existing guideline values capture the unknown synergistic and additive health effects of the individual compounds.
### Table 3.4 Results Static Sampling in Light Smoke
(Australian Safety and Compensation Council 1995)

<table>
<thead>
<tr>
<th>Air Toxic</th>
<th>15 Minute Sampling</th>
<th>2 Hour Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Smoke Chamber</td>
<td>Smoke Chamber</td>
</tr>
<tr>
<td></td>
<td>September 2004</td>
<td>October 2004</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>mg/m³</td>
<td>mg/m³</td>
</tr>
<tr>
<td>TWA 1.2 mg/m³</td>
<td>4 1.53 ± 0.39</td>
<td>4 1.74 ± 0.09</td>
</tr>
<tr>
<td>STEL 2.5 mg/m³</td>
<td>4 0.88 ± 0.10</td>
<td>4 0.58 ± 0.09</td>
</tr>
<tr>
<td>Acrolein</td>
<td>mg/m³</td>
<td>mg/m³</td>
</tr>
<tr>
<td>TWA 0.23 mg/m³</td>
<td>4 0.08 ± 0.10</td>
<td>4 0.58 ± 0.09</td>
</tr>
<tr>
<td>STEL 0.69 mg/m³</td>
<td>4 0.08 ± 0.10</td>
<td>4 0.58 ± 0.09</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>mg/m³</td>
<td>mg/m³</td>
</tr>
<tr>
<td>TWA 10 mg/m³</td>
<td>n/a</td>
<td>4 10.0 ± 4.10</td>
</tr>
<tr>
<td>STEL</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>ppm</td>
<td>ppm</td>
</tr>
<tr>
<td>TWA 30 ppm</td>
<td>27 ppm Range 2-130 ppm</td>
<td>131 ppm Range 5-742 ppm</td>
</tr>
<tr>
<td>STEL 200 ppm</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Total VOCs</td>
<td>ppm</td>
<td>ppm</td>
</tr>
<tr>
<td></td>
<td>2.1 ppm Range 0-12 ppm</td>
<td>2.1 ppm Range 0-22 ppm</td>
</tr>
</tbody>
</table>

°8-Hour Time Weighted Average
*15-Minute Short Term Exposure Limit
#Not detected
<Recommended TWA for inspirable non-toxic particles

Carbon monoxide levels varied considerably between the three trials in the smoke chamber. The mean values ranged from 27 to 257 ppm. Peak levels were measured at 130 ppm, 742 ppm, and 932 ppm (Figure 3.12 - Figure 3.14), which exceed the ceiling exposure limit of 400 ppm. Carbon monoxide levels for the field trials were not available.
Chapter 3 Analysis of Bushfire Smoke in Western Australian Conditions

Figure 3.12 CO Data Logger Record Smoke Chamber Trial (September 2004)°
(Courtesy Chemistry Centre Western Australia)

°Light smoke conditions

Figure 3.13 CO Data Logger Record Smoke Chamber Trial (October 2004)°
(Courtesy Chemistry Centre Western Australia)

CO (ppm)

°Light smoke conditions
Total VOCs were measured in the range 0 - 22 ppm (mean 2.7 ppm; SD ± 0.39). VOCs were characterised and quantified using the Hapsite™ Gas Chromatograph/Mass Spectrometer during one trial in the smoke chamber. The major VOCs identified in the experiment were benzene, toluene, ethylbenzene, xylenes, styrene, benzaldehyde, benzonitrile, phenol, benzofuran, alkanes, indene, and naphthalene. It was not possible to accurately quantify individual levels because many of the identified compounds were present only in trace amounts and were poorly resolved by this portable instrument (Wilkinson, S., pers. comm. 2005).

3.4.2 Personal Sampling

Personal sampling in the breathing zone of eight participants was undertaken with 3M™ Organic Vapour Monitors during one of the smoke chamber trials. The monitors were analysed for N-hexane, benzene, toluene, ethyl benzene, M & P xylenes, O-xylenes, and total C2 benzenes (i.e. xylenes and ethyl benzene). The presence of these organic vapours was demonstrated at extremely low levels compared to the established occupational standards (National Occupational Health and Safety Commission 1995) (Table 3.5). The mean toluene level was 7.57 (SD ± 3.67) ppm, with the maximum level of 14.60 ppm, which is approximately 10 percent of the STEL (150 ppm).
Table 3.5 Results Personal Sampling Volatile Organic Compounds in Light Smoke

<table>
<thead>
<tr>
<th>Volatile Organic Compound</th>
<th>N</th>
<th>Mean ± SD</th>
<th>Range</th>
<th>STEL</th>
<th>TWA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ppm</td>
<td>ppm</td>
<td>ppm</td>
<td>ppm</td>
</tr>
<tr>
<td>N-hexane</td>
<td>8</td>
<td>0.60 ± 0.28</td>
<td>0.34 - 1.18</td>
<td>Not established</td>
<td>50</td>
</tr>
<tr>
<td>Benzene</td>
<td>8</td>
<td>0.15 ± 0.19</td>
<td>0.04 - 0.60</td>
<td>OSHA 5</td>
<td>OSHA 1</td>
</tr>
<tr>
<td>Toluene</td>
<td>8</td>
<td>7.57 ± 3.67</td>
<td>3.39 - 14.60</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>Ethyl benzene</td>
<td>8</td>
<td>0.04 ± 0.01</td>
<td>0.03 - 0.06</td>
<td>125</td>
<td>100</td>
</tr>
<tr>
<td>M &amp; P xylenes</td>
<td>8</td>
<td>0.04 ± 0.01</td>
<td>0.03 - 0.06</td>
<td>150</td>
<td>80</td>
</tr>
<tr>
<td>O-xylenes</td>
<td>8</td>
<td>0.05 ± 0.02</td>
<td>0.02 - 0.06</td>
<td>150</td>
<td>80</td>
</tr>
<tr>
<td>Total C2 benzenes</td>
<td>8</td>
<td>0.13 ± 0.02</td>
<td>0.09 - 0.16</td>
<td>Not established</td>
<td>Not established</td>
</tr>
</tbody>
</table>

Finally, personal sampling of PM, formaldehyde, and acrolein was undertaken inside the participants’ respirators to compare the effectiveness of three different types of protective filters. This particular sampling was undertaken as part of the Filter Study, and therefore, will be discussed in Chapter 4.

### 3.5 Discussion

Experimental burns were undertaken in a smoke chamber and in the field, to identify and quantify the chemical composition of bushfire smoke in Western Australia. Although the emphasis of the sampling was on the toxic compounds already known from overseas studies, including PM, formaldehyde, acrolein and CO, breathing zone sampling of VOCs was undertaken as part of the Filter Study (Chapter 4).

The systematic sampling of PM, formaldehyde, acrolein and CO demonstrated the presence of these toxic compounds in Western Australian bushfire smoke. Levels of PM exceeded the TWA on one occasion in the smoke chamber. Formaldehyde and acrolein levels did not exceed the Australian occupational standards (Australian Safety and Compensation Council 1995) at any time in the smoke chamber or the prescribed burns. Yet, it must be noted that all measurements exceeded ACGIH ceiling limits for formaldehyde (0.3 ppm; 0.37 mg/m$^3$). CO monitoring with real time data loggers in the smoke chamber showed peak levels that exceeded the STEL. It is assumed that the high levels of PM and CO may have been caused by the confinement and the limited ventilation in the smoke chamber.

It is acknowledged that conditions during the trials, in particular in the smoke chamber, do not accurately replicate real bushfire fighting situations, due to the
nature of the burning process, humidity, variances in meteorological conditions, physical activity levels, and proximity to the smoke. Therefore, the concentrations of air toxics measured cannot be directly related to concentrations that fire fighters will be exposed to during bushfire fighting activities. Nonetheless, studies in the United States and in other Australian States have found similar results from smoke sampling during prescribed burns. Reinhardt et al. (2000) showed that during wildland fires, occupational exposure standards were exceeded for up to 14% of fire fighters’ exposures to respirable particles, formaldehyde, and acrolein, and 8% of exposures to CO. In another study, Reinhardt and Ottmar (2000) found that peak exposures at wildfires exceeded the STELs 50% of the time. Reisen et al. (2006) found during prescribed burns in Victoria, South Australia, and the Northern Territory that respirable particle levels frequently exceeded the TWA of 10 mg/m$^3$, and CO levels exceeded occupational exposure levels in a small (not specified) number of cases, related to specific tasks. Furthermore, formaldehyde and acrolein were identified as the major aldehydes present in the bushfire smoke.

Due to the number of variables it is difficult - if not impossible - to establish a clear-cut chemical profile of bushfire smoke. Nevertheless, since the 1980s researchers in the United States have identified a large number of chemicals in wildland fire smoke, including particulate matter, formaldehyde, acrolein, and CO. Further exposure studies have demonstrated associations between these chemicals and respiratory symptoms in wildland fire fighters.

The health effects of PM largely depend on the size and characteristics of the adhered compounds. Consequently, there is no single description available of the health effects of particles of smoke. Formaldehyde is a known human carcinogen (International Agency for Research on Cancer 2004a), and causes direct irritation of both the skin and the respiratory tract. Acrolein is an irritant, and adverse health effects associated with exposure are mostly confined to the tissue of first contact, which is often the respiratory tract, due to inhalation of smoke. Carbon monoxide has acute effects on the body, ranging from slightly diminished work capacity to acute nausea, severe headache, dizziness, and impaired judgement. Death can occur during extreme exposure levels, but these levels are unlikely to exist away from enclosed spaces.
The findings of the conducted sampling demonstrated that Western Australian bushfire smoke contains air toxics of concern. This provides a justification for further research into profiling the air toxics in bushfire smoke under different conditions, over longer time frames, and in different locations in Western Australia. Furthermore, it would be useful to minimise fire fighters’ exposure to bushfire smoke, and to ensure that fire fighters are issued with optimal respiratory protection to be used when necessary.

The next chapter describes the Filter Study undertaken to investigate the effectiveness of the respiratory protective equipment issued to the FESA career fire fighters in Western Australia. The particular equipment consists of a respirator and filters, which are to be used during bushfire fighting. Three types of filters will be tested and compared in an experimental setting in a smoke chamber and in the field during prescribed burns.
Chapter 4 Filter Study

4.1 Introduction

The previous chapter describes the components of bushfire smoke and the pattern of occupational exposure in the Australian environment. It was demonstrated that bushfire fighters are potentially at risk from inhalation injury caused by bushfire smoke. Given the increasing extent of the urban-rural interface with our expanding cityscapes, bushfire fighters are often involved in protecting life and property, and as a consequence have limited options to reduce their exposure. Although many different protective respirators and filters are available for use during bushfire fighting activities, it is not clear which is the most effective from a health and safety perspective.

For a number of years there has been considerable concern among the group of approximately 1,000 FESA career fire fighters in Western Australia about the effectiveness of the issued particulate filters (Chatfield 2002; White 2001). Fire fighters reported symptoms of wheezing, coughing, and shortness of breath, even days after bushfire fighting, despite using their respirator equipped with particulate filters. FESA considered this to be an important occupational health issue that needed to be addressed in a systematic and scientific way. The Respiratory Health Steering Committee, comprising of FESA managers, Occupational Health and Safety Officer, and FESA career fire fighters, was established to explore this issue further. In 2004, the Bushfire Cooperative Research Centre, of which FESA is a Core Partner, commissioned the School of Population Health, The University of Western Australia to investigate the effectiveness of the particulate filters during bushfire fighting. This resulted in a two-year research project ‘Respiratory Health of Fire Fighters’, which commenced in May 2004.

This chapter outlines the project, and describes the methodology used, the findings, conclusions, and recommendations for best practice.

4.2 Methodology

This section provides an overview of the project ‘Respiratory Health of Fire Fighters’. It describes the design, the study population, the recruitment and different
stages of the two-year project. The findings of the exposure trials are presented and discussed, which are then followed by the recommendations for best practice to minimise exposure to bushfire smoke and to protect fire fighters’ respiratory health during bushfire fighting.

4.2.1 Study Design

The study used a double-blind randomised experimental design. The fundamental reason for the use of randomisation is to ensure that the intervention groups were initially comparable, and that the differences that appear between the exposure groups relate (as far as possible) to actual differences between the interventions. Random allocation also maximises the likelihood that each intervention will be allocated in similar proportions to the participants (Ahrens & Pigeot 2005).

Double-blinding ensured that neither the participants nor the researchers had any knowledge of which intervention (i.e. which filter type) the individual participants were using during the trials. The aim of this method was to help prevent influences on the study outcomes as a result of the participants’ perceptions of using a particular type of filter (Ahrens & Pigeot 2005; Nickerson 1998).

4.2.2 Protocol

A study protocol was developed to provide a reference guide for the researchers during the exposure trials and to supply a permanent record of the conduct of the trials. The protocol outlined the background and the rationale for the trials, the study design, the methodology, the study population, the exclusion criteria, the trial procedures, the required conditions, the duration of the trials, the project timeline, the strategy for statistical analysis, and the ethical aspects. An emergency protocol was included for use in case of any adverse events during the trials.

4.2.3 Study Population

The source population from which the study participants were drawn consisted of the group of 1,000 male and female FESA career fire fighters in Western Australia. The study participants were defined as currently active career fire fighters based in fire stations in the Perth Metropolitan Area. The study population was randomly selected from the available FESA Staff Deployment System.
Given that the 20 metropolitan fire stations experience different bushfire attendances, two stratified random samples were taken from the fire stations. Stratified randomisation is the process of grouping members of the study population into homogeneous subgroups before sampling (i.e. bushfire attendance and consequently bushfire smoke exposure). It is aimed at improving the representativeness of the sample by reducing the sampling error. One stratum consisted of four fire stations experiencing high bushfire attendances (i.e. Balcatta, Canning Vale, Joondalup, Malaga fire stations). The second stratum consisted of the 16 remaining fire stations, which, according to work reports, experienced lower bushfire attendances.

Participants were enrolled for the study depending on their availability during the exposure trials and participated on a voluntary and confidential basis. Individuals with unstable asthma, current acute or chronic respiratory illness, or any other chronic or severe illnesses were excluded from the study.

Sample size calculation showed that, to detect at least a 20% variation in baseline respiratory status (with 95% confidence; power 80%) in any of the respiratory outcomes (as identified by the questionnaire and/or spirometry) across the three classifications of filter status, a total of 140 participants would be required.

Approval for the study was obtained from the Human Research Ethics Committee, The University of Western Australia.

4.2.4 Recruitment

In order to raise awareness about the study, the researchers arranged four information sessions at FESA House, Perth, at which hundreds of fire fighters attended. The information sessions consisted of presentations by the researchers about the objectives of the study and details about the exposure trials. The information sessions were concluded with a question and answer session.

The researchers designed posters, which outlined the study purpose and recruitment procedures, and circulated these around the fire stations. FESA released an Intranet Circular with the same information.
The researchers recruited the fire fighters by telephoning them at their fire station. They were informed about the study and asked whether they wished to participate. Next, the participants were admitted in the trial by entry of their details into a register and allocation of an identification number. Participation in the study was voluntary, and depended on the fire fighters’ availability during the trials. The researchers contacted 189 fire fighters initially, but due to non-availabilities, emergencies, and transport issues, a total of 131 fire fighters agreed to participate in the study. Individuals with self-reported unstable asthma, current acute or chronic respiratory illness, or any other chronic or severe illness were excluded. It was ensured that subjects in Phase I were excluded from participation in Phase II. Figure 4.1 and Figure 4.2 outline the various stages in the recruitment process of Phase 1 (Controlled Exposure Trials in Smoke Chamber) and Phase 2 (Field Validation Trials during Prescribed Burns).

The random allocation of the intervention was determined by the researchers after completion of the participant register. Therefore, the decision to participate in the study was made regardless of allocation into a particular intervention group. This precluded the possibility that particular filters were allocated to specific participants, and discouraged ‘guessing’ systems, in which participants attempt to find out which intervention is allocated to them (which may have resulted in ‘unblinding’ of the study).
Chapter 4 Filter Study

Figure 4.1 Recruitment Phase 1 Controlled Exposure Trials Smoke Chamber

Total source population (n = 1,000)

Assessed for eligibility (n = 91)

Exclusion or non-participation (n = 27):
- Failed to meet inclusion criteria (n = 2)
- Refused to participate (n = 8)
- Not available (n = 17)

Randomised (n = 64)

Allocated to P filter group (n = 24)
Allocated to P/OV filter group (n = 23)
Allocated to P/OV/F filter group (n = 17)

Figure 4.2 Recruitment Phase 2 Field Validation Trials - Prescribed Burns

Total source population (n = 936)

Assessed for eligibility (n = 98)

Exclusion or non-participation (n = 31):
- Failed to meet inclusion criteria (n = 2)
- Refused to participate (n = 7)
- Not available (n = 22)

Randomised (n = 67)

Allocated to P filter group (n = 13)
Allocated to P/OV filter group (n = 27)
Allocated to P/OV/F filter group (n = 27)
4.2.5 Test Filters

At the outset of the project it was intended that the study would include a group of participants who were not wearing any form of respiratory protection to provide a baseline measurement. However, as described in Chapter 3, the air sampling inside the smoke chamber during the experimental burn in September 2004 indicated high levels of particles ($13.1 \text{ mg/m}^3$), compared to the occupational standards for non-toxic particles ($10 \text{ mg/m}^3$). Thus, for safety and ethical reasons, it was decided not to proceed testing without some form of personal respiratory protection.

The three types of filters tested were:

1. Particulate\textsuperscript{8} filter (3M\textsuperscript{TM} 5925). This is a filter intended for use against both mechanically and thermally generated particles. It was selected for the trials because it is commonly issued to FESA career fire fighters in Western Australia, as per Standard Operational Procedures 51 (Fire and Emergency Services Authority Western Australia 2007).

   \textbf{Figure 4.3 Particulate Filter}

   ![Particulate Filter](image)

2. Organic Vapour filter (3M\textsuperscript{TM} 6057ABE1) with attached P filter (Figure 4.4). This OV filter is for use against certain organic and inorganic gases, sulphur dioxide, acid gases and vapours, and against particles when combined with the P filter.

\textsuperscript{8} For reader’s convenience the particulate filter will be abbreviated to P filter, the particulate/organic vapour filter to P/OV filter, and the particulate/organic vapour/formaldehyde filter to P/OV/F filter.

\textsuperscript{9} The use of trade names is for reader information only and does not imply endorsement by the author of any product.
This combination of these filters (P/OV) was selected for the trials because a group of FESA career fire fighters had independently elected to purchase their own P/OV filters. These fire fighters have advocated the use of these filters within FESA as they perceived they experienced considerably less respiratory symptoms following bushfire emergencies. In order to establish scientific evidence for these perceptions, and thus to determine which device is more effective in protecting the fire fighters’ respiratory health, this combination of filters was included in the trials;

Figure 4.4 Organic Vapour Filter - Particulate Filter - Retainer

3. Organic Vapour/Formaldehyde (OV/F) filter (3M™ 6075 A1) with attached P filter (Figure 4.5). This filter is for use against organic gases and formaldehyde vapour, and against particles when combined with a P filter. This particular filter combination (P/OV/F) was selected for the trials because initial air sampling in the smoke chamber indicated the presence of formaldehyde concentrations in the smoke (Chapter 3). Although levels detected in the experimental burns were well within STEL (but exceeded ACGIH ceiling limits of 0.3 ppm), formaldehyde is a compound of concern as it is a known carcinogen to humans (International Agency for Research on Cancer 2004a). It was therefore considered relevant to include the P/OV/F filter in the project to be tested against the P and the P/OV filter.
For the purpose of the trials, the filters were made similar in appearance in order to conceal the identity of the allocated filter. To achieve this, the researcher opened OV filters on one side and removed the sorbent material and then attached the P filter (3M™ 5925) and the retainer (3M™ 501) on the empty filters (Figure 4.4), and fitted the assembled filter combination (Figure 4.5) on the respirator (Figure 4.6). Blinding of the participants was instituted to prevent the outcome measurement being influenced by knowledge of which type of filter was used (an example of confirmation bias).

The three types of study filters were randomly allocated to the participants. Before the trials, the researcher assembled packages, consisting of an information sheet, a consent form, and a questionnaire. Every package was tagged with a number, which corresponded with one of the similarly numbered study filters. The researcher maintained a register of the three types of filters and its coding, which was kept in a locked filing cabinet in the office. On the day of the trial, the research-assistants
handed out the administration packages randomly to the participants. This ensured that the researcher and the participants were not aware of what type of filter the participants used during the trials.

4.2.6 Respirators

The respirators used for the trials were the 3M™ 6000 Series Standard Half Face Respirators. The respirators have a soft, lightweight elastomeric face piece with a cradle head harness and neck strap (Figure 4.7). The respirators are used with the filters, and are available in three sizes (small, medium, large) to fit various face sizes.

Figure 4.7 3M 6000 Series Standard Half Face Respirator

These respirators are issued to FESA career fire fighters in Western Australia for use during bushfire fighting. On the day of the trial, the participating fire fighters were requested to bring their own respirator as part of their ‘turn-out gear’.

4.2.7 Phase 1 - Controlled Exposure Trials - Smoke Chamber

Phase 1 of the study was conducted over seven trial sessions in a controlled environment at the FESA Training Centre at Forrestfield between September and December 2004. The smoke chamber used for the study was a modified sea container, which is commonly used by FESA for training purposes. The container had a door completely open for the fire fighters to exit at all times.

On arrival at the FESA Training Centre, the participants were informed about the aims of the study, the procedures, and safety issues during the trials. All participants were asked to read the information sheet, sign the consent form, and given the
opportunity to raise any questions about the study. They completed the first part of the questionnaire (Appendix 1 and 2). Before entering the smoke chamber, the participants were required to wear their full ‘turn-out gear’ (except the structural fire fighting helmet): goggles, turnout coat, turnout pants, and boots. The fire fighters’ used their own 3M™ 6000 Series Standard Half Face Respirators for the trials, given that the fire fighters were familiar with its use and fitting.

The researchers then attached the randomly allocated study filters to the participants’ respirator (Figure 4.8), and the participants were asked to perform a Positive Pressure Fit Check in accordance with Australian/New Zealand Standard 1715 to ensure an appropriate seal of the respirator.

![Figure 4.8 Participant with Respirator and Study Filter](image)

Smoke conditions within the smoke chamber were adjusted as much as possible to resemble a light smoke, which was determined as a white to light grey colour with reasonable visibility of at least 15 metres. The smoke was generated from a small incinerator in a standardised way to maximise reproducibility of the smoke characteristics throughout all trial sessions. Visual assessment of the smoke was undertaken by one consistent observer using the visual smoke exposure classification as described by Reinhardt and Ottmar (2000). Spray painted white dots on the rear panel of the smoke chamber served as indicators for the smoke density (Figure 4.9). The environment inside the smoke chamber was controlled as far as practicable, and a pedestal fan was used to ensure a consistent distribution and density of the smoke at all times.
The participants entered the smoke chamber at staggered five minutes intervals, thereby ensuring that participants could undergo spirometry measurement immediately after exiting the smoke chamber. The participants were asked to walk around in the smoke chamber to ensure exposure to a representative sample of the smoke. To obtain a sufficient sample volume for peak exposure measurement inside the respirators, the required exposure period inside the smoke chamber was set at 15 minutes. The participants were assured that they could step out of the chamber at any time, if they experienced any adverse health effects, such as shortness of breath, wheezing, dizziness, anxiety, or distress.

During the exposure trials, one of the researchers, being a Registered Nurse, maintained an oversight over the participants. Full first aid facilities were available at the test-site, and an emergency protocol was in place.

4.2.8  Phase 2 Field Validation Trials - Prescribed Burns

To validate the findings from the controlled exposure trials in the smoke chamber, four prescribed burns were undertaken in the field in October and November 2005. Section 3.2.2 outlines the rationale for the prescribed burns and the details of the environmental conditions.

The field validation trials were conducted utilising the same exposure methodology, used for the controlled trials in the smoke chamber (Chapter 33.2.1). On arrival at the site of the prescribed burns, the participants were informed about the aims of the study, the procedures, and safety issues during the trials. All participants were provided with an information sheet and a consent form. They then completed the
first part of the questionnaire and performed the spirometry and oximetry testing (Section 4.2.9). Before entering the smoke area, the participants were required to wear their full ‘turn-out gear’. The fire fighters used their own 3M™ 6000 Series Standard Half Face Respirators during the trials. After the researchers attached the study filters to the participants’ respirator, they were asked to perform a Positive Pressure Fit Check in accordance with Australian/New Zealand Standard 1715.

The participants were transported to the smoke area in the field, once the prescribed area had burnt sufficiently to produce light smoke conditions. The participants were requested to stay in the field for two consecutive periods of 60 minutes. They were asked to move around in the field to ensure exposure to a representative sample of the smoke (Figure 4.10). After the first exposure period of 60 minutes, the fire fighters were brought out of the smoke and transported to base where measurements were taken (Section 4.2.9). After approximately 10 minutes break, they were returned to the smoke zone for a further 60 minutes, after which they returned to base where final measurements were taken.

Figure 4.10 Fire Fighters in the Field during Prescribed Burns

During the trials the participants were assured that they could remove themselves from the smoke at any time if they experienced any adverse health effects, e.g. shortness of breath, wheezing, or dizziness. In addition, the participants were under the observation of a Registered Nurse. First aid facilities were available at the test-site, and an emergency protocol was in place.
4.2.9 Data Collection

The effectiveness of the three types of filters was assessed by measuring respiratory symptoms and pulmonary function before and after controlled exposure to bushfire smoke. In addition, the air toxics formaldehyde, acrolein, carbon monoxide and particles were sampled inside the respirators to determine the individual breakthrough levels of these toxics.

4.2.9.1 Questionnaire

The self-completed respiratory symptom questionnaire (Appendix 2 and 3) was designed to obtain information about the participants’ perception of respiratory symptoms before and after exposure to combustion products of Australian bushfire smoke. The questionnaire was based on the Medical Research Council questionnaire, a validated instrument designed to elicit details about symptoms and factors associated with pulmonary diseases and smoking history (Medical Research Council 1986).

The respiratory symptom list included questions pertaining to intensity and frequency of cough, wheeze, shortness of breath, tightness in the chest, and sore throat. Participants were classified as either non-smokers, past smokers or current smokers, and cigarette consumption was estimated in standard pack-years. Additional questions were included to obtain information about the participants’ risk perceptions in relation to the acute respiratory health effects of bushfire smoke exposure.

The questionnaires were administered at different time intervals relevant to the exposures. Table 4.1 outlines the administration times of the questionnaire during Phase 1 and Phase 2 of the project.
Table 4.1 Measurements of Respiratory Symptoms and Pulmonary Function

<table>
<thead>
<tr>
<th></th>
<th>Baseline Before Exposure</th>
<th>After 15 Minutes Exposure</th>
<th>After 30 Minutes Recovery Time</th>
<th>After 60 Minutes Exposure</th>
<th>After 120 Minutes Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1 Controlled Exposure Trials - Smoke Chamber - Exposure 15 min.</td>
<td>Questionnaire FEV₁ SaO₂</td>
<td>Questionnaire FEV₁ SaO₂</td>
<td>Questionnaire FEV₁ SaO₂</td>
<td>Questionnaire FEV₁ SaO₂</td>
<td>Questionnaire FEV₁ SaO₂</td>
</tr>
<tr>
<td>Phase 2 Field Validation Trials - Prescribed Burns - Exposure 120 min.</td>
<td>Questionnaire FEV₁ SaO₂</td>
<td>Questionnaire FEV₁ SaO₂</td>
<td>Questionnaire FEV₁ SaO₂</td>
<td>Questionnaire FEV₁ SaO₂</td>
<td>Questionnaire FEV₁ SaO₂</td>
</tr>
</tbody>
</table>

4.2.9.2 **Spirometry**

Pulmonary function testing was used to detect and quantify abnormal lung function. Forced expiratory volume in one second (FEV₁) was selected, which is known as one of the most valuable and reliable of all pulmonary parameters. FEV₁ is an extensively used index with good reproducibility, and provides the best method of detecting the presence and severity of airway obstruction (Pierce et al. 2005). In a fire-fighting context, reduction of spirometry measurements has been shown to relate to combined smoke inhalation injury and burns (Haponik & Munster 1990). Changes in FEV₁ across a work shift have been described as useful work-related response indices to measure impaired lung function (Venables 1994).

Spirometry was performed by the researcher, who is a Registered Nurse, and trained according to the guidelines for manoeuvre performance provided by the American Thoracic Society (ATS) (Miller et al. 2005). A single Welch Allyn PneumoCheck™ Spirometer was used in all tests to ensure standardisation of the measurements (Figure 4.11). Calibration of the equipment was performed with a 3 litre syringe before each testing session, and readings were automatically corrected to body temperature and barometric pressure.
A minimum of three manoeuvres was undertaken to meet the ATS criteria for collection and to obtain reproducible tracings with the two highest FEV$_1$ within 5% of each other. All participants were tested sitting straight up with their feet firmly on the floor, and without a nose clip (Figure 4.12). Spirometric data were collected before entering and immediately after exiting the smoke situation. The change in FEV$_1$ ($\Delta$ FEV$_1$) for each participant was measured by subtracting the FEV$_1$ obtained after the exposure from the baseline FEV$_1$ measured before the exposure.

4.2.9.3 Oximetry

Arterial hypoxemia and reduced haemoglobin oxygen saturation (SaO$_2$) have been shown to accompany smoke inhalation and cutaneous burn injury, either separately or in combination. Transient hypoxemia has been documented following the exposure of 21 fire fighters to dense smoke (Genovesi et al. 1977). Nineteen of these individuals were asymptomatic, and oxygen levels normalised within 20 hours. Whitener et al. (1980) noted reduced oxygen levels in patients who had large burns or burns with inhalation injury compared with those with small burns. A
decline in \( \text{SaO}_2 \) may indicate the presence of high levels of carbon monoxide in the bushfire smoke. Thus, the presence of hypoxemia can provide an indication of lung injury. However, it is important to note that arterial oxygen measurements must be interpreted not absolutely, but in relation to the inspired oxygen concentration.

The arterial oxygen saturation of haemoglobin was measured in percentages (%) using a Datex-Ohmeda TuffSat\textsuperscript{TM10} pulse oximeter (Figure 4.13). The change in \( \text{SaO}_2 \) (\( \Delta \text{SaO}_2 \)) for each participant was measured by subtracting the \( \text{SaO}_2 \) obtained after the exposure from the baseline \( \text{SaO}_2 \) measured before the exposure.

![Datex-Ohmeda TuffSat\textsuperscript{TM} Pulse Oximeter](image)

**Figure 4.13 Datex-Ohmeda TuffSat\textsuperscript{TM} Pulse Oximeter**

4.2.9.4 **Personal Air Sampling inside the Respirators**

Personal air samples from inside the respirators were collected via sampling ports, according to a method described and validated by Johnston et al. (1992). Jankovic et al. (1991) have discussed similar methods for SCBAs. Similar to Johnston’s method, the respirators were drilled and fitted with 60 cm Tygon\textsuperscript{TM} tubing (6 mm) (Figure 4.14).

\textsuperscript{10}The use of trade names in this report is for reader information only and does not imply endorsement by the author of any product.
The tubing was connected to the air sampling pump attached to the waist belts worn by the participants (Figure 4.15). Air sampled from inside the respirator was passed through a pre-weighed filter in a cassette and a carbonyl compound sorption tube connected in series using a calibrated air sampling pump (set at 1 litre/minute). In the smoke chamber, the sampling lasted for 15 minutes: that is, the minimum period to ensure collection of sufficient sample volume. In the field trials, the sampling lasted for 120 minutes, broken into two periods of 60 minutes.

4.2.10 Chemical Analyses

The CCWA performed all sampling procedures and laboratory analyses. PM sample filters were analysed gravimetrically as per Australian Standard AS 3640:2004. Formaldehyde and acrolein were analysed by High Performance Liquid
Chromatography in accordance with the National Institute for Occupational Safety and Health Method 2016. Samples were stored under refrigeration and transported in accordance with established procedures to prevent sample degradation. Electronic monitor data for oxygen, toxic gases and PM$_{10}$ were downloaded and printed out with summary results.

### 4.2.11 Statistical Analyses

Data analyses were performed using SPSS for Windows (Version 14.0) and Stata (Version 9.0). Kolmogorov-Smirnov analyses were used to test dependent and independent variables for violations of normal distribution. Respiratory health outcomes were measured by symptom scores. The differences in respiratory health outcomes (i.e. ‘better’, ‘no difference’, ‘worse’) were converted into dichotomous variables by collapsing the ‘better’ and the ‘no difference’ variables into one new variable: ‘better/no difference’. Binary logistic regression could then be used to compare differences in respiratory symptoms (now dichotomous: ‘better/no difference’ and ‘worse’) across the three types of filters.

Risk estimates were adjusted for potential confounding factors, including years in FESA, gender, smoking history, and asthma history. Adjusted odds ratios were calculated to compare the effectiveness of the filters based on the number of participants reporting an increase in respiratory symptoms following the exposure.

Individual $\Delta$ FEV$_1$ and $\Delta$ SaO$_2$ were assessed by paired $t$-tests. ANOVA and linear regression was used to assess the relationship between $\Delta$ FEV$_1$ and $\Delta$ SaO$_2$ across the three types of filters, while adjusting for potential confounders, such as smoking history, years of service, and previous exposures. ANOVA and linear regression was also used to assess the associations between the types of filter and the results of the air sampling inside the respirators.

### 4.3 Results

During the Phase 1 Controlled Exposure Trials in the Smoke Chamber, 24 P, 23 P/OV, and 17 P/OV/F filters were tested (Table 4.2). The findings from the smoke chamber trials showed that the P filter was the least effective in filtering out bushfire smoke components. Therefore, it was decided to under-sample this type of filter in
the Phase 2 Field Validation Trials during the Prescribed Burns. A total of 13 P, 27 P/OV filters, and 27 P/OV/F filters were tested in the Phase 2 trials.

Table 4.2 Details of Allocations in Exposure Trials

<table>
<thead>
<tr>
<th>Participants</th>
<th>P (n)</th>
<th>P/OV (n)</th>
<th>P/OV/F (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1 Smoke Chamber</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 October 2004</td>
<td>8</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>6 December 2004</td>
<td>8</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>9 December 2004</td>
<td>10</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>10 December 2004</td>
<td>10</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>13 December 2004</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>14 December 2004</td>
<td>13</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>15 December 2004</td>
<td>10</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Smoke chamber total</td>
<td>64</td>
<td>24</td>
<td>23</td>
</tr>
<tr>
<td>Phase 2 Prescribed Burns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 October 2005</td>
<td>25</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>20 October 2005</td>
<td>13</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>10 November 2005</td>
<td>12</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>24 November 2005</td>
<td>17</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Prescribed burn total</td>
<td>67</td>
<td>13</td>
<td>27</td>
</tr>
<tr>
<td>Combined Total</td>
<td>131</td>
<td>37</td>
<td>50</td>
</tr>
</tbody>
</table>

* Not tested

4.3.1 Phase 1 - Controlled Exposure Trials Smoke Chamber

Sixty-four (64) career urban or peri-urban fire fighters from 20 fire stations in the Perth Metropolitan area participated in the six controlled exposure trials. Sixty participants (93.7%) were male and four (6.3%) were female. The largest proportion of the participants was in the age group 40-49 years. Table 4.3 outlines the demographics of these participants. The mean number of years of employment at FESA was 13 years.
Table 4.3 Demographics and Occupational Variables FESA Career Fire Fighters (n=64)

<table>
<thead>
<tr>
<th>Gender</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>60</td>
<td>94</td>
</tr>
<tr>
<td>Female</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Age group</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-29</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>30-39</td>
<td>25</td>
<td>39</td>
</tr>
<tr>
<td>40-49</td>
<td>30</td>
<td>47</td>
</tr>
<tr>
<td>50-59</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>60+</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current fire station</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balcatta, Canning Vale, Joondalup, Malaga</td>
<td>30</td>
<td>47</td>
</tr>
<tr>
<td>Remaining stations</td>
<td>34</td>
<td>53</td>
</tr>
</tbody>
</table>

The analysis demonstrated no association between the demographic and occupational variables, such as gender, age group, FESA years, current fire station and the observed changes (Δ) in pre and post-exposure FEV₁/SaO₂ measurements or the self-reported respiratory symptoms.

Occupational exposures of relevance were measured by recording the frequency of past attendances of bushfires and self-reported associated symptoms for each individual. These were evaluated in relation to self-reported symptoms that the participant had experienced in relation to bushfire exposures in the past, including coughing, wheezing, and shortness of breath. Fifty percent of the participants (n=32) reported having experienced symptoms after previous attendances at bushfires, with 29 indicating symptoms of coughing, wheezing, and shortness of breath. However, no consistent relationship between previous exposures to bushfires or past symptoms and the Phase 1 measured differences in FEV₁/SaO₂, respiratory health outcomes, or exposure time could be demonstrated.

The majority of the participants rated their overall health as ‘very good’. None of the participants reported themselves to be in ‘fair’ or ‘poor’ health, perhaps attributable to a strong ‘healthy-hired effect’ among fire fighters, i.e. fire fighters are generally in good health because they are subject to stringent selection criteria at the time of the recruitment (Choi 2000). Despite these favourable health ratings, a range of pre-existing medical conditions were reported, including self-reported asthma, hay fever and other allergies, regular production of sputum, and use of bronchodilators. Table 4.4 summarises these findings.
Table 4.4 Pre-existing Medical Conditions in FESA Career Fire Fighters (n=64)

<table>
<thead>
<tr>
<th>Condition</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall health</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Very good</td>
<td>37</td>
<td>58</td>
</tr>
<tr>
<td>Excellent</td>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>Asthma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>No</td>
<td>58</td>
<td>91</td>
</tr>
<tr>
<td>Don’t know</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hay fever</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>24</td>
<td>38</td>
</tr>
<tr>
<td>No</td>
<td>37</td>
<td>58</td>
</tr>
<tr>
<td>Don’t know</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Allergies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>No</td>
<td>54</td>
<td>84</td>
</tr>
<tr>
<td>Don’t know</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Current use of bronchodilators</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>No</td>
<td>58</td>
<td>91</td>
</tr>
</tbody>
</table>

The pre-existing medical conditions could not be related to the Phase 1 measured differences in FEV₁/SaO₂, and respiratory health outcomes. However, the majority of the participants (54%) who reported an increase in coughing, wheezing, tightness, shortness of breath after the exposure in the smoke chamber indicated that they also suffered from hay fever.

Reported symptoms in the last 12 months (such as coughing wheezing, tightness, shortness of breath, and respiratory tract infections) could also not be related to any differences in the FEV₁/SaO₂, respiratory health outcomes, sputum in the Phase 1 trial.

There were no current smokers among the participants. Twenty-two participants were identified as past smokers, and 42 participants reported to have never smoked. Neither smoking status nor total pack years (packs/day/year) were related to differences in self-reported and measured respiratory health outcomes in the Phase 1 trial.

Fire fighter utilisation of the currently issued P filters was measured by variables assessing the frequency of use and the perceived effectiveness (Table 4.5). The
majority of the participants (69%, n=44) reported to ‘mostly’ or ‘always’ wearing the respirator while fighting bushfires, and a small majority (52%) believed that use of the respirator had a positive effect on their breathing.

| Table 4.5 Respirator Use by FESA Career Fire Fighters prior to the Study |
|---------------------------------|---|---|
| **Routinely wear a respirator** | n  | %  |
| Never                           | 5  | 8  |
| Sometimes                       | 14 | 22 |
| Mostly                          | 27 | 42 |
| Always                          | 17 | 27 |
| **Effect of respirator on breathing** |      |      |
| Not different                   | 11 | 17 |
| Worse                           | 19 | 30 |
| Better                          | 33 | 52 |
| **Usefulness of respirator**    |      |      |
| Don’t know                      | 12 | 19 |
| Disagree                        | 24 | 38 |
| Agree                           | 27 | 42 |
| **Comparability of smoke to real bushfire smoke** |      |      |
| Different                       | 20 | 31 |
| Similar                         | 42 | 66 |

Fire fighters who reported ‘mostly’ or ‘always’ wearing a respirator during bushfires were more likely to report coughing, wheezing, and shortness of breath following smoke exposure in this study. Of those who reported an increase in such symptoms in this study, 38.5% (n=5) were fire fighters who ‘always’ wore a respirator and 38.5% (n=5) ‘frequently’ wore a respirator. This compares to the low percentage of symptom reporting in those who ‘never’ or ‘sometimes’ wore a respirator during their usual fire fighting activities (7.7%, n=1 and 15.4%, n=2, respectively). However, these trends were not statistically significant (Figure 4.16).
The measurements of pulmonary function before and after exposure are presented in Table 4.6. A mean decline of 0.01L in FEV$_1$ was observed between the pre- and post- exposure FEV$_1$ measurements.

**Table 4.6 Phase 1: FEV$_1$ and SaO$_2$ Measurements before and after 15 Minutes Exposure***

<table>
<thead>
<tr>
<th></th>
<th>Before Exposure</th>
<th>After Exposure</th>
<th>Difference</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEV$_1$ (L)</td>
<td>4.16</td>
<td>4.15</td>
<td>0.01</td>
<td>ns$^*$</td>
</tr>
<tr>
<td>SaO$_2$ (%)</td>
<td>97.97</td>
<td>97.53</td>
<td>0.44</td>
<td>&lt; 0.05</td>
</tr>
</tbody>
</table>

*Data are presented as mean changes
$^*$Not statistically significant

Multiple linear regression analysis demonstrated that the declining trend in FEV$_1$ could not be predicted from the type of filter used, after controlling for years in FESA and smoking status (Figure 4.17).
A statistically significant decline of 0.44% ($p < 0.05$) was observed between the pre- and post-exposure SaO$_2$ measurements (Table 4.6). The type of filter, years in FESA, and smoking status did not significantly contribute to the regression model in which the SaO$_2$ was used as the dependent variable. Although the paired difference (0.44%) was statistically significant, the effect was very small in clinical terms (Figure 4.18).
Acute respiratory health effects were measured by self-reported symptoms of coughing, wheezing, and shortness of breath. After the 15-minute exposure to bushfire smoke, 40 participants (63%) reported no difference in these symptoms, with 13 participants (20%) reporting an increase in coughing, wheezing, and shortness of breath.

After 30 minutes recovery time, most of these symptoms had resolved, with 6 participants (9%) still experiencing an increase in coughing, wheezing, or shortness of breath compared to before the exposure. Although these observations are of potential importance from a clinical perspective, a statistically significant difference could not be established between the respiratory symptoms at baseline and after 15 minutes smoke exposure.

The relationship between the differences in acute respiratory health symptoms and the three types of filters were initially analysed using $\chi^2$ tests. Figure 4.19 shows that a significantly higher proportion of the participants in the P filter group (42%, n=10) and the P/OV filter group (14%, n=3) reported an increase in respiratory symptoms following exposure compared to the P/OV/F filter group (0%, n=0) ($p < 0.05$). Similar outcomes were observed after 30 minutes recovery time.
Further analyses using logistic regression demonstrated that the application of the P filter was a significant predictor for increases in acute respiratory outcomes, including cough, wheeze, and shortness of breath ($p < 0.05$). Potential confounders such as years in FESA, gender, smoking history, and history of asthma did not significantly contribute to the model.

**Figure 4.19 Post Exposure Changes in Respiratory Symptoms across three Filter Types**

Odds ratios comparing the effectiveness of the P filter with the effectiveness of the P/OV/F filter showed a statistically significant 12-fold reduction in respiratory symptoms following the exposure for participants who used the P/OV/F filter (OR 0.082, 95% CI 0.009 – 0.775, $p = 0.029$). Results also confirmed a statistically significant 5-fold reduction in respiratory symptoms following the exposure for participants who used the P/OV versus P filter (OR 0.191, 95% CI 0.039 – 0.931, $p = 0.041$) (Table 4.7).
Table 4.7 Phase 1: Odds Ratios for Increases in Respiratory Symptoms across Three Types of Study Filters

<table>
<thead>
<tr>
<th>Comparison of Filters</th>
<th>Adj. OR*</th>
<th>p-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>P filter vs. P/OV/F filter</td>
<td>0.082</td>
<td>0.029</td>
<td>0.009 – 0.775</td>
</tr>
<tr>
<td>P filter vs. P/OV filter</td>
<td>0.191</td>
<td>0.041</td>
<td>0.039 – 0.931</td>
</tr>
<tr>
<td>P/OV filter vs. P/OV/F filter</td>
<td>0.625</td>
<td>ns</td>
<td>0.037 – 10.693</td>
</tr>
</tbody>
</table>

*OR adjusted for FESA years, age group, pack years

In order to measure levels of particles, formaldehyde, and acrolein inside the respirators, air sampling was undertaken inside seven respirators fitted with P filters, seven respirators fitted with P/OV filters, and four respirators fitted with P/OV/F filters. Table 4.8 outlines the findings of the inside the respirator sampling. Particle levels inside the respirators fitted with the P filters and the P/OV filters were not significantly different (particle levels were not available for respirators fitted with the P/OV/F filter).

Table 4.8 Phase 1: Filter Types and Air Sampling Results

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Particles (\text{mg/m}^3)</th>
<th>Formaldehyde (\text{(\mu)g/m}^3) (STEL 2.5 (\text{mg/m}^3))</th>
<th>Acrolein (\text{(\mu)g/m}^3) (STEL 0.69 (\text{mg/m}^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range Mean ± SD</td>
<td>Range Mean ± SD</td>
<td>Range Mean ± SD</td>
</tr>
<tr>
<td>P filter (n = 7)</td>
<td>0.1 - 5.1 1.55 ± 2.38</td>
<td>0.02 - 1.73 0.93 ± 0.55</td>
<td>0.01 - 0.96 0.32 ± 0.31</td>
</tr>
<tr>
<td>P/OV filter (n = 7)</td>
<td>0.7 - 2.2 1.5 ± 0.76</td>
<td>0.03 - 0.10 0.06 ± 0.03</td>
<td>0 - 0.04 0.01 ± 0.01</td>
</tr>
<tr>
<td>P/OV/F filter (n = 4)</td>
<td>n/a</td>
<td>0.05 - 0.16 0.1 ± 0.05</td>
<td>0 - 0.01 0.01 ± 0.01</td>
</tr>
</tbody>
</table>

*STEL for toxic particles is not available (TWA non-toxic particles 10 \(\text{mg/m}^3\))

Formaldehyde and acrolein levels were significantly higher in the P filter group compared to the P/OV filter and the P/OV/F filter group \((p = 0.001 \text{ and } p = 0.006)\) (Figure 4.20). These findings suggest that the P filter is considerably less effective in filtering out volatile respiratory irritants such as formaldehyde and acrolein in comparison to either the P/OV or the P/OV/F filter. However, no statistically significant difference was found in formaldehyde and acrolein concentrations between the P/OV and the P/OV/F filters.
Particle levels were measured inside respirators fitted with P and the P/OV filters. The results showed no significant difference between these two types of filters (particle results for the P/OV/F filter were not available).

4.3.2 Phase 2 – Field Trials – Prescribed Burns
Sixty-seven (67) FESA career fire fighters from Perth Metropolitan fire stations participated in the four subsequent field trials during prescribed burns. The largest proportion of this group (45%, n=30) was in the 30-39 age group. Sixty-four (64) were male, and three were female (Table 4.9). The mean number of years employed at FESA was 11 years.
The analysis demonstrated no association between the demographic variables (gender, age group, and FESA years) and the observed differences in baseline and follow-up FEV\textsubscript{1}/SaO\textsubscript{2} measurements and self reported respiratory health symptoms.

<table>
<thead>
<tr>
<th>Gender</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>64</td>
<td>96</td>
</tr>
<tr>
<td>Female</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Age group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-29</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>30-39</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>40-49</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>50-59</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>60+</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Eighty-five percent of the participants (n=57) reported to be in ‘very good’ to ‘excellent’ health; 15% (n=10) stated that they were in ‘good’ health (Table 4.10). Three percent (n=2) of the participants reported suffering from asthma, and 25% (n=17) reported having hay fever. At baseline, 22% of the participants (n=15) reported to have slight to moderate coughing, wheezing, shortness of breath, with 16% (n=11) reporting to have had a cold, influenza or chest infection less than two weeks ago. Pre-existing medical conditions including perceived overall health, self reported asthma, allergies, and upper respiratory tract infections were not associated with the observed differences in FEV\textsubscript{1}/SaO\textsubscript{2} measurements, or with respiratory health symptoms.
### Table 4.10 Pre-existing Medical Conditions

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overall health</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Very good</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Excellent</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td><strong>Asthma</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>No</td>
<td>64</td>
<td>96</td>
</tr>
<tr>
<td>Don’t know</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Hay fever</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>No</td>
<td>44</td>
<td>66</td>
</tr>
<tr>
<td>Don’t know</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td><strong>Allergies</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>No</td>
<td>64</td>
<td>96</td>
</tr>
<tr>
<td>Don’t know</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Current use of bronchodilators (puffers)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>No</td>
<td>66</td>
<td>99</td>
</tr>
</tbody>
</table>

Approximately 40% of the participants (n=26) reported experiencing respiratory symptoms after bushfire fighting in the past, such as coughing, wheezing, shortness of breath. One participant reported having watery eyes after bushfire fighting. Previous exposure-related respiratory symptoms were not associated with the declines in FEV$_1$/SaO$_2$ measurements, or with self reported respiratory health symptoms.

Seventy percent (n=47) had never smoked, 25% (n=17) were past smokers, and 5% (n=3) were current smokers. The statistical analysis demonstrated no association between smoking history and respiratory outcomes in this study. However, it must be noted that the two participants who both exited the smoke early before completion of the first and the second hour (i.e. after 45 and 47 minutes) were, respectively, a past and a current smoker.

Twenty-five percent (n=17) reported to ‘always’ wearing a respirator while fighting bushfires, while the remaining 75% reported to ‘sometimes’ or ‘mostly’ wearing a respirator during bushfire fighting activities. Figure 4.21 shows the types of filter that are normally used by the participating FESA career fire fighters at the time of the study. The P filter was mostly used (72%, n=48), followed by the P/OV filter.
(9%, n=6). A total of 3% (n=2) reported using another unspecified type of filter, and 16% (n=11) of the participants could not recall what they used.

Table 4.11 illustrates the current respirator/filter use by FESA career fire fighters. Forty-three percent (n=29) stated that they agreed that their current respirator/filter was useful; in contrast, 36% (n=24) disagreed that the respirator/filter they were currently issued was useful. Of these, 65% (n=19) reported ‘sometimes’ or ‘mostly’ wearing a respirator, and 35% (n=10) reported ‘always’ wearing a respirator. Of the 24 participants who disagreed that their respirator/filter was useful, 79% (n=19) reported ‘sometimes’ or ‘mostly’ wearing them; 21% (n=5) reported ‘always’ wearing them despite their negative perceptions of their utility. Amongst those who disagreed that their current respirators were useful, nearly half of the participants (46%, n=11) indicated that the respirator/filter made breathing more difficult, whereas the remainder (54%; n=13) reported that the respirator made no difference or made it easier to breathe.
Table 4.11 Current Respirator/Filter Use by FESA Career Fire Fighters

<table>
<thead>
<tr>
<th>Routine wear a respirator/filter</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Always</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>Sometimes, mostly</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>Never</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of usual filter*</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate filter</td>
<td>48</td>
<td>72</td>
</tr>
<tr>
<td>Particulate/organic vapour filter</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Don’t know</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Usefulness of respirator/filter in protecting health</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly agree/agree</td>
<td>29</td>
<td>43</td>
</tr>
<tr>
<td>Strongly disagree/disagree</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>Don’t know</td>
<td>14</td>
<td>21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect of respirator/filter on breathing</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Much/slightly worse</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>Not different</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>Slightly/much better</td>
<td>26</td>
<td>39</td>
</tr>
</tbody>
</table>

*See also Figure 4.21

After the first 60 minutes exposure to smoke in the prescribed burn, 15% percent of the participants (n=10) reported to be ‘quite a bit’ to ‘extremely’ thirsty, 63% (n=42) reported to be ‘slightly’ to ‘moderately’ thirsty, and 22% (n=15) was ‘not thirsty at all’. After 120 minutes 13% (n=9) reported to be ‘quite a bit’ to ‘extremely’ thirsty, and 58% (n=39) reported to be ‘slightly’ to ‘moderately’ thirsty.

Sixteen percent of the participants (n=11) reported experiencing headaches after the first 60 minutes; five (45%) of these were allocated a P filter. After 120 minutes the majority of this group (n=6) still reported experiencing headaches. Four of these (67%) were allocated a P filter.

Across the study population there was a significant decline in FEV$_1$ both after 60 minutes (0.08L, $p < 0.05$), and 120 minutes (0.15L, $p < 0.05$) compared to the baseline measurements (Figure 4.22). These declines however, were not associated with the type of filter used during the trials.
A decline in SaO$_2$ was measured across the study population both after 60 minutes (1.2%, $p < 0.05$) and 120 minutes (1%, $p < 0.05$) compared to baseline measurements (Figure 4.23). Although the SaO$_2$ declines were statistically significant, the effect is small in clinical terms, and was not associated with the type of filter.
During the field validation trials a total of 13 P filters, 27 P/OV filters, and 27 P/OV/F filters were tested. After 60 minutes smoke exposure, 13% of the participants (n=9) reported increased coughing, wheezing, and/or shortness of breath (Figure 4.24).

A significant difference in the number of participants was seen between:

- The P filter and the P/OV filter group (67% (n=6) vs. 22% (n=2)) \( p = 0.03 \);
- The P filter and the P/OV/F filter group (67% (n=6) vs. 11% (n=1)) \( p = 0.03 \).

Potential confounders such as years in FESA, gender, smoking history, and asthma did not significantly contribute to the model.
These findings were relatively comparable after 120 minutes. Eighteen percent of the total study population (n=12) reported increased coughing, wheezing and shortness of breath following exposure. A significantly higher proportion of this group was allocated the P filter (64%, n=8) compared to the P/OV filter (18%, n=2), and the P/OV/F filter (18%, n=2) ($p = 0.01$).

Following the 60-minute exposure period, there was a statistically significant 20-fold reduction in the number of participants - with increased respiratory symptoms for the P/OV filter compared to the P filter (OR 0.050, 95% CI 0.004 – 0.597, $p = 0.02$), and a four-fold reduction in the number of participants - with increased respiratory symptoms for the P filter group compared to the P/OV/F filter group (OR 0.234, 95% CI 0.068 – 0.797, $p = 0.02$). These findings were comparable after 120 minutes exposure (Figure 4.12).
Table 4.12 Phase 2: Odds Ratios for Increases in Respiratory Symptoms across the Three Types of Filters

<table>
<thead>
<tr>
<th>Comparison of Filters</th>
<th>Adj. OR*</th>
<th>p-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-60 minutes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P filter vs. P/OV filter</td>
<td>0.050</td>
<td>0.02</td>
<td>0.004 – 0.597</td>
</tr>
<tr>
<td>P filter vs. P/OV/F filter</td>
<td>0.234</td>
<td>0.02</td>
<td>0.068 – 0.797</td>
</tr>
<tr>
<td>P/OV filter vs. P/OV/F filter</td>
<td>0.484</td>
<td>ns</td>
<td>0.034 – 6.802</td>
</tr>
<tr>
<td></td>
<td>0-120 minutes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P filter vs. P/OV filter</td>
<td>0.048</td>
<td>0.00</td>
<td>0.006 – 0.358</td>
</tr>
<tr>
<td>P filter vs. P/OV/F filter</td>
<td>0.237</td>
<td>0.00</td>
<td>0.092 – 0.613</td>
</tr>
<tr>
<td>P/OV filter vs. P/OV/F filter</td>
<td>1.300</td>
<td>ns</td>
<td>0.149 – 11.359</td>
</tr>
</tbody>
</table>

*OR adjusted for FESA years, age group, pack years
ns Not statistically significant

Although not a statistically significant outcome, it is notable that the only two participants who exited the smoke early (after 45 and 47 minutes) in the first as well as in the second hour were both issued a P filter during the trials. These two participants also reported to be a past and a current smoker, suggesting that tobacco use may be a risk factor in terms of health-related responses to bushfires.

Formaldehyde levels were significantly higher in the P filter group compared to the P/OV and the P/OV/F filter group both in the first and second hour of smoke exposure (both \( p < 0.05 \)). No significant difference could be demonstrated between the P/OV filter group and the P/OV/F filter group with regard to formaldehyde levels (Error! Reference source not found.).

Table 4.13 Phase 2: Formaldehyde Levels inside Three Filter Types
(American Conference of Governmental Industrial Hygienists 2003)

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Formaldeh dy ( \text{mg/m}^3 ) (Ceiling Value 0.36 mg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>After 60 Minutes Range Mean ± SD</td>
</tr>
<tr>
<td>P filter (n=2)</td>
<td>0.44 ± 0.00</td>
</tr>
<tr>
<td>POV filter (n=6)</td>
<td>0.01-0.08</td>
</tr>
<tr>
<td>POVF filter (n=6)</td>
<td>0.01-0.04</td>
</tr>
</tbody>
</table>
4.3.3 **Compilation of Comments from Fire Fighters in the Trial**

Box 4.1 provides a compilation of the feedback collected from the participating fire fighters in Phase 1 and 2 (from the comment section of the questionnaire) to provide a qualitative description of their experience after using various filters.

**Box 4.1 Summary of Fire Fighters' Feedback**

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Feedback Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P filter</td>
<td>My eyes burnt a lot, because mask and goggles don’t fit well enough. Could taste smoke and burnt in my throat.</td>
</tr>
<tr>
<td>P/OV filter</td>
<td>I found taking a deep breath difficult, and feel that under a heavy workload that getting enough oxygen may be a factor.</td>
</tr>
<tr>
<td>P filter</td>
<td>I found very little effects, as the filters seemed to do very little. The type of smoke was not close to what we get at a bushfire. It was not intense enough.</td>
</tr>
<tr>
<td>P/OV/F filter</td>
<td>Upon completion of the 15 minutes, and the filters being removed from the mask, I was instantly able to smell the bushfire smoke. This was absent while the filters were in place, which was good. At past attended bushfires, my nasal area (sinus) becomes very dry upon blowing my nose, the mucus comes out black stained. This test did not produce the same results; my sinus was not affected to the same degree.</td>
</tr>
<tr>
<td>P filter</td>
<td>The major discomfort I was having was a burning sensation in my throat which became worse as I tried to breathe. The burning started immediately on entering the chamber becoming progressively worse, until I had to vacate before time due out. After half an hour my main symptoms were burning sensation in lower lungs with slight tightness.</td>
</tr>
<tr>
<td>P/OV/F filter</td>
<td>The mask I was testing seemed to keep out most of the smoke, only discomfort was stinging eyes and thirst after the test.</td>
</tr>
<tr>
<td>P filter</td>
<td>The mask I used was as CHEESE.</td>
</tr>
<tr>
<td>P filter</td>
<td>My mask/filter did not work very well at all.</td>
</tr>
<tr>
<td>P/OV filter</td>
<td>Couldn’t detect the smell of smoke initially; however towards the end of the time in the smoke chamber I could smell the smoke quite well.</td>
</tr>
<tr>
<td>P filter</td>
<td>Mask is very poor. It is of similar quality to our current mask – useless.</td>
</tr>
<tr>
<td>P filter</td>
<td>Did not feel the mask worked, but it did improve as time went on, maybe it just clogged up.</td>
</tr>
<tr>
<td>P/OV filter</td>
<td>I was quite impressed by the filter I used and would recommend it.</td>
</tr>
<tr>
<td>P filter</td>
<td>during the test the filter I was using allowed very acrid air into my throat. It was not quite bad enough to cause choking or coughing fit, but I feel had I been exposed for a further length of time I would have exited the container.</td>
</tr>
<tr>
<td>P/OV filter</td>
<td>I found my filter to be effective in the test environment. I only experienced a slight smoky smell through the mask.</td>
</tr>
<tr>
<td>P filter</td>
<td>I walked out a couple of minutes early as the taste in my mask was very bad.</td>
</tr>
<tr>
<td>P/OV filter</td>
<td>Filter in study was a great improvement over standard FESA issue P2 filter.</td>
</tr>
<tr>
<td>P/OV/F filter</td>
<td>The filter I used was excellent. Never once did I smell or taste smoke.</td>
</tr>
<tr>
<td>P/OV filter</td>
<td>Could taste and smell smoke at all times.</td>
</tr>
<tr>
<td>P filter</td>
<td>The filter was very poor, could smell and/taste smoke as soon as entering the smoke.</td>
</tr>
<tr>
<td>P filter</td>
<td>My filter was useless in heavy smoke and not much better in light smoke. I was not able to stay with the others – using different filters.</td>
</tr>
</tbody>
</table>
P/OV/F filter: I felt little discomfort, could only slightly smell smoke. Some fire fighters in the trial stayed out of heavy smoke, because of their discomfort.

P/OV filter: The mask I had was brilliant. The only time I had trouble was adjusting the mask and goggles on my face.

P filter: Mask was ineffective. Could not withstand the same amount of smoke as some of the others.

P/OV filter: Great mask 100% on what we have now. Can I have one please?

P/OV/F filter: Excellent, hope to have one of these masks in the future.

P filter: It was like I wasn’t wearing a mask at all.

P filter: Filter performed poorly. Headache, tightness of chest occurred rapidly and I was not even working. In the second hour lightness/dizziness occurred, runny nose.

P/OV filter: During the first hour I had a constant taste of smoke in my mouth, same for the second hour.

P/OV filter: It was noted that when the smoke was very heavy the eyes would start to water, but I could not smell the smoke. Shortly after my nose would run. The amount of snot produced was related to the time and density of the smoke encountered.

P/OV/F filter: Filter was much better than what we currently have, although wearing mask for two hours was very uncomfortable.

Note: The filters types indicate the test filters used by the participating fire fighter during the exposure trials.

4.4 Discussion

This chapter presents the results of a two year project investigating the effectiveness of three types of protective filters on fire fighters’ respirators. The study was specific to the respirator/filter use by FESA career fire fighters in Western Australia in bushfire situations. The project was designed in two Phases, i.e.: Phase 1 involved controlled exposure trials in a smoke chamber, and in Phase 2 these findings were validated in the field under prescribed burn conditions. In Phase 1, both the measured and self reported respiratory health outcomes demonstrated that fire fighters exposed to a light bushfire smoke for 15 minutes (regardless of filter) may experience minimal transient respiratory health effects, ranging from a slight cough to marginal declines in $\text{FEV}_1$ and $\text{SaO}_2$.

Testing the efficacy of the three types of filters under controlled conditions indicated that the P filter was only effective in filtering out particles, and was ineffective in filtering out other bushfire smoke components, particularly respiratory irritants such as formaldehyde and acrolein. Although the P/OV filter was effective in filtering out these compounds, the P/OV/F filter was most effective in preventing acute respiratory health symptoms. After adjusting for possible confounders such as
FESA service years, age, and history of tobacco smoking, a significant 12-fold reduction was found in the number of participants with increased respiratory symptoms following the smoke exposure with the P/OV/F filter compared with the P filter. In addition, a 5-fold reduction was found in the number of participants with increased respiratory symptoms following the smoke exposure that used the P/OV versus the P filter.

Those participants with existing allergies, such as hay fever, may present an at-risk population within the fire fighting group. Although these findings were not statistically significant, the analysis suggested that short-term exposure to bushfire smoke may trigger the development of acute respiratory symptoms such as cough, wheeze and shortness of breath in people with pre-existing hay fever.

Anecdotal evidence showed that the P/OV and the P/OV/F filter both noticeably reduced the participants’ detection of smoke odours during the exposure period:

“On 10 Feb 2006 we were at a bush fire, this being the first opportunity I have had to use the new filters.... I really couldn't believe that a mask could achieve this. For the first time I went home with my lungs not reeking of smoke (a comment often made by my wife and kids).”

In Phase 2, field trials during prescribed burns were undertaken to validate the findings from the controlled exposure trials. Measurements during the prescribed burns demonstrated that after 60 and 120 minutes smoke exposure, a significantly higher number of participants in the particulate filter group reported an increase in respiratory symptoms (such as coughing, wheezing and shortness of breath) compared to the other two filter groups. Although declines in both FEV₁ and SaO₂ were observed after 60 and 120 minutes, these were not statistically associated with a particular type of filter. After adjusting for possible confounders such as FESA service years, age, and history of tobacco smoking, a significant four-fold reduction was found in the number of participants reporting an increase in respiratory symptoms in the P/OV/F filter group compared to the P filter group. In addition, a twenty-fold reduction was found in the number of participants reporting an increase in respiratory symptoms following smoke exposure, in the P/OV filter group compared to the P filter group. Air sampling inside the respirators demonstrated a
significantly higher mean level of formaldehyde inside the P filters compared to the other two filters both after 60 and 120 minutes.

Past smokers may also be more vulnerable to the effects of bushfire smoke. During the field trials, two study participants had to exit the smoke area early, because of shortness of breath and coughing. These two participants were using a P filter, but were also reported to be a past and a current smoker.

The study revealed an apparent discrepancy between the chemical analysis of agents in the respirator and the reported respiratory health outcomes. Results indicated that measured levels of particles, formaldehyde and acrolein were comparable in respirators fitted with P/OV and P/OV/F filters, yet a significantly lower proportion of the participants in the P/OV/F filter group reported an increase in respiratory symptoms after the exposure. At least two possible explanations may account for this apparent anomaly between the similarity of measured chemicals and difference in respiratory effects across the two filters. Firstly, a number of volatile organic compounds were detected in the smoke, e.g. terpenes, xylenes and other organic by-products of vegetation smoke. Although many of these compounds were present at levels below STEL, such individual components of the smoke - many of which are known respiratory irritants - may have exerted a synergistic effect on the respiratory health of the participants. Therefore, although not specifically examined in the chemical analysis within the respirators (which focused on the most ‘common’ compounds: particles, formaldehyde and acrolein), the P/OV/F filter may in fact have been more effective in removing many other volatile compounds, thereby reducing the possibility of synergistic toxic effects and consequently the rate of reported respiratory symptoms. Such combined irritant effects are poorly recognised in the literature and existing standards, and it is acknowledged that the full synergistic toxicity is probably impossible to measure due to the complexity of the smoke composition.

Another explanation for the discrepancy relates to inadequate seals of the respirators. Inadequate sealing of the respirator against the user’s face may, in some cases, have resulted in the leaking of toxic compounds into the respirators, thereby causing adverse respiratory health effects. Although the fire fighters were instructed to perform a Positive Pressure Fit Check in accordance with Australian/New
Zealand Standard 1715:1994 (Standards Australia 1994) to ensure an appropriate seal, leakage may have occurred due to perspiration, helmets pushing the respirators downwards, and movements of the head and neck by participants unintentionally causing displacement.

The study also showed a discrepancy between some of the results from the smoke chamber compared to the field trials. In the smoke chamber, the number of participants reporting an increase in respiratory symptoms was significantly lower in the P/OV/F filter group. Yet in the field trials the number of participants reporting an increase in symptoms was comparable in the P/OV and the P/OV/F filter group. A possible explanation for the variation in these findings is the apparent dilution of the smoke in the field trials. The data suggest that the formaldehyde levels were three to five times lower during the prescribed burns compared to the formaldehyde levels in the smoke chamber. In addition, carbon monoxide levels in the smoke chamber exceeded the STEL considerably during two trials. The reason for the high levels recorded in the smoke chamber is no doubt due to the confined space in the chamber where pathways for ventilation were reduced, thus concentrating the various compounds. In the field trials, the dilution effect due to wind would account for lower values. This variability may in turn have resulted in smaller differences in respiratory outcomes between the P/OV and the P/OV/F filter group in the field trials.

The findings of this study may have been influenced by selection bias. Selection bias is encountered when those with a condition versus a control (or comparator) population and/or those who exposed versus non-exposed to some factor of interest are selected in a way that leads to an inaccurate measurement of the degree of association between exposure and disease (Choi 2000). This may occur when study participants are not representative of the general population at risk. Selection bias may have arisen because of at least two major dynamics: the selection process may have favoured those who are healthier, and therefore attended, or, conversely, those who are concerned about the health effects of smoke exposure may disproportionately have chosen to participate. Therefore, in a study of this type in which a representative group of fire fighters is required, it is imperative to ensure that the selection procedures do not preferentially result in the entry of
‘diseased/unwell’ versus ‘non-diseased/well’ (or who are more or less likely to have been exposed to some factor) (Choi 2000). However, even in an experimental study, random differences in background risk may occur between the comparison groups. These differences tend to diminish in importance as the study size increases, but there is no guarantee that differences in background risks between the exposure groups will balance each other (Gordis 2000).

Another potential impact on the validity of the results is the influence of self-reporting bias. Although self-reporting of occupational exposures is generally valid, Teschke et al. (2002) found that validity and reliability estimates with regard to self-reporting may vary greatly from study to study, and also within studies. In this project, the participants may have inaccurately reported information regarding their health, either intentionally or unintentionally. For example, the occurrence of asthma could have been under-reported given that not all fire fighters may either admit to having asthma or seek medical attention for asthma symptoms, perhaps because of self-denial or fear of job loss.

Bias may also arise from fire fighters pre-conceptions regarding the efficiency of particular filters. In order to minimise potential self-reporting bias caused by the participants’ prior perceptions of the superiority of one of the three filters, the study filters were as similar in appearance as possible, thereby effectively blinding the participants to the type of filter used. This strategy of blinding the participants and researchers at the time of allocation was aimed at preventing the fire fighters from identifying the different filters, thereby ensuring that the health outcomes were not affected by the participants’ perception of wearing a particular type of filter.

Another limitation of the study was the initial selection of the most appropriate filters for comparison. Defining an optimal filter may be problematic, if not impossible, due to the complex and variable mixture of the products of combustion present in bushfire smoke. In this study, it was decided to use the P and the P/OV filter, because these were the two types of filter that were currently used among FESA career fire fighters in Western Australia. A P/OV/F filter was added to the study after smoke analysis during a pilot burn in September 2004 (Chapter 3) demonstrated elevated levels of formaldehyde - a Class 1 carcinogen - in the smoke. It must be noted however that levels of formaldehyde measured were within STELs
(National Occupational Health and Safety Commission 1995), ensuring that none of the participating fire fighters - with or without formaldehyde filters - were exposed to unacceptably high levels of formaldehyde during the course of this study.

The role of carbon monoxide in explaining some of the findings is uncertain. It is likely that accumulation of carbon monoxide may play a role in the SaO\(_2\) decline. This is important, given that prolonged exposure to high carbon monoxide concentrations may affect fire fighters’ safety and cognitive functioning. However, the adverse effects of carbon monoxide were not specifically examined in this project and would be an important focus of future research.

Finally, the present study attempted to compare three types of filters in an experimental setting and did not address work load factors such as job tasks, heat and physical exertion. In addition, the study did not incorporate the combined impact of stress of fire fighting and wearing respirators (Sharkey 1997a; Budd et al. 1997; Barnes 1999), nor did it deal with the health effects associated with wearing respirators (Bollinger & Schutz 1987). This raises issues of the generalisability of the findings, and this aspect of the study will be discussed in detail in Chapter 7.

In conclusion, testing the effectiveness of 37 particulate, 50 particulate/organic vapour, and 44 particulate/organic vapour/formaldehyde filters under controlled and semi-controlled bushfire smoke conditions from 15 minutes up to 2 hours demonstrated that the particulate/organic vapour/formaldehyde filter provides clinically and statistically significant better protection for the fire fighters’ airways. These findings suggest that the FESA career fire fighters’ respiratory health would be best protected by the provision of the particulate/organic vapour/formaldehyde filter.

### 4.5 Recommendations

Based on the findings of this study the following recommendations were made to FESA:

1. The strongest commendation is offered to FESA for commissioning this work with the full knowledge that the findings could point to a possible need for reviewing current best practice. It is acknowledged that the recommendations are
based solely on the findings of this study, and that many other factors (including practicality, costs, and acceptability issues) will need to be taken into consideration before a decision can be made on implementation or otherwise.

2. In keeping with the current FESA practice, the recommendation to wear a respirator and protective filter during bushfire fighting is strongly supported, as PM levels in the smoke chamber exceeded Time Weighted Average standards for both inspirable and respirable particles.

3. The particulate filter (3M™ 5925) was found to be ineffective in removing the main organic compounds, formaldehyde and acrolein, which are found in bushfire smoke in Western Australia. Given that formaldehyde is a human carcinogen, the use of a filter which removes these compounds is essential in protecting the respiratory health of FESA career fire fighters.

4. Based on the overall health outcomes reported by the participants, the particulate/organic vapour/formaldehyde filter (3M™ 6075A1) performed to a significantly higher level than the particulate/organic vapour filter, and is therefore considered the most appropriate filter of the three tested, to protect the respiratory health of FESA career fire fighters in bushfire fighting.

NOTE: In 2005 FESA implemented the recommendations from the ‘Filter Study Phase 1 Preliminary Report March 2005’ by providing the option for FESA career fire fighters of using the particulate/organic vapour/formaldehyde filter pending the finalisation of this study.

5. Consideration should be given to the development of a respiratory health training program for fire fighters. Key elements in such a program may include:
   • Appropriate use, maintenance, service life, and limits of the respiratory protective equipment;
   • Fit testing procedures in accordance with Australian/New Zealand Standard 1715:1994 (Standards Australia 1994); and
   • Training of the fire fighters in the respiratory hazards to which they are potentially exposed during bushfire fighting.
6. Consideration should be given to determining the service life of the particulate/organic vapour/formaldehyde filter. This study did not test the filters for service life or breakthrough time. However, as a ‘rule of thumb’ filters should be replaced when fire fighters can detect the odour of smoke compounds penetrating through the filter.

7. Until the research or the evidence on the service life is determined as indicated in Recommendation 6, a review of the Bush Fire Smoke Management Standard Operational Procedures 51 should be considered as to the most appropriately wording to be used to indicate service life of the filter. The current wording ‘Extended periods’ and ‘Short duration’ may need to be changed and substituted with the ‘rule of thumb’ approach.

8. Consideration should be given to the provision of a suitable bag/container for the storage of the particulate/organic vapour/formaldehyde filter when not in use to ensure the filter does not further deteriorate and reduce service life due to exposure to ambient contaminants.

9. A follow-up questionnaire survey should be considered at the end of the 2007 summer bushfire season to ascertain fire fighters’ usage of the particulate/organic vapour/formaldehyde filter, its effectiveness, and any indications of service life, e.g. breakthrough of smoke sensation.

10. FESA may wish to consider further research work into:
   - The correlation between carbon monoxide and formaldehyde, given that research in the USA has shown strong correlations between levels of carbon monoxide, formaldehyde, acrolein, and respirable particles in smoke samples from prescribed burns (Reinhardt et al. 2000).
   - The use of CO alarm dosimeters to warn of concomitant CO overexposure. This will greatly increase hazard awareness because it provides the crews and managers with feedback about the hazards of smoke.
In August 2006, the report ‘Respiratory Health of Fire Fighters - Bushfire CRC Project D4 - Final Report’ (De Vos et al. 2006) was presented to the FESA Board of Management. This report included the above recommendations for best practice, and as a result, FESA has changed its policy with regard to personal respiratory protection.

FESA career fire fighters are now being issued with the recommended particulate/organic vapour/formaldehyde filter. The filters are mainly used for high intensity, short duration bushfires at the urban interface (Parlour, L., pers. comm. 2007). The use of these filters is voluntary, and most of the fire fighters choose to use them. A minority of the fire fighters do not use them because they find the filters uncomfortable. FESA is currently considering whether or not to make the use of respirators (i.e. respirators and filters) mandatory for all FESA career fire fighters and to develop criteria to enable distribution for volunteer fire fighters working in similar conditions (Parlour, L., pers. comm. 2007).

The next chapter reviews the Occupational Health and Safety legislation and policies with regard to the use of Personal Protective Equipment for fire fighters, and in particular the use of respirators during bushfire fighting operations.
Chapter 5 Evaluation of the Effectiveness of the Particulate/Organic Vapour Formaldehyde Filter

5.1 Introduction

The previous chapters described the significance of bushfires in the Australian environment, and the effects of exposure to bushfire smoke toxics on fire fighters’ respiratory health. PM, formaldehyde, acrolein, and CO – the major respiratory health hazards – may potentially cause respiratory symptoms, such as coughing, shortness of breath and wheezing. These findings demonstrate the need for adequate and appropriate respiratory protection for fire fighters, particularly during bushfire fighting. Although a wide range of protective filters are available to protect fire fighters from inhaling air toxics from bushfire smoke, it remains unclear which of the available filters are most effective in protecting fire fighters’ respiratory health.

Three types of filters were tested during controlled bushfire smoke exposure trials in a smoke chamber and under prescribed burn conditions. The findings demonstrated that the P/OV/F filter provides better respiratory protection from air toxics in bushfire compared to the particulate and the particulate/organic vapour filter. In August 2006, these findings were presented to FESA in the report ‘Respiratory Health of Fire Fighters - Bushfire CRC Project D4 - Final Report’ (De Vos et al. 2006). In November 2006, FESA endorsed the use of the P/OV/F filter during bushfire fighting.

Following the introduction and the use of the P/OV/F filter for one bushfire season (October 2006 - March 2007), a cross-sectional survey was conducted in April 2007. The aims of the survey were:

- To evaluate FESA’s policy change with regard to the use of the P/OV/F filter as a result of the Bushfire CRC Project ‘Respiratory Health of Fire Fighters’;
- To evaluate the introduction of the filters, the use and perceived effectiveness during bushfire fighting; and
- To correlate the fire fighters’ tasks (e.g. supervising, attack, suppression) with the time period for which filters are effective during bushfire fighting.
5.2 Methodology

5.2.1 Study Design

This study involved a cross-sectional semi-qualitative survey designed to elicit information about the use and effectiveness of the P/OV/F filters in protecting fire fighters’ respiratory health. Ethics approval for the survey was obtained from the Human Research Ethics Committee, The University of Western Australia.

5.2.2 Study Population and Recruitment

The source population for the survey was the group of approximately 1,000 FESA career fire fighters in the Metropolitan area of Perth, Western Australia. To raise awareness about the survey, promotional materials were produced. These included a circular on the FESA intranet, and a poster for all fire stations in the Metropolitan area. Figure 5.1 presents a flow chart of the survey methodology.

Figure 5.1 Methodology Flow Chart

<table>
<thead>
<tr>
<th>Obtain sample of participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrange FESA circular and mail out posters</td>
</tr>
<tr>
<td>Approach random sample of potential participants</td>
</tr>
<tr>
<td>Seek voluntary participation</td>
</tr>
<tr>
<td>Arrange interview time</td>
</tr>
<tr>
<td>Mail consent form and information sheet to participant</td>
</tr>
<tr>
<td>Telephone interview</td>
</tr>
<tr>
<td>Data analysis</td>
</tr>
<tr>
<td>Dissemination of results</td>
</tr>
</tbody>
</table>

A sample of 50 participants was drawn from the available FESA Staff Deployment System. The objective of the sampling was to obtain a representative group of fire fighters. The selected fire fighters were approached by telephone to seek voluntary
participation in the survey. Next, a consent form, information sheet, and a reply paid
envelope were mailed to fire fighters, who had agreed to participate in the study.
The telephone interviews were arranged and scheduled at a convenient time during
the participant’s work shift. The interviews were expected to take approximately 10
minutes.

5.2.3 Data Collection

The survey was originally designed to obtain qualitative information about the
perceived effectiveness of the newly introduced P/OV/F filters. The telephone
questionnaire was set up in three sections:

(1) Identification and Personal Characteristics

- Gender
- Age group
- Current fire station
- Previous participation in the Bushfire CRC Project D4 ‘Respiratory Health of
  Fire Fighters’
- Awareness of FESA’s policy change with regard to the use of the P/OV/F
  filters

(2) Exposure Information

- Previous bushfire attendance
- Range of work activities during exposure:
  - Supervising
  - Holding
  - Attack
  - Mop-up
  - Pump operator
  - Other
- Length of bushfire smoke exposure
- Estimated density of smoke encountered at the most recent bushfire. The
  participants were given four classifications of smoke density to select from:
  (1) No smoke;
Chapter 5 Evaluation

(2) Light smoke situation: white to light grey colour with moist fuels with a visibility of more than 15 metres;

(3) Medium smoke situation: dark grey to black colour with moist to dry fuels with a visibility of 8-15 metres; and

(4) Heavy smoke situation: black to copper-bronze colour with very dry fuels with a visibility of 5-8 metres.

(3) Previous and current respirator and filter use

• Fitting of the respirators/filters, perceived protection by the filters, including respiratory symptoms, breathing capacity, time period of perceived protection; and

• Storage of filters when not in use.

The questionnaire had a comment section, in which the participants could provide additional feedback on the introduction and the use of the new filters. All participants were advised that any feedback would be treated confidentially.

Difficulties were encountered arranging the telephone interviews during the fire fighters’ shifts, because of the various duties and the call-outs to incidents. Therefore, the researcher instead visited the fire stations of the participating fire fighters at an arranged time. Questionnaires were administered to the subjects, which they completed at the time, and returned to the researcher. As anticipated for the interview, it took approximately 10 minutes to complete the questionnaire.

5.2.4 Statistical Analysis

The responses to the questionnaire were coded and the data were analysed using SPSS™. Descriptive analysis of the collected data included frequencies and proportions of the use of the newly issued P/OV/F filters and the perceived protection estimates.

5.3 Results

This cross-sectional survey evaluated the use and the perceived effectiveness of the newly introduced P/OV/F filters after FESA career fire fighters had used these for one bushfire season. The participating fire fighters completed a standardised
questionnaire and provided additional feedback on the introduction and the use of the new filters.

Forty-seven fire fighters completed the questionnaire. The majority of the surveyed participants was male (n = 44; 94%). With regard to age, the highest proportion of the participants (40%; n = 19) was in the 40 – 49 age group. Before the introduction of the P/OV/F filter, 68% (n= 32) used the P filter, 9% (n= 4) used the P/OV filter, and 4% (n=2) could not recall what type of filter they used for respiratory protection.

Forty-six (98%) of the participating fire fighters were aware of the Filter Study, which resulted in FESA endorsing the use of the P/OV/F filter (Table 5.1). Seventeen (36%) fire fighters reported to have participated in the Filter Study smoke exposure trials in 2005-2006. All participants reported using the P/OV/F filter on their respirator during the current bushfire season (2006-2007).

<table>
<thead>
<tr>
<th>Table 5.1 Use of the P/OV/F Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Awareness of Filter Study</td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>n = 46</td>
</tr>
<tr>
<td>% = 98</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>No</td>
</tr>
<tr>
<td>n = 1</td>
</tr>
<tr>
<td>% = 2</td>
</tr>
<tr>
<td>Participant in Smoke Exposure Trials</td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>n = 17</td>
</tr>
<tr>
<td>% = 36</td>
</tr>
<tr>
<td>No</td>
</tr>
<tr>
<td>n = 30</td>
</tr>
<tr>
<td>% = 64</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Awareness of new filters</td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>n = 42</td>
</tr>
<tr>
<td>% = 89</td>
</tr>
<tr>
<td>No</td>
</tr>
<tr>
<td>n = 5</td>
</tr>
<tr>
<td>% = 11</td>
</tr>
<tr>
<td>Use the new P/OV/F filter?</td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>n = 47</td>
</tr>
<tr>
<td>% = 100</td>
</tr>
<tr>
<td>No</td>
</tr>
<tr>
<td>n = 0</td>
</tr>
<tr>
<td>% = 0</td>
</tr>
<tr>
<td>Only filter you use?</td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>n = 47</td>
</tr>
<tr>
<td>% = 100</td>
</tr>
<tr>
<td>No</td>
</tr>
<tr>
<td>n = 0</td>
</tr>
<tr>
<td>% = 0</td>
</tr>
</tbody>
</table>

All participating fire fighters reported to be involved in bushfire fighting. In the last three months before the interview, the bushfire attendance frequency ranged from 0 to 50 (one fire fighter had just started the job, and had not attended a bushfire) (Figure 5.2). The estimated mean number of bushfire attendances per fire fighter was 20 in the last three months. The largest number of the participants (n=8; 17%) reported to have attended 20 bushfires in the last three months.
The majority of the respondents (n=27; 57%) attended a bushfire less than a week before the data collection (Table 5.2). During the last bushfire, 68% of the participants (n=32) reported to be exposed to smoke for a period between 0-4 hours, and 13 participants (28%) reported a smoke exposure period of 5-10 hours. Two fire fighters (4%) reported to have been in smoke for their entire shift (11-14 hours).

Table 5.2 Characteristics of Last Bushfire Attendance

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>When</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than a week ago</td>
<td>27</td>
<td>57</td>
</tr>
<tr>
<td>Between 8-14 days ago</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Between 15-21 days ago</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Between 22-28 days ago</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Over a month ago</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td><strong>Smoke Exposure Period</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-4 hours</td>
<td>32</td>
<td>68</td>
</tr>
<tr>
<td>5-10 hours</td>
<td>13</td>
<td>28</td>
</tr>
<tr>
<td>11-14 hours</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>Smoke Density</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No smoke</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Light</td>
<td>15</td>
<td>32</td>
</tr>
<tr>
<td>Medium</td>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td>Heavy</td>
<td>12</td>
<td>25</td>
</tr>
</tbody>
</table>
Fifteen participants (32%) classified the smoke they were exposed to during the last attended bushfire as ‘light’, 20 participants (43%) classified the smoke as ‘medium’, and 12 participants (25%) as heavy smoke. None of the participants selected the option ‘no smoke’ during the last bushfire (Table 5.2).

The participants were asked what type of job task they were involved in during bushfire fighting, while wearing the respirator and the recommended P/OV/F filter. Ten fire fighters (21%) reported they were supervising, twenty-nine (62%) reported they were involved in a combination of attack and mop-up, and 8 (17%) reported that their job tasks involved a combination of holding, attack, mop-up, and pump operator. No relationship was found between job tasks and duration of the perceived effectiveness of the P/OV/F filters.

Thirty-eight (81%) of the interviewed FESA career fire fighters reported routinely wearing a respirator during bushfire fighting. Twenty-eight (60%) of the interviewed fire fighters considered the respirator was ‘comfortable’, while 15 (32%) expressed their concerns about the fitting of the respirator. ‘The respirator hurts the nose’, and ‘the helmet pushes down the respirator’ was indicated by 15 (32%) of the participating fire fighters. Three fire fighters in the study group (6%) indicated that the helmet, goggles, and respirator were not compatible, and one fire fighter considered the respirator as ‘bulky’ and ‘restricting the air flow’.

During bushfire fighting, twenty-six (55%) of the survey participants reported using the new filter ‘continuously’, nineteen (41%) reported using it ‘sometimes’, and two (4%) reported ‘never’ using the filter. Thirty-nine (83%) of the study participants perceived the performance of the new P/OV/F filter as ‘better’ to ‘much better’ compared to the performance of the previous P filter. When asked for more detail, 26 participants explained why they perceived better respiratory protection from the P/OV/F filter (Table 5.3). Less smoke inhalation was the most commonly reported reason for better performance of the P/OV/F filter compared to the P filter.
Table 5.3 Reasons for perceived better performance of the P/OV/F Filter compared to the P Filter (of n=26 who reported an improvement)

<table>
<thead>
<tr>
<th>Reason</th>
<th>n=26</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Better filtration</td>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td>Cleaner air</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Easier to breathe</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Less smoke inhalation</td>
<td>13</td>
<td>50</td>
</tr>
<tr>
<td>Less taste</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Particulate filter is like not wearing a filter at all</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Before the introduction of the P/OV/F filters, a major concern for FESA career firefighters was the smell and taste of bushfire smoke inside the respirators, and the impact of these on their respiratory health (Chapter 4). After using the P/OV/F filters for one bushfire season during bushfire fighting, 35 (75%) of the study participants reported that they did not notice smoke odour inside the respirators fitted with the P/OV/F filters.

However, it was noted that the respirator still accumulates moisture inside. More than half of the participating fire fighters (51%; n=24) reported moisture build-up in the respirator with the P/OV/F filters, thereby compromising the seal of the respirator. Two participants reported that the performance of the filters was affected as a consequence of the moisture build-up in the respirators, which in turn resulted in ‘heavier breathing’ and ‘the filters becoming useless’.

Thirty-seven (79%) of the study group remove the respirator during the job for a number of reasons, with communication being the most frequently reported (Table 5.4).

Table 5.4 Reasons for Removing Respirator during Bushfire Fighting

<table>
<thead>
<tr>
<th>Reasons</th>
<th>n=37</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>18</td>
<td>49</td>
</tr>
<tr>
<td>Cooling off</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Drinking</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>In fresh air</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Refilling truck</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Removing sweat</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>Breathing deeply</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>No reason stated</td>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>
According to 17 study participants (36%), wearing the respirator - since 2006 fitted with the P/OV/F filter instead of the P filter - affects the breathing, either in a positive or negative way during bushfire fighting (Table 5.5). Thirty (64%) study participants reported no impact on their breathing. When asked for further details with regard to the effects of using the P/OV/F filter, seven study participants reported an improvement in their breathing. A further ten study participants reported negative effects, such as smoke leaking inwards due to poor fitting of the respirator, and restrictive breathing under high physical exertion.

<table>
<thead>
<tr>
<th>Effect</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easier to breathe, no more choking</td>
<td>7</td>
<td>41</td>
</tr>
<tr>
<td>Allows smoke in due to poor fit</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Harder to exhale</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Harder to breathe</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>Restriction under high physical exertion</td>
<td>5</td>
<td>29</td>
</tr>
</tbody>
</table>

With regard to the longer term effect of the P/OV/F filter on respiratory symptoms in the days following the bushfire incident, 87% reported no respiratory symptoms after bushfire attendance. When asked for more details, one fire fighter commented:

“The filters reduce the respiratory symptoms”, and

“I don’t cough and wheeze as much”. Another fire fighter reported

“Less smoke inhalation” and

“With the P/OV/F filters I don’t need a recovery period after bushfire fighting”.

The storage conditions of the filters impacts on their effective service life. Therefore, 3M™ recommends storing the respirator and filters in a storage bag to protect against damage, contamination, dust, sunlight, extreme temperatures, excessive moisture, and damaging chemicals. Thirty-two (68%) of the fire fighters reported storing their respirator and filters in the particular storage bag. Five (11%) used a plastic container for storage, seven (15%) used a fabric bag, and three (6%)
reported that they did not provide any form of protective cover for their respirator and filter.

5.3.1 **Compilation of Comments from Fire Fighters**

In the comments section of the questionnaire, the participants provided a range of information and comments with regard to the respiratory protection, the introduction of the P/OV/F filter, and effectiveness during bushfire fighting. Box 5.1 presents a compilation of these verbatim comments, and provides a valuable insight into their views of the effectiveness of the issued P/OV/F filter.

**Box 5.1 Summary of Fire Fighters’ Feedback**

The new filters are much better than the old ones by far.

Great work.

Harder to breathe with filters, compared to no mask at all, but we can breath.

This was not a FESA idea. It was introduced when Balcatta/Duncraig finding out about them.

I think the next step would be to introduce a full face mask with battery pack delivering positive pressure to the mask to solve the problem of the goggles breaking the seal of the mask.

A full face mask would reduce the effect of smoke in the eyes. The helmet is constantly pushing down on the mask. Conversation is difficult when wearing the mask.

Mask and filters are great. However we need a better system for wearing goggles with them, for example an all in one goggles and mask.

Have been using filters for more than 10 years. They work. It’s good to see FESA has woken up to the problems in the fire ground.

I was one of the first to purchase my own and start using them. I was on the original working party that chose the first mask and goggles and water bottle. We chose the 3M mask knowing the filters could be upgraded.

Not sure if the total filter should not be disposed of after each use. Mask difficult to use with helmet and goggles.

Improve comfort with mask, goggles, and helmet being used.

Goggles and mask do not match. Helmet can ride up higher at brim, small goggles fit better but fog easier. Mask would be better if there was only one attachment point. In the dark of night not easy to don.

Mask and helmet don’t work.

All in one face mask would be better.

The wearing of the helmet, goggles and mask together do not fit the face properly. The goggles and mask cause discomfort on the bridge of the nose and affect the seal.

Very poor protection. Very impracticable – needs to be integrated with eye protection and helmet.

With mask on communication is difficult.

No longer feel symptoms similar to occupational asthma. No longer smell of smoke in breath after days.
5.4 Discussion

This chapter presents the results of the survey undertaken to evaluate the use and the perceived effectiveness of the particulate/organic vapour/formaldehyde filters on respirators. The respirators and filters are issued to FESA career fire fighters to prevent the inhalation of toxic pollutants from bushfire smoke during bushfire fighting. At the time of the survey, the fire fighters had been using the P/OV/F filters for one bushfire season. Therefore, it was expected that the fire fighters had sufficient experience with the filters to contribute to the evaluation, and their responses can be considered representative.

The collected data demonstrates that the majority of the study participants perceived the performance of the new P/OV/F filter as an improvement over the performance of the previous P filter. Participating fire fighters reported better filtration of the inhaled air and consequently less smoke inhalation by using the P/OV/F filter during bushfire fighting. The study participants also reported the absence of smoke odour inside the respirators as a positive outcome.

Over the years 2006-2007, FESA recorded 7,336 bushfire incidents in Western Australia (Fire and Emergency Services Authority of Western Australia 2007). To obtain an individual profile of fire fighter’s bushfire attendance and smoke exposure, a number of questions in the questionnaire related to bushfire attendance.

All participating fire fighters reported frequent attendance at bushfires, with largest proportion of the respondents (n=8; 17%) attending 20 bushfires in the last three months before the survey. Nearly 60% of the respondents attended a bushfire less than a week before the survey.

Occupational exposure to bushfire smoke can often be prolonged and sustained, without much opportunity for breaks or recovery periods. The results of this survey show that fire fighters can be exposed to bushfire smoke for their entire shift (for up to 14 hours). The majority of the fire fighters in this study reported to be exposed for a period of up to 4 hours during their last bushfire attendance. The severity of smoke exposure not only depends on the length of the exposure, but also on the smoke density. Nearly half of the fire fighters classified the smoke that they encountered during the last bushfire to be of medium density (i.e. dark to black colour with moist to dry fuels with a visibility of 8 – 15 metres).
The results of this survey demonstrated that fire fighters wear the respirator and filters during bushfire fighting. The majority of the study participants wear the respirator and P/OV/F filters continuously during bushfire fighting, with the remainder of the surveyed group wearing the respirator and P/OV/F filters ‘sometimes’. Two indicated that they never use the respirator and P/OV/F filters, even though they had the opportunity avail themselves of the equipment.

There are still ergonomic issues to be resolved, in particular with regard to the fitting of the respirator. Although the respirator has a soft, lightweight elastomeric face piece, fire fighters indicate that the respirator is ‘not comfortable’ and ‘hurts the nose’. Some of the respondents indicated that the helmet, goggles, and the respirator are not compatible, resulting in the helmet pushing down the goggles and the respirator and thereby compromising the seal of the respirator. As a consequence, the fire fighters are likely to be inhaling the air toxics from the bushfire smoke, despite using optimal filters on their respirators.

The surveyed fire fighters reported moisture build-up inside the respirators as another issue of concern. The moisture is most likely the result of condensed exhaled air or perspiration, which becomes trapped inside the respirator. The build-up moisture may compromise the seal by any movement of the respirator. Two participants reported that the moisture build-up ‘requires heavy breathing’ and ‘makes the filters useless’.

Nevertheless, after using the P/OV/F filters for one bushfire season, eighty percent of the surveyed fire fighters consider this type of filter performs better than the previously issued P filter. The P/OV/F filter has different filtration properties compared to the P filter (Chapter 2). According to the surveyed fire fighters, this results in less smoke inhalation and the absence of smoke odour inside the respirator. The surveyed fire fighters consider these outcomes as very important in regard to the performance of the filters.

A large proportion of the surveyed group (80%) remove the respirator intermittently during bushfire fighting, mainly for communication purposes. Given that it is impossible to communicate verbally with the respirator in place, fire fighters have
few other options than to remove the respirator, and consequently inhale bushfire smoke every time they communicate, whether this be face-to-face or over the radio.

Firefighters need an adequate water intake before, during, and after fire fighting, as they commonly dehydrate at a rate of about 700 g (1% body mass) per hour and a maximum rate of 2 kg per hour (2.6% body mass) (Ham et al. 2005; Hendrie et al. 1997). However, this implies that firefighters need to remove their respirator for every sip of water they take. Such a behaviour pattern is reflected in the high proportion of respondents who report removing their respirator intermittently during bushfire fighting for ‘drinking’.

Most study participants reported that the respirator and the P/OV/F filters have no effect on the breathing rate or breathing pattern. A small proportion reported a positive effect, such as ‘easier to breath’ and ‘no more feelings of choking’. Others reported that ‘breathing was harder’, in particular during physical exertion. However, this may also have been an indication of the end of the service life of the filter.

With regard to changing the filters, the *Bush Fire Smoke Exposure Standard Operational Procedures 51* (SOP 51) (Fire and Emergency Services Authority Western Australia 2007) follows the recommendations of the manufacturer 3M™. These recommendations are:

- The end of service life of gas/vapour filters is indicated by the wearer smelling or tasting traces of the contaminant inside the face piece; and

- Particulate filters must be changed when breathing resistance becomes unacceptable.

Although these recommendations are subjective and depend on the observational capacities of the individual firefighter, they do however provide a ‘rule of thumb’ approach that is a very practical measure. To determine the effective service life, given the many variables as mentioned above, further laboratory or field testing would be required, which was not part of this study.
In the United States, OSHA has changed the regulations, requiring a more objective method of determining cartridge service life. Either of the two following objective methods can be used:

1. The respirator is equipped with an end-of-service-life indicator (ESLI) certified by the NIOSH; or

2. Alternatively, if there is no ESLI appropriate for the conditions in the workplace, a cartridge change schedule based on objective information can be implemented to ensure cartridges will be changed before the end of their service life.

As shown in the Filter Study, the use of the P/OV/F filter has a more protective effect with regard to the onset of respiratory symptoms in comparison to the P filter. In the Phase 1 trials, a significant 12-fold reduction was found in the number of participants with increased respiratory symptoms following the smoke exposure with the P/OV/F filter compared with the P filter (Chapter 4). The reported symptoms included coughing, wheezing, and shortness of breath. The results of this survey support these findings. Nearly 90% of the surveyed fire fighters reported that they no longer suffer respiratory symptoms during and after bushfire fighting when P/OV/F filters are used. In addition, fire fighters indicated that they do not need recovery time following bushfire attendance, which was often necessary before they were issued with the P/OV/F filters.

In Western Australia, FESA is responsible for issuing respirators and P/OV/F filters to their 1,000 career fire fighters. Currently, FESA is considering making the use of respirators and P/OV/F filters mandatory for all career fire fighters and to develop criteria to enable distribution of filter to volunteer fire fighters working in similar conditions (Parlour, L., pers. comm. 2007).

In conclusion, this survey has investigated the effectiveness of the P/OV/F filter in preventing short-term respiratory symptoms during and after bushfire smoke exposure. The survey of a small random selection of fire fighters has shown that all the participants use the P/OV/F filters during bushfire fighting activities. The reported benefits are less smoke inhalation and fewer respiratory symptoms during and after bushfire fighting. These outcomes support the findings from the Filter
Study. While there is measurable benefit from the use of the P/OV/F filters, ergonomic issues remain about the incompatibility of the respirator, the helmet and the goggles.

The study has not focussed on long-term health outcomes, as the P/OV/F filters have only been used for one bushfire season. Nevertheless, it is likely that the elimination of multiple short-term exposures has a preventative effect on the onset of long-term respiratory disease, such as Chronic Obstructive Pulmonary Disease (COPD) or asthma. The introduction of the P/OV/F filters goes a long way to protecting fire fighters’ respiratory health and its efficacy is confirmed by this post-introduction survey. However, the results indicate that minor movements may still be possible as a result of respirator design, and the problem can therefore not be considered to have been definitively solved.
Chapter 6 Legislation and Policy Development

6.1 Introduction

The previous chapters described the importance of appropriate respiratory protection for fire fighters during bushfire fighting. Following recommendations from the report ‘Respiratory Health of Fire Fighters - Bushfire CRC Project D4’, FESA reviewed the Bush Fire Smoke Exposure Standard Operational Procedures 51 (SOP 51). As a result, FESA career fire fighters in Western Australia are now issued with the P/OV/F filters during bushfire fighting.

This chapter analyses the policy context of making such a recommendation, and implications thereof at both the national and international level. An analysis is presented of the occupational health and safety (OHS) legislation and policy regarding the use of personal protective equipment (PPE), and in particular the use of the air-purifying respirators for fire fighters. The review focuses on national and international legislation and policy, particularly in countries that frequently encounter bushfires/wildfires. Strategies for best practice are discussed, which are aimed at appropriate and effective use of respirators and minimisation of exposure to air toxics in bushfire smoke.

6.2 Regulatory Framework

The following section describes the regulatory framework for the use of PPE, and in particular, the respirators in the work place. A review is provided of relevant Occupational Health and Safety Acts, Regulations and Standards from countries that frequently encounter bushfires. The practical implications for fire fighters on the fire ground are discussed and strategies for best practice and potential health benefits are explored.

It is important to note that in general, OHS Acts and Regulations consider reducing the environmental levels of air toxics, through engineering controls and work practices, as the first measure to protect the health of workers. The use of any form of PPE (Box 6.1), including respirators, is usually considered as a secondary measure only (Stranks 1995; Boehlecke 1996; Rajhans & Pathak 2002).
Box 6.1 Personal Protective Equipment
(Stranks 1995)

- Head protection: safety helmets, hard hats, caps;
- Eye protection: goggles, safety glasses, visors, screens;
- Face protection: face shields;
- Respiratory protection: air-purifying respirators, positive pressure-powered respirators, SCBA;
- Hearing protection: ear plugs, ear muffs and pads, ear valves, acoustic wool;
- Skin protection: barrier creams;
- Body protection: overalls, aprons, safety harnesses, body warmers, oil skin over clothing;
- Hand and arm protection: fibre gloves, PVC fabric gauntlets, gloves and sleeves;
- Leg and foot protection: safety shoes or boots, gaiters and anklets.

Information is first presented for Australia, the United States of America, and Europe (Table 6.1), and then integrated to draw general conclusions about the state of the legislation for the respiratory protection for fire fighters.

6.2.1 Commonwealth of Australia

The Occupational Health and Safety Act 1991 is a Commonwealth Act to promote the OHS of persons employed by Commonwealth authorities. The duties of employers in relation to their employees are presented in Box 6.2. The Act refers to the health and safety matters affecting employers and employees, although there is no specific reference to the use of PPE.

Box 6.2 Duties of Employers in Relation to their Employees
(Occupational Health and Safety Act 1991)

- An employer must take all reasonably practicable steps to protect the health and safety at work of the employer’s employees;
- An employer contravenes the previous subsection if the employer fails to take all reasonably practicable steps:
  - To provide and maintain a working environment:
    - that is safe for the employer's employees and without risk to their health; and
    - that provides adequate facilities for their welfare at work; and
  - In relation to any workplace under the employer’s control, to:
    - ensure the workplace is safe for the employees and without risk to their health; and
    - provide and maintain a means of access to, and egress from, the workplace that is safe for the employees and without risk to their health.

The requirements, selection, use and maintenance of respiratory protective devices is specified in the Australian/New Zealand Standard 1715:1994 (AS/NZS 1715) (Standards Australia 1994) and Australian/New Zealand Standard 1716:2003 (AS/NZS 1716) (Standards Australia 2003b; Standards Australia 1994). The AS/NZS 1715 sets out the principles of respiratory protection, and makes recommendations for the selection, use and maintenance of respirators for the
protection of the body against harmful substances which could enter the body through the respiratory system. The design, manufacturing and type approval test requirements for respiratory protective devices are covered in the AS/NZS 1716.

6.2.2 **Australian Capital Territory**

The Australian Capital Territory *Occupational Health and Safety Act 1989* is an Act to promote and improve standards for occupational health, safety and welfare and for related purposes. The objects of the Act are to:

- **Secure the health, safety and welfare of employees at work;**
- **Protect persons at or near workplaces from risks to health or safety arising out of the activities of employees at work;**
- **Promote an occupational environment for employees that is adapted to their health and safety needs;**
- **Foster a co-operative consultative relationship between employers and employees on the health, safety and welfare of employees at work.**

The Act also outlines the duties of employers in relation to employees, which are similar to the duties described in the Commonwealth Occupational Health and Safety Act 1991, which are presented in Box 6.2.

Division 3.3.2 of the *Occupational Health and Safety (General) Regulation 2007* provides the requirements for the use of PPE:

> ‘If measures taken by an employer to minimise a risk include the use of PPE, the employer must provide each person at risk with personal protective and safety equipment’.

The Regulation refers to the AS/NZS 1715 and 1716 (Standards Australia 1994; Standards Australia 2003b), in regard to the provision and use of PPE. The Regulation states that an employer commits an offence if personal protective and safety equipment used to minimise risk at a workplace is not stored in an accessible place at the workplace. The Occupational Health and Safety (General) Regulation
2007 includes provisions for communication problems associated with the use of PPE:

‘If the use of equipment may affect a person’s ability to communicate with other people, appropriate steps must be taken to ensure that this does not create a risk to the health or safety of the person or anyone else’.

This provision is extremely relevant given the findings from the evaluation (Chapter 5) demonstrated that the majority (53%) of the fire fighters remove the respirator at some stage during their tasks to communicate. Removing the respirator in smoke conditions potentially increases the risk of inhaling the toxic compounds in bushfire smoke.

The Australian Capital Territory Fire Brigade supplies Class 2 particulate filters for all their staff to be used at their discretion. However, the Fire Brigade does not specify the use of respiratory protection in Standard Operational Procedures. Their SOPs only cover operational tactics and strategies (Kent, G., pers. comm. 2008).

6.2.3 New South Wales

Under the New South Wales Occupational Health and Safety Act 2000, employers have a general duty of care and obligation to ensure the health, safety and welfare of their employees and others at their workplace.

The Occupational Health and Safety Regulation 2001 refers to specific hazards in the work environment, and includes requirements for employers to eliminate any foreseeable risk to the health and safety of any employee or any other person legally at the employer’s place of work. The Regulation also has provisions for PPE (Box 6.3) in controlling the risk, and refers to the relevant AS/NZS 1715 and 1716 (Standards Australia 1994; Standards Australia 2003b).
Box 6.3 Occupational Health and Safety Regulation 2001 Requirements for PPE

- The equipment provided is appropriate for the person and controls the risk for that person;
- The person is informed of any limitations of the equipment;
- The person is provided with the instruction and training necessary to ensure that the equipment controls the risk for the person;
- The equipment is properly maintained and is repaired or replaced as frequently as is necessary to control the risk for that person;
- The equipment is provided in a clean and hygienic condition to the person;
- The equipment is stored in a place provided by the employer for the purpose;
- Areas in places of work where PPE must be used are clearly identified.

The New South Wales Fire Brigades (NSWFB) supplies Class 2 particulate filters to be used in light smoke conditions, but there are no guidelines or procedures in place for their use. The NSWFB has in place the Breathing Apparatus Standard Operational Guidelines (No. 9.1), which require fire fighters to wear the SCBA, when working in smoke conditions or suspect atmosphere (New South Wales Fire Brigade 2000). The NSWFB regards the use of the SCBA the only safe way to prevent the inhalation of smoke (Bootsma, J., pers. comm. 2008).

The New South Wales Rural Fire Service (NSW RFS), which is the main combat authority for bushfires in New South Wales, uses a Service Standard on Compressed Air Breathing Apparatus (CABA)\textsuperscript{11}. The Standard provides guidelines for the use of CABA during structural fires, transport fires, hazardous material incidents, or when exposure to toxic gases or particles is unavoidable. The NSW RFS has Class 2 particulate filters available for the fire fighters. These filters are to be used in specific circumstances, such as the aftermath of a structural fire, an asbestos contaminated area, or during bushfires by any fire fighter if considered necessary. The NSW RFS does not have operating procedures in place to manage bushfire smoke exposure or to regulate the use of protective filters: this is left to the discretion of the crew leader and the individual fire fighter (Brinkworth, A. D., pers. comm. 2008).

6.2.4 Northern Territory

The Northern Territory Work Health Act 1986 aims to promote OHS, to prevent workplace injuries and diseases, and to protect the health and safety of the public in relation to work activities. In addition, the Act promotes the rehabilitation and

\textsuperscript{11} In New South Wales synonym for SCBA.
recovery from incapacity of injured workers, and provides financial compensation to workers incapacitated from workplace injuries or diseases, and to the dependants of workers who die as the results of workplace injuries or diseases. This is a provision that is not present in the OHS legislation in other Australian States or Territories.

The Work Health (Occupational Health and Safety) Regulations include requirements for the use of PPE. Division 7, Section 71 states that an employer shall ensure that PPE is worn by a worker, where the equipment is the means by which the worker's exposure to a hazard is to be controlled. Section 72 includes provisions for the use, maintenance and replacement of PPE, and states that the employer who provides a worker with PPE shall ensure that:

- The worker is instructed in the correct fitting, use and maintenance of the equipment;
- The worker is provided with information on the limitations of the use of the equipment;
- The equipment is maintained in good working order; and
- The equipment is replaced when it:
  - No longer provides the level of protection;
  - Has exceeded its working life as specified by the manufacturer; or
  - Is damaged.

Section 74 includes duties of workers using PPE, and states that a worker provided with PPE shall wear the equipment at all times and in all areas as required by the worker's employer. Section 78 specifically states that:

- Where a worker may be exposed at a workplace to
  - A concentration of airborne contaminants which may:
    - pose a risk to the health and safety of the worker; or
    - produce unsafe working conditions at the workplace; or
  - An atmosphere containing less than 18 % oxygen, and no other means of controlling the worker's exposure is practicable;
• An employer shall provide the worker with respiratory protective equipment complying with AS/NZS 1716.

The Northern Territory Fire and Rescue Service has no operational procedures in place relating to respiratory equipment to be used during bushfire fighting (Stephens, A. R., pers. comm. 2008).

6.2.5 Queensland

Under the Queensland Workplace Health and Safety Act 1995, the employer has an obligation to ensure the workplace health and safety of each of the employer's workers at work. The Act also obliges the employer to ensure that the workplace health and safety is not affected by the way in which the employee is required to carry out their duties.

Section 105 of the Workplace Health and Safety Regulation 1997 provides regulations for the use of PPE as a measure to control exposures in the workplace. However, these provisions are meant to be considered in the context of spray painting or lead exposure. There are no further references to fire fighters and smoke exposures in the Regulations.

There is no evidence that Queensland has operational procedures in place regarding the use of respirators during bushfire fighting.

6.2.6 South Australia

The South Australia Occupational Health, Safety and Welfare Act 1986 includes general provisions for occupational health, safety and welfare. An employer must ensure that the employee is, while at work, safe from injury and risks to health (Box 6.4).
Box 6.4 Occupational Health, Safety and Welfare Act 1986 Employers’ Obligations

- Provide and maintain so far as is reasonably practicable:
- A safe working environment;
- Safe systems of work;
- Plant and substances in a safe condition;
- Provide adequate facilities of a prescribed kind for the welfare of employees at any workplace that is under the control and management of the employer;
- Provide such information, instruction, training and supervision as are reasonably necessary to ensure that each employee is safe from injury and risks to health;
- Monitor the health and welfare of the employees in their employment with the employer, insofar as that monitoring is relevant to the prevention of work-related injuries;
- Keep information and records relating to work-related injuries suffered by employees in their employment and retain that information and those records for such period as may be prescribed;
- Provide information to the employer’s employees in relation to health, safety and welfare in the workplace.

Division 2.12 of the *Occupational Health, Safety and Welfare Regulations 1995* ensures that PPE and clothing is provided and maintained where a risk at work could be minimised by its use. The Regulation states that:

- *An employer must ensure that appropriate PPE or clothing is provided to an employee if it is reasonably foreseeable that the employee could, while at work be subject to a risk to health or safety through exposure to a substance, agent, contaminant, radiation, or extreme of temperature;*
- *A person who must use or wear equipment or clothing under this regulation must receive proper training and instruction in the use and maintenance of the equipment or clothing;*
- *If the use or wearing of equipment or clothing could affect proper communication with another, appropriate steps must be taken to ensure that this situation does not create a risk to health or safety;*
- *This regulation does not require a person to use or wear equipment or clothing in circumstances where to do so would create a greater risk to health or safety.*

The South Australia Country Fire Service (CFS) does not have specific Standard Operational Procedures in place for PPE. However, the use of PPE is comprehensively covered in the *Basic Firefighting 1 Training*, in particular in the Unit 3 *Prevent Injury*, which covers the requirements for the selection and the use of PPE. The *Fire Ground Practices*, which are trainings tools designed to cover a range of fire fighting tasks and activities, also include requirements for the minimum level of PPE to be utilised for each task (Sandford, R., pers. comm. 2008).
6.2.7  **Tasmania**

Under the Tasmania *Workplace Health and Safety Act 1995* employers have the duty to ensure that the employee is safe from injury and risks to health, while at work. In particular, the employer must:

- *Provide and maintain so far as is reasonably practicable:*
  - A *safe working environment;*
  - Safe systems of work;
  - Plant and substances in a safe condition;
  - Provide facilities of a prescribed kind for the welfare of employees at any workplace that is under the control or management of the employer;
  - Provide any information, instruction, training and supervision reasonably necessary to ensure that each employee is safe from injury and risks to health.

The *Workplace Health and Safety Regulations 1998* refer to the use of PPE. The regulations require that:

- *An accountable person must ensure that any PPE or clothing required to be provided by these regulations, and the PPE should:*
  - Meet the requirements of the relevant standard issued by a prescribed authority;
  - Be hygienically maintained and used so as to provide the protection for which it was designed.

- *A person provided with PPE or clothing must:*
  - Wear the equipment or clothing at any time, and in any area, required by an accountable person;
  - Take reasonable care of the equipment or clothing;
  - Not deliberately damage or misuse the equipment or clothing.

- *A person who becomes aware of any damage to, or defect in, any PPE or clothing must immediately notify the accountable person.*
The Tasmania Fire Service provides the Class 2 particulate filters as per Australian Standards (Standards Australia 1994), but the Fire Service does not have Operational Procedures in place to assist in the selection and the use of respiratory protection. Currently, the Class 2 particulate filter is the most effective filter, in terms of user compliance amongst fire fighters in Tasmania. The Tasmania Fire Service anticipates that the use of new respirators and filters will bring logistical issues and concerns with respect to selection of the most appropriate filter, health and hygiene, and the service life of the filters (Green, J., pers. comm. 2008). Therefore, the Service is awaiting the research findings regarding the operational acceptance and effectiveness of the P/OV/F filters used by the FESA career fire fighters in Western Australia since 2006.

6.2.8 Victoria

The Victoria Occupational Health & Safety Act 2004 requires employers to provide and maintain for employees of the employer a working environment that is safe and without risks to health.

The Occupational Health and Safety (Hazardous Substances) Regulations 1999 require the employer to provide an employee with air-supplied respiratory protective equipment (i.e. SCBA) if the employee carries out emergency procedures in a confined space, or in a setting that either does have a safe oxygen level or has a harmful level of any contaminant. However, the Regulations do not provide requirements for air-purifying respirators.

There is no evidence that Victoria has a policy or operational procedures in place regulating the use of respiratory protection during bushfire fighting.

6.2.9 Western Australia

Under the Western Australia Occupational Safety and Health Act 1984 employers have a duty of care to ensure the health, safety and welfare of their employees at their workplace, and to provide and maintain a working environment, in which the employees are not exposed to hazards. The Act also includes the provision for employers to provide the employees with adequate personal protective clothing and equipment without any cost to the employees, where it is not practicable to avoid the presence of hazards in the workplace.
Under the *Occupational Safety and Health Regulations 1996*, an employer must ensure that each person who may be exposed to a toxic atmosphere (Box 6.5) is provided with respiratory protective equipment when it is not practicable to prevent the exposure. The respiratory protective equipment must be selected, used, and maintained in accordance with AS/NZS 1715 (Standards Australia 1994), and comply with the relevant requirements of AS/NZS 1716 (Standards Australia 2003b).

**Box 6.5 Definition of Toxic Atmosphere as per Occupational Safety and Health Regulations 1996**

- An atmosphere, in which there is an atmospheric contaminant in a concentration exceeding the exposure standard for the contaminant specified in the National Exposure Standards;
- Where an inspirable dust or respirable dust is not within the scope of the National Exposure Standards, an atmosphere in which a person at the workplace would be exposed to
  - The inspirable dust that, when measured in accordance with AS 3640, exceeds 10 mg/m³;
  - The respirable dust that, when measured in accordance with AS 2985, exceeds 5 mg/m³, as an average over a work period of eight hours; and
- An atmosphere containing gas, vapour, dust or any other particle, which is a risk to the safety and health of a person at the workplace.

The management of bushfire smoke for FESA career fire fighters in Western Australia is regulated by the *Bush Fire Smoke Exposure Standard Operational Procedures 51* (SOP 51) (Fire and Emergency Services Authority Western Australia 2007), which are based on the Occupational Safety and Health Act 1984, the Occupational Safety and Health Regulations 1996, and the AS/NZS 1715 (Standards Australia 1994). The SOP 51 provide a management tool for fire fighters to determine the most appropriate method to manage bushfire smoke exposure, and to assist in decision making about the level of respiratory protection. In 2006, the SOP 51 was reviewed as a result of the recommendations from the ‘Respiratory Health of Fire Fighters - Bushfire CRC Project D4 – Final Report’ (De Vos et al. 2006). The recommended P/OV/F filter was added to the SOP 51 as a second level of respiratory protection from bushfire smoke (Box 6.6).
Box 6.6 Bush Fire Smoke Exposure SOP 51: Levels of Respiratory Protection  
(Fire and Emergency Services Authority of Western Australia 2007)

1. Particulate filters protect fire fighters from breathing particulate matter produced during the burning of vegetation;
2. Particulate/organic vapour/formaldehyde filter prevent the entry of particulates and some (but not all) known respiratory irritants into the respiratory tract.

Both level 1 and 2 are designed to provide comfort to the wearer in bushfire smoke environments.
3. Breathing apparatus (SCBA) can be used, but this should only be used in extreme cases for essential or critical tasks such as asset protection in heavy smoke.

Currently, the use of the P/OV/F filters is voluntary. However, FESA is considering whether or not to make the use of the P/OV/F filters mandatory for all FESA career fire fighters in Western Australia (Parlour, L. pers. comm. 2007).

6.2.10 United States

The Occupational Safety and Health Administration (OSHA) administers the Occupational Safety and Health Act 1970. The Act aims to ensure employee safety and health by: (i) working with employers and employees to create better working environments by assuring safe and healthy conditions; (ii) authorizing enforcement of the standards developed under the Act; (iii) assisting and encouraging the States in their efforts to assure safe and healthy working conditions; and (iv) providing for research, information, education, and training in the field of occupational safety and health.

State and local government employees are exempt from Federal OSHA standards. However, in the 25 States currently authorized by OSHA to run their own safety and health programs, all OSHA regulations apply to both public and private employees (United States Department of Labor 2007; United States Department of Labor Occupational Safety & Health Administration 2007).

The OSHA regulations that apply to respiratory protection are the 29 Code of Federal Regulations (CFR) 1910.134. The regulations require employers to provide respirators suitable for the purpose intended, and to establish and maintain a respiratory protection program with required worksite specific procedures and provisions (Box 6.7). However, these requirements for PPE apply explicitly to general industry, construction, shipyard, and marine terminal workplaces, and do not apply to wildland fire fighting operations.

- Procedures for selecting respirators for use in the workplace;
- Medical evaluations of employees required to use respirators;
- Fit testing procedures for tight-fitting respirators;
- Procedures for proper use of respirators in routine and reasonably foreseeable emergency situations;
- Procedures and schedules for cleaning, disinfecting, storing, inspecting, repairing, discarding, and otherwise maintaining respirators;
- Procedures to ensure adequate air quality, quantity, and flow of breathing air for atmosphere supplying respirators;
- Training of employees in the respiratory hazards to which they are potentially exposed during routine and emergency situations;
- Training of employees in the proper use of respirators, including putting on and removing them, any limitations on their use, and their maintenance; and
- Procedures for regularly evaluating the effectiveness of the program.

The National Institute for Occupational Safety and Health (NIOSH) is the United States federal agency responsible for conducting research and making recommendations for the prevention of work-related injury and illness, and plays an important role in the development of OSHA standards (McCunney 2003).

The National Fire and Protection Association (NFPA) administers standards, recommended practices, and guides, which are developed through a consensus standards development process approved by the American National Standards Institute. The Standard on Protective Clothing and Equipment for Wildland Fire Fighting (National Fire Protection Association 2005) is the standard, which specifies the minimum design, performance, testing, and certification requirements for wildland fire fighting protective clothing and equipment. However, it specifically states that it does not provide criteria for respiratory protection for wildland fire fighting operations. In 2007, the NFPA Technical Committee on Respiratory Protection was directed to develop a new NFPA Standard on Respirators for Wildland Firefighting. Its projected publication is early 2011.

In April 2007, a Bill for the Wildland Fire Safety and Transparency Act 2007 was presented in the 110th Congress. The Act aims to promote wildland fire fighter safety, and requires annual reports on wildland fire fighter safety, including (a) a description of changes to wildland fire fighter safety practices, and (b) training programs for wildland fire fighting, prescribed burning, and wildland fire use. The Bill was put on the Senate Legislative Calendar in June 2007, but (as of February
2008) it is unknown when the bill will be considered and voted on by the Senate (GovTrack.US 2007).

In summary, since the mid 1980s researchers have demonstrated an association between exposure to wildland fire smoke and respiratory symptoms in wildland fire fighters in the United States. Recommendations were formulated to emphasise the importance of respiratory protection for wildland fire fighters. However, these recommendations have not resulted in OHS legislation for wildland fire fighters. Although the use of respiratory protection is regulated for fire brigades and private fire departments, forest fire fighters in the United States are not considered to be at risk from smoke inhalation, and consequently are not covered by any Code of Federal Regulations or Standard.

6.2.11 Europe

The European Parliament, together with the Council of the European Union, has established Directives to protect the health and safety of workers in the European Union. Two Directives relate to PPE:

2. Directive 89/656/European Economic Community - Use of PPE in the workplace.

The Directive 89/686/EEC details the basic safety requirements that a product must satisfy. It also details the conditions for placing PPE on the market for free movement of goods within the European Union.

The Directive 89/656/EEC is concerned with improving standards of health and safety in the workplace, and also covers the use of PPE (Box 6.8). PPE is defined as ‘all equipment designed to be worn or held by the worker to protect him against one or more hazards likely to endanger safety and health at work’. The Directive states that, ‘where risks to health and safety can be identified, the first priority should be to eliminate the risk by finding safer alternatives, changing the work practice or providing collective protection’. PPE should only be considered when it is not possible to achieve the required degree of protection by any of the previously described methods.

- PPE: equipment designed to be worn or held by the worker to protect him against hazards encountered at work. A number of items are excluded from the definition, such as equipment used by emergency and rescue services.
- Such equipment must be used when the existing risks cannot be sufficiently limited by technical means of collective protection or work organisation procedures.
- Employers’ obligations:
  - To ensure that PPE complies with the relevant Community provisions on design and manufacture with respect to safety and health and with the conditions set out in the directive;
  - To provide the appropriate equipment free of charge and ensure that it is in good working order and hygienic condition;
- Before choosing PPE, the employer is required to assess the extent to which it complies with the conditions set out in the directive. This includes analysis of risks which cannot be avoided by other means and definition and comparison of the requisite characteristics of the equipment.
- Workers shall be informed of all measures to be taken. Consultation and participation shall take place on the matters covered by the directive.

The Directive further places obligations on employers to ensure that all PPE in the workplace conforms to relevant EEC standards, and also to conduct a risk assessment of the hazards, define the characteristics of equipment necessary to protect employees, and keep records of assessments and reasons for selecting particular types of PPE. However, the Directive 89/656/EEC excludes equipment used by emergency and rescue services (Box 6.8), which implies that the use of PPE for European forest fire fighters is not covered by this particular Directive. This has important implications for forest fire fighters in locations such as Greece, Spain and Portugal, where forest fires are a regular occurrence (Gomes 2006; Briassoulis 1992).
### Table 6.1 Regulatory Approach for Respiratory Protection, Recommendations for Best Practice, and Potential Occupational Health Benefits

<table>
<thead>
<tr>
<th>Region</th>
<th>Act, Regulation or Standard</th>
<th>Recommendations for Best Practice</th>
<th>Occupational Health Benefits</th>
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<tr>
<td>Australia</td>
<td><strong>Commonwealth</strong>&lt;br&gt;Occupational Health and Safety Act 1991&lt;br&gt;AS/NZ Standard 1715 - 1994 Selection, Use and Maintenance of Respiratory Protective Devices&lt;br&gt;AS/NZ Standard 1716 - 2003 Respiratory Protective Devices&lt;br&gt;Australian Capital Territory&lt;br&gt;Occupational Health and Safety Act 1989&lt;br&gt;Occupational Health and Safety (General) Regulation 2007</td>
<td>OHS legislation should include a requirement for fire agencies to provide respirators for the purpose of bushfire fighting&lt;br&gt;OHS legislation should include a requirement for fire agencies to establish and maintain a respiratory protection program including worksite-specific procedures and provisions for bushfire fighting operations such as:&lt;br&gt;Procedures for selecting appropriate respirators for use on the fire ground&lt;br&gt;Medical evaluation&lt;br&gt;Fit-testing procedures for respirators&lt;br&gt;Procedures for proper use during bushfire fighting&lt;br&gt;Procedures and schedules for cleaning, storing, maintaining, and changing respirators&lt;br&gt;Training of fire fighters on respiratory hazards of bushfire fighting&lt;br&gt;Training of fire fighters in the proper use of respirators, donning and removing them, and the limitations of their use&lt;br&gt;Procedures for regularly evaluating the effectiveness of the program</td>
<td>Increased awareness of the hazards of smoke inhalation&lt;br&gt;Reduced bushfire smoke exposure&lt;br&gt;Less acute bushfire smoke related symptoms and disease, including coughing, wheeze, shortness of breath&lt;br&gt;Healthier fire fighters in the long term&lt;br&gt;Less smoke injury related compensation claims</td>
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<tr>
<td>Northern Territory</td>
<td>Work Health Act 1986&lt;br&gt;Work Health (Occupational Health and Safety) Regulations</td>
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<td>South Australia</td>
<td>Occupational Health, Safety and Welfare Act 1986&lt;br&gt;Occupational Health and Safety Regulations 1995</td>
<td>Conduct long term cohort studies with career, volunteer, and seasonal fire fighters&lt;br&gt;Inform policy decision makers about respiratory health effects of bushfire smoke toxics exposure</td>
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<tr>
<td>Country</td>
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<tr>
<td>Western Australia</td>
<td>Occupational Safety and Health Act 1984&lt;br&gt;Occupational Safety and Health Regulations 1996 &lt;br&gt;Bush Fire Smoke Exposure SOP 51</td>
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Basic Firefighting 1 Training<br>Fire Ground Practices
6.2.12 Summary

The previous sections have demonstrated a lack of consistent legal provisions and requirements for the use of PPE, and in particular the air-purifying respirator for firefighters during bushfire fighting. Although some Australian States and Territories have established comprehensive OHS Regulations, internationally there is an apparent lack of effective regulations and standards.

In Australia, the requirements, selection, use and maintenance of respiratory protective devices is specified in the AS/NZS 1715 and AS/NZS 1716. The AS/NZS 1715 sets out the principles of respiratory protection, and makes recommendations for the selection, use and maintenance of respirators for the protection of the respiratory tract. The design, manufacturing and type approval test requirements for respiratory protective devices are covered in the AS/NZS 1716.

The OHS of workers in Australia is regulated by State Acts and Regulations. In general, the requirements for the use of PPE are considered as a means of controlling hazards in the workplace. As such, the employer is required to provide respiratory protective equipment to safeguard employees’ health and safety. However, the requirements vary between the States and Territories. The Northern Territory, South Australia, and Tasmania have extensive provisions in their respective regulations for the use, maintenance and replacement of PPE, and have incorporated a limited form of a respiratory protection program\(^\text{12}\). The Regulations also make reference to the relevant AS/NZS 1715 and 1716. In contrast, in Queensland and Victoria, the use of respiratory protection for bushfire fighters is not formally regulated. The Queensland Regulations refer to the use of PPE only in the context of spray painting or lead exposure. The Victorian Occupational Health and Safety Regulations provide requirements for the use of air-supplied respiratory equipment (SCBA) during emergency procedures only. In Western Australia, the provision of respiratory protective equipment is regulated by the Occupational Safety and Health Regulations 1996 with reference to the AS/NZS 1715 and 1716.

\(^{12}\) Respiratory Protection Program: See Section 6.3.
On an operational level FESA is the only Australian fire agency which has Standard Operational Procedures in place. These procedures assist in the management of bushfire smoke exposure, and help guide the decision-making process about the most appropriate level of respiratory protection.

In the United States, the 29 CFR 1910.134 provides comprehensive requirements for employers to develop and implement a respiratory protection program. However, these Regulations only apply to general industry, shipyard, and marine terminal workplaces, and not to wildland fire operations. The Standard on Protective Clothing and Equipment for Wildland Fire Fighting (National Fire Protection Association 2005) specifies the performance and certification requirements for wildland fire fighting protective clothing and equipment. However, it does not include criteria for respiratory equipment. A new NFPA Standard on Respirators for Wildland Firefighting is expected for early 2011. In 2007, a Bill for the Wildland Fire Safety and Transparency Act 2007 promoting wildland fire fighter safety was presented to Congress, but (in February 2008) has not been passed through to the Senate.

In Europe, the use of respirators for fire fighters is not covered by any Act, Standard or Regulation. The Europe Directive 89/656/EEC deals with improving standards of health and safety in the workplace, and also covers the use of PPE, but it excludes equipment used by emergency and rescue services. This implies that the use of PPE for European forest fire fighters is not covered by this Directive.

In summary, legislation and policy with respect to the use of respirators for bushfire fighters is well established in Western Australia. FESA is to be commended for endorsing the recommendations from the ‘Respiratory Health of Fire Fighters - Bushfire CRC Project D4 - Final Report’ (De Vos et al. 2006). As a result, FESA career fire fighters in Western Australia are now issued with the more effective P/OV/F filter. This provides a compelling example of how health research can be translated into practice. FESA’s decision can be viewed as pro-active and in advance of national and international legislation. Fire fighter organisations in other countries with a high frequency of wildland fires could learn from this example, and develop a regulatory framework for the introduction of personal protective
equipment. The following guidelines for best practice may support the development of such an approach.

### 6.3 Recommendations for Best Practice

OHS legislation should include a requirement for fire agencies to provide respirators for the purpose of bushfire fighting to be used in conjunction with CO monitoring. Although the requirement for providing PPE is covered by OHS legislation in some countries, it mostly applies to structural fire fighting and does not include bushfire fighting operations. This may be explained by the fact that bushfire smoke is still considered to be harmless for humans, despite the ample scientific evidence of the health damaging effects of exposure to air toxics.

In work situations where respirators are used to protect the employer’s health from occupational hazards, such as bushfire smoke, it may be argued that it is the fire agency’s responsibility to develop a respiratory protection program as part of their respiratory protection policy. Ideally, such a program should establish the responsibilities of the fire agency, station officers, and fire fighters and step-by-step procedures for selection, use, and maintenance of respirators. The program should be in accordance with the OHS legislation, and should be an integral part of the fire agency’s overall hazard control strategy.

It is recommended that the fire agencies appoint a program administrator to coordinate the program. Such an individual should have sufficient knowledge, gained by training and experience, to develop and implement the respiratory protection program, and to make informed decisions based on an understanding of the hazards of air toxics exposure. The respiratory protection program needs to be tailored to cover the specific bushfire fighting operations and practices. In an optimal situation, the entire respiratory protection program should be outlined in written standard operating procedures and be readily available to all employers involved.
The following procedures should be incorporated in a respiratory protection program:\(^\text{13}\):

- **Procedures for selecting appropriate respirators for use on the fire ground**

The fire agency should be responsible for selecting an appropriate respirator based on the respiratory hazards on the fire ground. The respirator should be approved and certified by Australian Standards (AS) (Australia) or National Institute of Occupational Safety and Health (NIOSH) (United States). The fire agency should undertake a hazard assessment to determine the potential toxicity of the air toxics. Where an air toxic is regulated by substance-specific occupational standards (e.g. ‘Exposure Standards for Atmospheric Contaminants in the Occupational Environment’), the most reliable and accurate method to determine exposure is to conduct personal air monitoring. Next, the respirators should be selected after considering (1) the nature of the hazard; (2) characteristics of the hazards; (3) location of the hazardous area with respect to a safe area having respirable air; (4) period of time in use; (5) nature and level of work; and (6) the capabilities and limitations of the various respirators. The fire agency ideally should provide respirators, training, and medical evaluations at no cost to the fire fighter.

- **Medical evaluation**

Fire agencies should provide a medical evaluation to determine fire fighters’ fitness to wear a respirator. The evaluation must be provided before the initial fit-testing and before the respirator is used for the first time. The capability of the fire fighter to wear a respirator should initially be determined through pulmonary function testing. Further medical evaluation consists of the administration of a medical questionnaire, or provision of a physical examination that elicits the same information as the questionnaire. These evaluations should be performed annually, and be required for all respirator users.

\(^{13}\) This section is largely based on the 29 Code of Federal Regulations 1910.134.
• **Fit-testing procedures for respirators**

The fire agency should establish and retain fit-testing records in accordance with required Standards (Standards Australia 1994; Standards Australia 2003b; National Occupational Health and Safety Commission 1995; National Institute for Occupational Safety and Health 2007). Fit testing should be required for all fire fighters using respirators. The fit test must be performed before the respirator is used on the fire ground. It must be repeated at least annually and whenever a different respirator is used or a change in the fire fighter’s physical condition could affect the respirator fit. If the respirator subsequently becomes unacceptable (i.e. causes irritation or pain) to the fire fighter, he/she should be given the opportunity to select a different respirator and be retested. Fit-testing records should be made available to the fire fighter, and should contain the fire fighter’s identification, type of fit test, date last tested, the results of the test, and the make, model and size of the respirator and filters tested.

• **Procedures for proper use during bushfire fighting**

Fire agencies should establish and implement procedures for the proper use of respirators. These procedures include prohibiting conditions that may result in face-piece leakage. For example, the presence of facial hair (more than one day's growth) between the sealing surface of the respirator and the face may result in face-piece seal leakage (Rajhans & Pathak 2002; Skretvedt & Loschiavo 1984). Glasses, goggles or other PPE, such as helmets should not interfere with the face-to-face piece seal. If the fire fighter wears other safety equipment with the respirator, he should pass an appropriate fit test while wearing the equipment to determine if it interferes with the seal. Fire fighting agencies should prevent fire fighters from removing respirators in hazardous environments, and ensure continued respirator operation throughout the shift.

• **Procedures and schedules for cleaning, storing, maintaining, and changing respirators**

Procedures and schedules should be developed to ensure that respirators are cleaned and disinfected as often as necessary to keep them in a sanitary condition.
Furthermore, procedures should establish that respirators are stored properly to prevent damage and contamination. Inspection procedures for respirators should be incorporated, to include a check of respirator function, tightness of connections and the condition of the various parts, including the face piece, head straps, valves, and filters.

The respiratory protection program should incorporate a transparent filter change schedule, based on objective information that ensures the filters are replaced before the end of their service life. This is critical to prevent contaminant breakthrough in the respirator, thereby over-exposing fire fighters. However, since neither objective nor experimental data is available for mixtures of contaminants, it should be assumed that the mixture stream behaves as a pure system involving the most rapidly migrating compound with the shortest breakthrough time. Therefore, the service life of the filter should be based on the contaminant with the shortest breakthrough time. The use of warning properties, such as abnormal odour or irritation, as the sole basis for determining change schedules should be prohibited. However, it is important to note that fire fighters should be trained to understand that abnormal odour or irritation is evidence that respirator filters need to be replaced (Section 2.7.3.2).

- **Training of fire fighters on respiratory hazards of bushfire fighting**

It is suggested that the respiratory protection program should incorporate training on the respiratory hazards for which the respirator is being used. The training may include:

- Basic information on the chemical composition of bushfire smoke and associated health effects;

- Applied information of fire fighting techniques aimed at reducing bushfire smoke exposure;

- Techniques for assessing levels of smoke exposure of the tasks to be performed before committing personnel to action; and
- **Instruction into monitoring carbon monoxide (CO) levels on the fire ground.**
  The use of CO alarm dosimeters increases hazard awareness, because the monitors provide immediate feedback about CO overexposure.

- **Training of fire fighters in the proper use of respirators, their effectiveness and limitations**

  The fire agency should provide effective respirator training to fire fighters. The training should be comprehensive and understandable, and should be provided prior to the fire fighter’s use of the respirator. The training should cover the following topics at a minimum:

  - Instruction in the nature, the extent, and effect of respiratory hazards that the fire fighters are exposed to during bushfire fighting;
  - Explanation of the reason for selecting a particular type of respirator;
  - Discussion of the effectiveness and limitations of the respirator;
  - Practical demonstrations in donning, wearing and removing the respirator; and
  - Instruction and training in actual use.

  Training sessions should be arranged annually and more frequently if retraining appears necessary to ensure safe use. The effectiveness of the training program can be evaluated by determining how well the fire fighters understand how to use their respirators. If respirators have missing parts or are improperly worn, dirty, or improperly stored, the OHS officer should interview the fire fighter for knowledge of the respirator requirements.

- **Procedures for regularly evaluating the effectiveness of the program**

  The fire agency should conduct evaluations of the workplace to ensure the written respiratory protection program is properly implemented. This includes observing and consulting fire fighters to determine if they have any problems with the program and ensuring that the respirators are used properly.
In order to better understand the long term health effects of bushfire smoke exposure, and thus better inform policy decisions makers, it would be useful to conduct cohort studies of fire fighters who have experienced long term exposures. Although the short term health effects of air toxics exposure are well established, there is a lack of evidence into the long term health effects of air toxics exposure from bushfire smoke. These cohort studies could include both career, volunteer, and seasonal fire fighters.

### 6.4 Health Benefits

Regardless of any legislation, the responsibility of every fire agency should be to safeguard the health, safety, and well-being of its fire fighters. The previous section introduced the respiratory protection program, which is a tool to assist in the selection, use, and maintenance of respirators with the ultimate aim to protect fire fighters’ respiratory health. Establishing such a program will increase levels of awareness of the hazards of smoke inhalation by both the fire agency management and the fire fighters on the fire ground. The provision of suitable respirators, in conjunction with appropriate training on the effectiveness and limitations of the respirators, will help to ensure that fire fighters have increased understanding how to protect themselves during bushfire fighting operations. Carbon monoxide dosimeters also have a role in increasing hazard awareness, since such devices provide immediate feedback about overexposure, thereby allowing fire fighters to take instantaneous action to reduce their exposure.

Introducing and implementing bushfire fighting strategies aimed at reducing personal smoke exposure will most likely result in less smoke-related symptoms and disease in fire fighters, both in the short and long term. This will lead to healthier fire fighters, and consequently less smoke injury related compensation claims.

### 6.5 Discussion

This chapter has reviewed the OHS legislation and policy with respect to the use of air-purifying respirators to be used during bushfire fighting by fire fighters.

Respiratory protection for wildland fire fighters in the United States is poorly regulated. Current legislation with respect to respiratory protective equipment for fire fighters does not include wildland fire fighting operations, despite the fact that
in the United States thousands of individuals are engaged in wildland fire fighting and are potentially at risk of inhalation injury (Booze et al. 2004). Forest fire fighters in Europe, even in high risk areas such as Greece and Portugal, are not covered by any OHS legislation regarding the use of respiratory protective equipment. Although the Directive 89/656/EEC incorporates the use of respiratory protective equipment, it excludes equipment used by emergency and rescue services.

In the Northern Territory, South Australia, and Tasmania, the OHS legislation has comprehensive provisions and requirements for the use of respiratory protection. However, Western Australia is the only Australian State, that has Standard Operational Procedures in place to assist in the decision making process about the most appropriate level of respiratory protection. Following the recommendations from the ‘Respiratory Health of Fire Fighters - Bushfire CRC Project D4 – Final Report’, the SOP 51 was reviewed and consequently the P/OV/F filter was added as a third level of respiratory protection from bushfire smoke.

The recommendation introduced by FESA can be seen as a pro-active and in advance of national and international legislation. In general terms, it is rewarding to see that health research can translate into practice that protects the wellbeing of employees without the need for waiting for the lengthy process of legislative reform. Fire fighter organisations in other countries with a high frequency of wildfires could learn from this example, and move to introduce personal protective equipment immediately.

Incorporating the requirements for a respiratory protection program would greatly benefit fire fighters’ health through the multi-faceted approach. This includes not only the provision of effective respirators, but also appropriate training in the occupational hazards of air toxics exposure, and the introduction of smoke reducing work practices on the fire ground.
Chapter 7 Discussion

This thesis set out to investigate the respiratory health effects of fire fighters during and after bushfire smoke exposure, with particular emphasis on the effectiveness of the provided respiratory protective equipment. The research encompassed five components: (1) the review of the literature with regard to the likely exposures involving bushfires in Australia, and in particular in Western Australia; (2) the identification and quantification of air toxics in Western Australian bushfire smoke; (3) the profiling of the acute respiratory health effects associated with bushfire smoke exposure; (4) the assessment of the effectiveness of three different types of filters under controlled conditions in a smoke chamber, and in the field during fuel reduction burn-off; and (5) the formulation of recommendations to inform policy decision makers about the most effective form of respiratory protective equipment for bushfire fighting.

In greater detail, the study commenced with experimental burns undertaken to identify and quantify the air toxics in bushfire smoke. The air sampling of the bushfire smoke demonstrated the presence of PM, formaldehyde, acrolein and CO. Moreover, levels of PM and CO exceeded the STEL significantly. It was acknowledged that conditions during the trials, in particular in the smoke chamber, do not exactly replicate real bushfire fighting situations, and the concentrations of air toxics measured cannot be directly related to concentrations that fire fighters will be exposed to during bushfire fighting activities. Nevertheless, other studies in the United States and in other Australian States have found similar results from smoke sampling during prescribed burns. Reinhardt et al. (2000) showed that during wildland fires, occupational exposure standards were exceeded for up to 14% of fire fighters’ exposures to respirable particles, formaldehyde, and acrolein, and 8% of exposures to CO. In Australia, Reisen et al. (2006) found during prescribed burns in Victoria, South Australia, and the Northern Territory that respirable particle levels frequently exceeded the STEL of 10 mg/m$^3$, and CO levels exceeded occupational exposure levels in a small (not specified) number of cases, related to specific tasks. Furthermore, formaldehyde and acrolein were identified as the major aldehydes present in the bushfire smoke. These findings in combination provide justification for further research into profiling the air toxics in bushfire smoke under more
realistic conditions, over longer time frames, and in different locations in (Western) Australia. Conducting air sampling during more realistic conditions will contribute to the exact profiling of the air toxics in bushfire smoke.

Testing the effectiveness of the three types of filters under controlled conditions indicated that the P filter was only effective in filtering out particles, and was ineffective in filtering out other bushfire smoke components, particularly respiratory irritants such as formaldehyde and acrolein. Although the P/OV filter was effective in filtering out these compounds, the P/OV/F filter was most effective in preventing acute respiratory health symptoms. The field validation measurements demonstrated that after 60 and 120 minutes smoke exposure, a significantly higher number of participants in the P filter group reported an increase in respiratory symptoms (such as coughing, wheezing and shortness of breath) compared to the other two filter groups. Declines in both FEV$_1$ and SaO$_2$ were observed after 60 and 120 minutes, but not statistically associated with a particular type of filter. It is likely that accumulation of CO may play a role in the SaO$_2$ decline.

After adjusting for possible confounders, a significant four-fold reduction was found in the number of participants reporting an increase in respiratory symptoms in the P/OV/F filter group compared to the P filter group and a twenty-fold reduction in the P/OV filter group compared to the P filter group. Air sampling inside the respirators demonstrated a significantly higher mean level of formaldehyde inside the P filters compared to the other two filters both after 60 and 120 minutes.

The findings of this study may have been influenced by selection biases, in which study participants are not representative of the population at risk. Such bias may have arisen, because the selection process may have favoured those who are healthier and therefore participated, or conversely, those who are concerned about the health effects of smoke exposure may have chosen to participate. Self-reporting bias may have also arisen through participants’ inaccurately reporting information regarding their health, either intentionally or unintentionally. In order to minimise potential self-reporting bias caused by the participants’ prior perceptions of the superiority of one of the three filters, the study filters were as similar in appearance as possible to prevent fire fighters from identifying the different filters.
The study attempted to compare three types of filters in an experimental setting and did not address workload factors such as job tasks, heat and physical exertion. In addition, the study did not incorporate the combined impact of stress of fire fighting and wearing respirators (Sharkey 1997a; Budd et al. 1997; Barnes 1999), nor did it deal with the health effects associated with wearing respirators (Bollinger & Schutz 1987). Therefore, it has to be emphasised that the findings can be interpreted only within the context of the experimental setting. This justifies the need for further research under more realistic conditions and for longer exposure periods, for example over a bushfire season or for a number of years. Personal factors such as fatigue and stress could then be taken into consideration, and the findings could be generalised to the broader fire fighting community.

Since the presentation of the report ‘Respiratory Health of Fire Fighters - Bushfire CRC Project D4 – Final Report’ (De Vos et al. 2006) in August 2006, FESA has changed its policy with regard to personal respiratory protection. FESA career fire fighters are now being issued with the recommended P/OV/F filter. The filters are mainly used for high intensity short duration urban interface bushfires (Parlour, L., pers. comm. 2007). The use of these filters is voluntary, and most of the fire fighters choose to use them. A minority of the fire fighters do not use them because they find the filters uncomfortable. FESA is currently considering whether or not to make the use of respirators (i.e. respirators and filters) mandatory for all FESA career fire fighters and to develop criteria to enable distribution for volunteer fire fighters working in similar conditions (Parlour, L., pers. comm. 2007).

The final conclusions were therefore as follows:

1) In Australia, bushfires can occur throughout the year due to continent’s climatic variation, with a tendency to aridity, and vast tracts of bushland. As a result, Australian bushfire fighters can be exposed to bushfire smoke on a regular basis and for prolonged periods. Previous research in the United States has demonstrated that occupational exposure to bushfire smoke can lead to declines in pulmonary function and increased respiratory symptoms both in the short and long term. Some career fire fighters in Australia are issued with the Class 2 particulate filters, which are to be used during bushfire fighting. Despite the use of these filters, there has been growing concern, particularly among Western Australian
fire fighters, about their respiratory symptoms during and after exposure to bushfire smoke. The literature therefore, suggests a need to carefully select the most appropriate and effective respiratory protection for fire fighters with these exposures.

2) To assess the chemical constituents inherent in these exposures, systematic sampling of PM, formaldehyde, acrolein and CO was undertaken in the smoke chamber and in the field. The results demonstrated the presence of these toxic compounds in Western Australian bushfire smoke. However, it is not possible to establish a clear-cut chemical profile of bushfire smoke, given the complex mixture of the toxic compounds. Nevertheless, levels suggested that exposures were above STEL recommendations for PM and CO (respectively 13.1 mg/m$^3$ and 932 ppm). To protect fire fighters it was necessary to establish an evidence base to assist in the selection of appropriate respiratory protection for fire fighters, and to inform the policy development process on the regulation of respiratory protective equipment for bushfire fighters.

3) Testing the effectiveness of 37 particulate, 50 particulate/organic vapour, and 44 particulate/organic vapour/formaldehyde filters under controlled and semi-controlled bushfire smoke conditions from 15 minutes to 2 hours demonstrated that the P/OV/F filter was most effective in preventing acute respiratory health symptoms, such as coughing, wheezing, and shortness of breath. Significant reductions were found in the number of participants with increased respiratory symptoms following the smoke exposure with the P/OV and the P/OV/F filter compared with the P filter. The testing also demonstrated that the P filter was only effective in filtering out particles, and was ineffective in filtering out other bushfire smoke components, particularly respiratory irritants such as formaldehyde and acrolein. These findings suggest that the FESA career fire fighters’ respiratory health would be best protected by the provision of the P/OV/F filter. These filters were therefore provided by FESA, and after using the filters for one season, we evaluated the filters on their perceived performance.
4) The cross-seasonal survey indicated that FESA career fire fighters perceived the performance of the P/OV/F filter as an improvement compared to the performance of the previous P filter. Better filtration of the inhaled air and consequently less smoke inhalation were the main reported reasons for improvement. In addition, absence of smoke odour inside the respirators was perceived as a positive outcome. The introduction of the new filters clearly improved protection in exposed fire fighters. However, this was a local study, with a local policy change. There is clearly a need to apply respiratory protection according to more generalisable policy guidelines.

5) The use of air-purifying respirators for bushfire fighters is poorly regulated worldwide. In the United States current legislation and policies for respiratory protective equipment do not include wildland fire fighting operations. Furthermore, wildland fire fighting standards on protective clothing and equipment do not include respiratory protective equipment. Forest fire fighters in Europe, even in high risk areas (such as Greece and the Iberian Peninsula) are not covered by any Occupational Health and Safety legislation. In Australia, Occupational Health and Safety legislation and policies vary between States and Territories. Western Australia is the only State which has Standard Operational Procedures in place to assist in the decision making process about the most appropriate level of respiratory protection.

Taken together, the components of this dissertation demonstrate that the Occupational Health and Safety legislation in Australia does not adequately deal with the use of respiratory protective equipment for bushfire fighters. Bushfire smoke contains air toxics of concern, and bushfire fighters are at risk of inhaling air toxics during bushfire fighting when not equipped with appropriate and effective respiratory protection. Inhaling air toxics may result in the onset of acute or more protracted respiratory symptoms and disease. Therefore, it is paramount that the Government and fire agencies recognise the importance of protecting fire fighters’ respiratory health from this occupational hazard.

The present research has contributed data to assist in the policy development on the regulation of respiratory protective equipment for bushfire fighters. It is expected that transparent polices with regard to respiratory protection will provide guidelines
for both fire agencies and fire fighters. As a result, informed decisions can be made regarding the selection of the most appropriate respiratory protection for the job, which will ultimately lead to a decrease in the number of fire fighters with respiratory health related symptoms.

The recommendation introduced by FESA can be seen as a pro-active and in advance of national and international legislation. In general terms, it is rewarding to see that public health research can translate into practice that protects the public health without the need for waiting for the lengthy process of legislative reform. Fire fighter organisations in other countries with a high frequency of wildfires could learn from this example, and move to introduce personal protective equipment immediately.
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Appendix 1: Filter Study - Phase 1 Questionnaire
FILTER STUDY
Phase 1

QUESTIONNAIRE

Part 1: Before contact with smoke
1.1 How many years have you been working as a career firefighter with FESA?

|   |   | Years

1.2 At which station are you currently working?

____________________________

1.3 Are you male or female?

☐ Male

☐ Female

1.4 In which age group are you?

☐ 20 to 29 years

☐ 30 to 39 years

☐ 40 to 49 years

☐ 50 to 59 years

☐ 60+ years

1.5 In general, would you say your health is:

(Please tick one)

<table>
<thead>
<tr>
<th>Excellent</th>
<th>Very good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>
1.6 Are you a current smoker or have you ever smoked in the past?

- Never smoked
- Current smoker → what do you mainly smoke? (tick all that apply)
  - cigarettes → How old were you when you started smoking? □□□ years
  - On average how many cigarettes per day? □□□
  - other forms of smoking → specify __________________________
    - For how many years? □□□ years
- Past smoker → what did you mainly smoke? (tick all that apply)
  - cigarettes → How old were you when you started smoking? □□□ years
  - How many cigarettes per day? □□□
  - How old were you when you stopped smoking? □□□ years
  - other → specify __________________________
    - For how many years? □□□ years
    - How many per day? □□□
    - How many years ago did you stop? □□□ years

1.7 Have you ever been diagnosed with:

Asthma?

- Yes → At what age were you diagnosed? □□□ years
- No
- Don’t know

Hay fever?

- Yes → At what age were you diagnosed? □□□ years
- No
- Don’t know

Any type of allergies not already mentioned?

- Yes → Please, specify __________________________
  → At what age were you diagnosed? □□□ years
- No
- Don’t know
1.8 Do you regularly bring up phlegm (sputum) from your chest?

☐ Yes → Please specify: For how many years has this occurred? [__] years

Does it occur most years?  ☐ Yes ☐ No

If yes → Please specify → For how many months of the year?

[__] months

☐ No
☐ Don’t know

1.9 In the past 12 months, have you experienced any of the following on a regular basis?:

<table>
<thead>
<tr>
<th>(Please tick one of the answers)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Coughing</td>
</tr>
<tr>
<td>Wheezing or whistling in your chest</td>
</tr>
<tr>
<td>Tightness in your chest</td>
</tr>
<tr>
<td>Shortness of breath</td>
</tr>
<tr>
<td>Other symptoms affecting your chest or breathing? Please specify</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

1.10 Do you suffer from any of these symptoms after bushfires?

☐ I don’t attend bushfires

☐ Yes → Please specify what symptoms: ________________________________

______________________________

☐ No
☐ Don’t know
1.11 Do you take any medicines (such as puffers, inhalers, tablets) to help with wheezing?

☐ Yes → If yes, what is the medicine? __________________________

On average, how many times a WEEK do you take it?

______________ a week

☐ No

☐ Don’t know

1.12 During the past two weeks, have you suffered from any of the following: cold, flu, throat or chest infection?

☐ Yes

☐ No

☐ Don’t know

1.13 During the past two weeks, have you suffered from any other type of infections?

☐ Yes → If yes, please describe: __________________________

☐ No

☐ Don’t know

1.14 Apart from any already mentioned, have you been treated for any medical conditions in the last year?

☐ Yes → If yes, what was the condition?: __________________________

Are you taking any medications for this condition?

☐ Yes → If yes, what are the medicines?

__________________________

☐ No

☐ Don’t know
FILTER STUDY
Phase 1

QUESTIONNAIRE

Part 2: After contact with smoke
2.1 After the exposure do you experience any of the following:

<table>
<thead>
<tr>
<th>Symptom</th>
<th>Not at all</th>
<th>Slightly</th>
<th>Moderately</th>
<th>Quite a bit</th>
<th>Extremely</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coughing</td>
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<td>Wheezing or whistling in your chest</td>
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<td>Tightness in your chest</td>
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<tr>
<td>Shortness of breath</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Choking</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Thirst</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blocked nose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Throat pain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoarseness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nausea/ want to vomit or have vomited</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light headed or dizzy</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Headache</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Racing or irregular heartbeat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other symptoms not listed above, please specify</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Please tick one of the answers)
2.2 After your time in the smoke chamber, are you bringing up phlegm (sputum) from your chest?

- Yes
- No *(Please go to 2.4)*

**Fill out this table ONLY if you are bringing up phlegm or sputum:**

2.3 Which of the following statements about the aspect of your phlegm (sputum) from your chest is true or false?

<table>
<thead>
<tr>
<th>(Please tick true or false)</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td><strong>Colour</strong></td>
</tr>
<tr>
<td>➢ Transparent</td>
</tr>
<tr>
<td>➢ White</td>
</tr>
<tr>
<td>➢ Yellow</td>
</tr>
<tr>
<td>➢ Green</td>
</tr>
<tr>
<td>➢ Blood stained</td>
</tr>
<tr>
<td>➢ Black/soot stained</td>
</tr>
<tr>
<td><strong>Taste/smell</strong></td>
</tr>
<tr>
<td>➢ No taste or smell</td>
</tr>
<tr>
<td>➢ Faint taste or smell</td>
</tr>
<tr>
<td>➢ Strong taste or smell</td>
</tr>
<tr>
<td><strong>Amount of phlegm/sputum</strong></td>
</tr>
<tr>
<td>➢ Small (less than ½ a teaspoon)</td>
</tr>
<tr>
<td>➢ Moderate (½ to 1 teaspoon)</td>
</tr>
<tr>
<td>➢ Large (over 1 teaspoon)</td>
</tr>
<tr>
<td><strong>Texture</strong></td>
</tr>
<tr>
<td>➢ Thin</td>
</tr>
<tr>
<td>➢ Thick (hard to cough up)</td>
</tr>
</tbody>
</table>
2.4 Do you routinely wear a mask when fighting bushfires?

(Please tick one)

- Always
- Mostly
- Sometimes
- Never

2.5 Do you think wearing your usual mask has any effect on your breathing when fighting a real bushfire?

When wearing a mask, my breathing is:

(Tick the box closest to your opinions)

- MUCH WORSE
- SLIGHTLY WORSE
- NOT DIFFERENT
- SLIGHTLY BETTER
- MUCH BETTER

2.6 To what extent do you agree or disagree that your usual mask is useful in protecting your health?

(Tick the box closest to your opinions)

- STRONGLY AGREE
- AGREE
- DON’T KNOW
- DISAGREE
- STRONGLY DISAGREE

2.7 Was the smoke in the smoke chamber similar compared to smoke of a real bushfire?

(Tick the box closest to your opinions)

- VERY SIMILAR
- SIMILAR
- QUITE SIMILAR
- QUITE DIFFERENT
- DIFFERENT
- VERY DIFFERENT
FILTER STUDY

Phase 1

QUESTIONNAIRE

Part 3: After Recovery

Study Identification Number:  

Date:  day ___ month ___ year ___

Time:  hour ___ minutes ___
3.1 At this point in time after the exposure are you experiencing any of the following:

<table>
<thead>
<tr>
<th>Symptom</th>
<th>Not at all</th>
<th>Slightly</th>
<th>Moderately</th>
<th>Quite a bit</th>
<th>Extremely</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coughing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheezing or whistling in your chest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tightness in your chest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shortness of breath</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Choking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thirst</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blocked nose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Throat pain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoarseness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nauseated / want to vomit or have vomited</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light headed or dizzy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Headache</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Racing or irregular heartbeat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other symptoms not listed above, please specify</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

__________
__________

(Please tick one of the answers)
3.2 After the 30 minute recovery period, are you bringing up phlegm (sputum) from your chest?

☐ Yes
☐ No (Please go to next page)

**Fill out this table ONLY if you are bringing up phlegm or sputum:**

3.3 Which of the following statements about the aspect of your phlegm (sputum) from your chest is true or false?

<table>
<thead>
<tr>
<th>(Please tick true or false)</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Transparent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ White</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Green</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Blood stained</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Black/soot stained</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taste/smell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ No taste or smell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Faint taste or smell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Strong taste or smell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount of phlegm/sputum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Small (less than ½ a teaspoon)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Moderate (½ to 1 teaspoon)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Large (over 1 teaspoon)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Thin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>➢ Thick (hard to cough up)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
This is the end of the questionnaire. Thank you very much for your time and effort in answering these questions.

Is there any comment you would like to make or any information that you think is relevant?

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________
Appendix 2: Filter Study - Phase 2 Questionnaire
FILTER STUDY
Phase 2

QUESTIONNAIRE

Baseline
1.1 How many years have you been working as a career firefighter with FESA?

[ ] [ ] Years

At which station are you currently working?

________________________________________

1.2 Are you male or female?

☐ Male

☐ Female

1.3 In which age group are you?

☐ 20 to 29 years

☐ 30 to 39 years

☐ 40 to 49 years

☐ 50 to 59 years

☐ 60+ years

1.4 In general, would you say your health is:

(Please tick one)

<table>
<thead>
<tr>
<th>Excellent</th>
<th>Very good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>
1.5 Are you a current smoker or have you ever smoked in the past?

- Never smoked

- Current smoker → What do you mainly smoke? (Tick all that apply)
  - Cigarettes → How old were you when you started smoking? [__] years
    - On average how many cigarettes per day? [__]

- Other forms of smoking → Specify _____________________
  - For how many years? [__] years
    - How many times per day do you smoke? [__]

- Past smoker (stopped more than 12 months ago)
  → What did you mainly smoke? (Tick all that apply)
  - Cigarettes → For how many years? [__] years
    - How many cigarettes per day? [__]

- Other forms of smoking → Specify _____________________
  - For how many years? [__] years
    - How many per day? [__]

1.6 Have you ever been diagnosed with:

- Asthma
  - Yes → At what age were you diagnosed? [__] years
  - No
  - Don’t know

- Hay fever
  - Yes → At what age were you diagnosed? [__] years
  - No
  - Don’t know

- Any type of allergies not already mentioned
  - Yes → Please, specify _____________________
    → At what age were you diagnosed? [__] years
  - No
  - Don’t know
1.7 Do you regularly bring up phlegm (sputum) from your chest?

☐ Yes → Please specify:

For how many years has this occurred? [| ] years

Does it occur most years? ☐ Yes ☐ No

If yes → Please specify → For how many months of the year?

☐ No

☐ Don’t know

1.8 In the past 12 months, have you experienced any of the following on a regular basis?

<table>
<thead>
<tr>
<th></th>
<th>Not at all</th>
<th>Slightly</th>
<th>Moderately</th>
<th>Quite a bit</th>
<th>Extremely</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coughing</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Wheezing or whistling in your chest</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Tightness in your chest</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Shortness of breath</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Other symptoms affecting your chest or breathing? Please specify</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>______________________________________________________________</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

1.9 Do you suffer from any of these symptoms after bushfires?

☐ I don’t attend bushfires

☐ Yes → Please specify what symptoms: ________________________________

☐ No

☐ Don’t know
1.10 Do you take any medicines (such as puffers, inhalers, tablets) to help with wheezing?
   □ Yes → If yes, what is the medicine? ____________________________
   On average, how many times a WEEK do you take it?
   __________________ a week
   □ No
   □ Don’t know

1.11 During the past two weeks, have you suffered from any of the following: cold, flu, throat or chest infection?
   □ Yes
   □ No
   □ Don’t know

1.12 During the past two weeks, have you suffered from any other type of infections?
   □ Yes → If yes, please describe: ________________________________
   □ No
   □ Don’t know

1.13 Apart from any already mentioned, have you been treated for any medical conditions in the last year?
   □ Yes → If yes, what was the condition?: __________________________
   Are you taking any medications for this condition?
   □ Yes → If yes, what are the medicines?__________________________
   □ No
   □ Don’t know
1.14 Do you routinely wear a mask when fighting bushfires?

(Please tick one)

<table>
<thead>
<tr>
<th></th>
<th>Always</th>
<th>Mostly</th>
<th>Sometimes</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

1.15 When wearing a mask, what type of filter do you use on your mask?

(Please tick one)

<table>
<thead>
<tr>
<th>Filter Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate filter</td>
</tr>
<tr>
<td>Particulate/organic vapour filter</td>
</tr>
<tr>
<td>Don’t know</td>
</tr>
<tr>
<td>Other, please specify</td>
</tr>
</tbody>
</table>

1.16 To what extent do you agree or disagree that your usual mask is useful in protecting your health?

(Tick the box closest to your opinion)

<table>
<thead>
<tr>
<th>Opinion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly agree</td>
</tr>
<tr>
<td>Agree</td>
</tr>
<tr>
<td>Don’t know</td>
</tr>
<tr>
<td>Disagree</td>
</tr>
<tr>
<td>Strongly disagree</td>
</tr>
</tbody>
</table>

1.17 Do you think wearing your usual mask has any effect on your breathing when fighting a real bushfire?

When wearing a mask, my breathing is:

(Tick the box closest to your opinion)

<table>
<thead>
<tr>
<th>Breath Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Much worse</td>
</tr>
<tr>
<td>Slightly worse</td>
</tr>
<tr>
<td>Not different</td>
</tr>
<tr>
<td>Slightly better</td>
</tr>
<tr>
<td>Much better</td>
</tr>
</tbody>
</table>
FILTER STUDY
Phase 2

QUESTIONNAIRE

After 60 minutes

Study Identification Number:  |||||-|||-
Date:  day || month || year ||
Time:  hour || minutes ||
2.1 After 60 minutes exposure to the smoke do you experience any of the following?

<table>
<thead>
<tr>
<th>Symptom</th>
<th>Not at all</th>
<th>Slightly</th>
<th>Moderately</th>
<th>Quite a bit</th>
<th>Extremely</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coughing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheezing or whistling in your chest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tightness in your chest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shortness of breath</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Choking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blocked nose</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Throat pain</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Hoarseness</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nausea/ want to vomit or have vomited</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light headed or dizzy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Headache</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Racing or irregular heartbeat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other symptoms not listed above, please specify</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2 At this point in time, are you bringing up phlegm (sputum) from your chest?

☐ Yes
☐ No *(Please go to 2.4)*

Fill out this table ONLY if you are bringing up phlegm or sputum:

2.3 Which of the following statements about the aspect of your phlegm (sputum) from your chest is true or false?

<table>
<thead>
<tr>
<th>Colour</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparent</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>White</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Yellow</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Green</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Blood stained</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Black/soot stained</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Taste/smell</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>No taste or smell</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Faint taste or smell</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Strong taste or smell</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amount of phlegm/sputum</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small (less than ½ a teaspoon)</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Moderate (½ to 1 teaspoon)</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Large (over 1 teaspoon)</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Texture</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Thick (hard to cough up)</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>
FILTER STUDY
Phase 2

QUESTIONNAIRE

After 120 minutes

Study Identification Number: ___|_|_|_|_|_|_|_|___
Date: day ___ month ___ year ___
Time: hour ___ minutes ___
### 3.1 After 120 minutes exposure to the smoke do you experience any of the following?

<table>
<thead>
<tr>
<th></th>
<th>Not at all</th>
<th>Slightly</th>
<th>Moderately</th>
<th>Quite a bit</th>
<th>Extremely</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coughing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheezing or whistling in your chest</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tightness in your chest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Shortness of breath</td>
<td></td>
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<td></td>
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<tr>
<td>Choking</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Thirst</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blocked nose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Throat pain</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Hoarseness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nausea/ want to vomit or have vomited</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light headed or dizzy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Headache</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Racing or irregular heartbeat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other symptoms not listed above, please specify</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

________________________
3.2 At this point in time, are you bringing up phlegm (sputum) from your chest?

- Yes
- No *(Please go to 2.4)*

Fill out this table ONLY if you are bringing up phlegm or sputum:

2.3 Which of the following statements about the aspect of your phlegm (sputum) from your chest is true or false? *(Please tick true or false)*

<table>
<thead>
<tr>
<th>Colour</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparent</td>
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<td>☐</td>
</tr>
<tr>
<td>White</td>
<td>☐</td>
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</tr>
<tr>
<td>Yellow</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Green</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Blood stained</td>
<td>☐</td>
<td>☐</td>
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<tr>
<td>Black/soot stained</td>
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<tr>
<th>Taste/smell</th>
<th>True</th>
<th>False</th>
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<tbody>
<tr>
<td>No taste or smell</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Faint taste or smell</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Strong taste or smell</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amount of phlegm/sputum</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small (less than ½ a teaspoon)</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Moderate (½ to 1 teaspoon)</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Large (over 1 teaspoon)</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Texture</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Thick (hard to cough up)</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>
3.3 What work activity were you doing during the exposure in the field?  

<table>
<thead>
<tr>
<th>Please tick one of the answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supervisor</td>
</tr>
<tr>
<td>Lighting</td>
</tr>
<tr>
<td>Holding</td>
</tr>
<tr>
<td>Attack</td>
</tr>
<tr>
<td>Mop-up</td>
</tr>
<tr>
<td>Pump Operator</td>
</tr>
<tr>
<td>Other work activity, please specify</td>
</tr>
</tbody>
</table>
Appendix 3: Filter Study - Evaluation Questionnaire
FILTER STUDY
Evaluation

QUESTIONNAIRE

Study Identification number |__|__|-|__|-|__|-|__|_ _|-|__|__|__|__|

Date: day |__|__| month |__|__| year |__|__|____
Section 1 – Identification and Personal Characteristics

Are you?

☐ Male
☐ Female

In what age group are you?

☐ 20 to 29 years
☐ 30 to 39 years
☐ 40 to 49 years
☐ 50 to 59 years
☐ 60+ years

3. At which station are you currently working?

________________________________________

4. Are you aware of the mask/filter study carried out by UWA for FESA?

☐ Yes
☐ No

5. Did you take part in the trials?

☐ Yes
☐ No

6. Are you aware that FESA provided the option of FESA fire fighters to use the new filter?

☐ Yes
☐ No
7. Did you take up the option to use the new filter?
   
   Yes
   No

8. Can you give an approximate date when you took on the new filter?
   
   ________________________________

9. Is this the only filter you now use?
   
   Yes
   No
Section 2 – Exposure Information

10. Are you involved in bushfire fighting?

☐ Yes

☐ No

11. How many bushfires have you attended in the last three months?

____________________

12. How long ago did you attend the last bushfire?

☐ Less than a week ago

☐ Between 8-14 days ago

☐ Between 15-21 days ago

☐ Between 22-28 days ago

☐ Over a month ago

13. During the last bushfire, how long were you exposed to bushfire smoke?

☐ 0 – 4 hours

☐ 5 -10 hours

☐ 11 – 14 hours

14. Can you describe the smoke density that you were exposed to during the last bushfire?

☐ No smoke

☐ Light smoke situation (*i.e. white to light grey colour with moist fuels and mild behaviour with visibility more than 15 metres*)

☐ Medium smoke situation (*i.e. dark grey to black colour with moist to dry fuels and moderate behaviour with visibility of 8-15 metres*)

☐ Heavy smoke situation (*black to copper-bronze colour with very dry fuels and severe behaviour with visibility 5-8 metres*)
15. What type of task did you do while wearing the mask? (Tick all that apply)

- Supervising
- Holding
- Attack
- Mop-up
- Pump operator
- Other work activity, please specify ___________________________
Section 3 – Previous and Current Mask/Filter Use

16. Do you routinely wear a mask when fighting bushfires?
   - [ ] Yes
   - [ ] No

17. How does the mask fit? *(Tick all that apply)*
   - [ ] Comfortable
   - [ ] Too tight
   - [ ] Too loose
   - [ ] Hurts the nose
   - [ ] Helmet pushes the mask down
   - [ ] Other, _______________________________

18. What type of filter do you currently use on your mask?
   - [ ] Particulate/organic vapour/formaldehyde filter issued by FESA
   - [ ] Other, please specify _________________________ *(Go to the end of the questionnaire)*
   - [ ] I don’t know *(Go to the end of the questionnaire)*

19. What type of filter did you use on your mask, before you started using the new FESA particulate/organic vapour/formaldehyde filters in 2005?
   - [ ] Particulate filter
   - [ ] Particulate/organic vapour filter
   - [ ] Particulate/organic vapour/formaldehyde filter
   - [ ] Other, please specify _________________________
   - [ ] I don’t know
20. During the last bushfire fighting (refer to Q13), for what period of time did you use the newly issued FESA particulate/organic vapour/formaldehyde filter?

- Continuously
- Sometimes
- Never

21. To what extent does the performance of your current filter differ from the previous one?

- Much better
- Better
- Similar
- Worse
- Much worse

22. If there is a difference, can you explain this in more detail?

________________________________________________________

23. After donning the mask and new filters during a bushfire, do you still notice smoke odour?

- Yes  
  *If yes: After how long _________________________________

- No

24. Do the mask and new filters get wet inside during use?

- Yes  
  *If yes: Was its performance affected? __________________________

- No

25. Do you remove the mask at any time while fighting a bushfire?

- Yes  
  *If yes: For what reason? ________________________________

- No
26. Does the new filter affect your breathing in any way? (e.g. restrict, make it easier to breath)

☐ Yes

If yes: Can you explain how? __________________________

☐ No

27. Does wearing the mask and the FESA issued filters have any effect on respiratory symptoms in the days following the bushfire fighting? (With respiratory symptoms I mean coughing, wheezing, shortness of breath)

☐ Yes

If yes: What are these effects? __________________________

☐ No

28. How do you store your filters when not in use?

_____________________________________________________________________

This is the end of the questionnaire. Are there any further comments you’d like to make or any information that you think is relevant?

_____________________________________________________________________

_____________________________________________________________________

_____________________________________________________________________

Thank you very much for your time and effort in answering these questions.
Appendix 4: American Journal of Industrial Medicine
Effect of Protective Filters on Fire Fighter Respiratory Health During Simulated Bushfire Smoke Exposure

Annemarie J.B.M. De Vo,’ RN, MPH, 1,2,3, Angus Cook, MChir(Eng), VATER 1,2,3
Brian Devine, BSc, DPM, 1,2,3 Philip J. Thompson, MBBS, FRACGP, MCLMCA, 2
and Philip Wakefield, RN, MSW, MPDA, RN, FRANAN 1,2

Background: Bushfire fighters are potentially exposed to toxic bushfire smoke. Although many different protective masks and filters are available, it is not clear which is the most effective from a health and safety perspective. The effect of protective filters on the respiratory health of Western Australian urban fire fighters under controlled simulated conditions is investigated.

Methods: Twenty-four healthy, Fire and Emergency Services Authority of Western Australia (FESA) urban career fire fighters were subjected to controlled simulated bushfire smoke in a closed smoke chamber for 15 minutes. The fire fighters were allocated one of the three types of protective filters: particulate only (P), particulate/organic vapor (POV), and particulate/organic vapor/formaldehyde (POVF) filters using a double-blind randomized procedure. Personal air sampling inside the fire fighters’ masks, spirometry, oximetry, and self-reported symptom data were collected at baseline and at two time intervals after the smoke exposure.

Results: A significant decline in oxygen saturation was seen immediately after exposure; however, the trend was small and no significant relationships could be established between this and the type of filter used. A significantly higher number of participants in the Pard and POV filter groups self-reported an increase in coughing, wheezing, and throat soreness compared to the POV filter group. Air sampling demonstrated a significantly higher level of formaldehyde and acrolein inside the masks fitted with filters compared to POV and POVF filters.

Conclusions: Testing the effectiveness of POV, POVF, and POVF filters under controlled conditions has demonstrated that the POVF filter provides statistically significant better protection for the fire fighters’ airways in a simulated bushfire exposure chamber. Am. J. Ind. Med. 49:740–750, 2006. © 2006 Wiley-Liss, Inc.

KEY WORDS: bushfire smoke; fire fighters; occupational exposure; respiratory health; respiratory protection; particulates; filters

INTRODUCTION

Fire fighting is one of the most difficult and hazardous of occupational activities associated with a range of uncertain and unpredictable work-related risks. Apart from enduring heat, noise, and the stress of completing complex and physically demanding tasks (Brotherhood et al., 1997; Budd et al., 1997a,b,c,d), fire fighters are often exposed to smoke of varying densities containing elevated concentrations of
irritating and toxic gases. Moreover, fire fighters are frequently confronted with situations in which they have little or no knowledge of which chemicals are present at significant levels in their surroundings.

The hazardous nature of bushfires is usually underestimated compared to urban and structural fires. Although toxic exposures are generally higher among structural fire fighters, bushfire firefighters have potentially longer periods of exposure to bushfire smoke, which can range from hours to several days with limited rest periods [Betchley et al., 1997]. In addition to particulates, the presence of toxic smoke components, such as carbon monoxide, formaldehyde, sulfur, and hydrocarbons in bushfire smoke suggests that such exposure may pose occupational risks in both the short- and long-term [Dott, 1991; Markov et al., 1992; Searle et al., 1996; Reid and O’Byrne, 1999; Reid et al., 1999].

Although the respiratory effects of exposure to combustibles have been considered in a number of studies [Matera et al., 1992; Searle et al., 1996; Betchley et al., 1997; Slaughter et al., 2004], little is known about the synergistic effects between different chemicals and the degree to which exposure at “safe levels” individually may synergistically produce adverse health impacts.

A limited number of studies of pulmonary function in fire fighters demonstrate that their exposure to smoke may result in acute as well as chronic lung function impairment [Biscoe and Latham, 2005]. Tachypnea, reduced forced vital capacity (FVC), forced expiratory volume after 1 s (FEV1), and forced expiratory flow (PEF), have been documented in fire fighters after exposure to smoke [Musk et al., 1979; Sheppard et al., 1986; Large et al., 1989]. An acute increase in airway reactivity has been observed after experimental exposure of fire fighters in a smoke chamber with durations of service being found to be the major contributing factor [Chia et al., 1999]. Both cross-sectional and co-registered studies on wildland fire fighters in the United States have shown significant acute decrements in respiratory function associated with increasing exposure [Butcher et al., 1991; Liu et al., 1993; Betchley et al., 1997; Slaughter et al., 2004].

There is conflicting evidence about the contribution of cigarette smoking to airways obstruction in fire fighters [Lowe et al., 1980; Yeong et al., 1980; Brojnowski et al., 1990; Liu et al., 1993]. It has also been suggested that fire fighters may eventually progress to the development of chronic lung disease following acute exposures [Sparrow et al., 1992; Burtonson et al., 1948].

Bushfire firefighters have limited options for controlling their exposure to smoke constituents, particularly in emergency fire situations. They can step back from the flames and smoke, or they can be rotated through the tactics by the fire managers to minimize long-lasting exposure to the dense smoke (R. Smith and R. Steenwijk, personal communication). Suitable respiratory protection is not available in simultaneously control exposure to carbon monoxide, formaldehyde, particulates, and other possible contaminants. Use of self-contained breathing apparatus worn by structural fire fighters is not feasible under the conditions of bushfire fighting, because the volume of air in the cylinders usually does not last for a sufficiently long period to fight bushfires in an effective manner. Moreover, the cylinder are too heavy for prolonged use in high temperatures with a heavy workload (Gorman, 2004).

In Western Australia, the management of bushfire smoke exposure for the Fire and Emergency Services Authority (FESA) career fire fighters is regulated by the Bushfire Smoke Management Standard Operational Procedures 31 (SOP31) [Fire and Emergency Services Authority Western Australia, 2009]. This document is based on the Occupational Safety and Health Act 1984, the Complementary Safety and Health Regulations 1990, and the Australian/New Zealand Standard 1715 [Standards Australia, 1994]. SOP31 provides a tool to determine the most appropriate method to manage bushfire smoke exposure for fire fighters. In accordance with these procedures, FESA career fire fighters in Western Australia are issued half-face-piece masks with particulate filters (Fig. 1), intended for use against both mechanically and thermally generated particulates. However, career fire fighters are required to purchase their own particulate/organic vapor (POV) filters, as they perceive the particulate filter to be ineffective in protecting their airways.

The performance of the filters is tested by the manufacturers, in order to comply with Australian/New Zealand Standard 1715:1994 and Standard 1716:2002 [Standards Australia, 1994, 2003]. Yet there is no published evidence available whether the application of the particulate filter, the POV filter, or no filter differs in the effectiveness to
protect the firefighters' airways from combustion products generated during bushfires. In an experimental study, comparison of toxic gas concentrations using a combined carbon monoxide and particulate pre-filter versus a simple cloth bandana, it was concluded that neither filter performed well (Foote, 1994). The carbon monoxide with the particulate pre-filter collected formaldehyde for approximately 60 mins and collected only 85% of the challenge particulate. Although the performance of the respirators and their effects on the firefighters' physical and mental performance have been widely discussed (Johnston et al., 1992; Jemielniak et al., 1993; Nelson and Cotton, 2000), the various types of filters have never been rigorously compared with regard to respiratory health outcomes.

To address these issues, this study profiled the respiratory health effects of occupational exposure to bushfire smoke in Australian settings and assessed the efficacy of available protective filters on the firefighters' health under controlled conditions. The data will also be used as the basis for field trials during prescribed burns and bushfire situations.

Methods

The study used a randomized experimental design, in which the participants were allocated one of three types of filters: Particulate (M3M™ 5925) (P), particulate/organic vapor (POV) (M3M™ 6875) and Particulate/organic vapor formaldehyde filter (M3M™ 6375) (POVF). Allocation was blinded by using three types of filter as similar in appearance as possible to ensure that outcomes would not be affected by the participants' perceptions of wearing a particular type of filter.

Study Population

The study population was selected from the group of 300 male and female career urban firefighters based on fire stations in the Perth Metropolitan area in Western Australia. Given that a significant determinants of respiratory health outcomes was likely to be the frequency of previous bushfire exposures, two stratified random samples were taken from 20 fire stations in areas experiencing high versus low bushfire frequencies (i.e., Baldivis, Canning Vale, Joondalup, Malaga fire stations vs. remaining stations). Subjects were needed for the study only if they had been exposed to smoke during the six exposure trials and participated on a voluntary and confidential basis. Individuals with uncontrolled asthma, current acute or chronic respiratory illness, or any other chronic or severe illnesses and self-reported unstable asthma were excluded. Before exposure, the participants signed a consent form and had an opportunity to present questions and concerns about the study. Approval for the study was obtained from the Human Research Ethics Committee of The University of Western Australia.

Test Site and Conditions

The exposure trials were conducted at the FESA Training Centre, Forrestfield, Western Australia. The smoke chamber used for the study was a modified gas cabinet (1.2 m x 2.4 m x 2.4 m), which had one end completely open for participants to enter at any time. The smoke was produced from controlled combustion of pre-dried Western Australian native vegetation, including banksia, plants from coastal heathland, and flaxton grass. It was produced at the FESA Training Centre and had a low moisture content (approximately 9%) at the time of the trial burns. Based on workplace reports, these are known to cause severe smoke levels during bushfires.

For the purpose of the study, a light smoke situation was produced, determined as a density of smoke producing a white to light gray color with reasonable visibility of at least 15 m (Fire and Emergency Services Authority, Western Australia, 2003). Visual assessment of the smoke was undertaken by an observer present on the site, using the visual smoke exposure classification [Reinhardt and Ottmann, 2000]. The smoke was generated in a standardized way from a small incinerator to ensure that the smoke characteristics were reproducible during the subsequent trial sessions. The environment was controlled for temperature and wind as far as practicable, to ensure that the only variable possibly affecting the outcomes was the type of filter worn.

All participants were requested to wear their full "furnace" gear, that is, standard uniform, helmet, protective goggles, and mask, before entering the smoke chamber. The equipment attached to randomly allocated study filters consisted of the mask of the participant. Participants were asked to perform a Positive Pressure Fit Check in accordance with Australian/New Zealand Standard 1715:1994 (Standards Australia, 1994) to ensure an appropriate seal of the mask (M3M™ 6000 Series Standard Full Face Respirator). Participants entered the smoke chamber at staggered 5 min intervals between entries, thereby ensuring that participants could undergo spirometry measurement immediately after exiting. They were asked to walk around in the smoke chamber to ensure exposure to a representative sample of the smoke. To obtain a sufficient sample volume for peak exposure measurements inside the mask, the required exposure period inside the smoke chamber was set at 15 min. Despite these requirements, the participants were assured that they could stop out of the chamber at any time if they did not feel adequately.
facilities were available at the test site, and an emergency protocol was in place.

**Data Collection**

Respiratory health outcomes were measured before (baseline) and after the period of controlled, smoke exposure using a respiratory symptom questionnaire, FEV₁, and oxygen saturation (SaO₂) measurement. In addition, active sampling of air inside the firefighters’ masks completed the assessment of the protective filters.

**Respiratory symptom questionnaire**

The respiratory symptom questionnaire was a standardized self-completed form based on the Medical Research Council questionnaire (Medical Research Council, 1988), a well-validated instrument designed to elicit details about symptoms and factors associated with chronic pulmonary diseases and smoking history. The symptom list included questions pertaining to intensity and frequency of cough, wheeze, shortness of breath, tightness in the chest, and sore throat. Subjects were classified as either non-smokers, past smokers, or current smokers. Cigarette consumption was estimated in standard pack-years. Participants were also asked about risk perception in relation to acute respiratory health effects of bushfire smoke exposure. Questionnaires were administered at three points: before, immediately after exposure, and after a 30 min recovery time.

**FEV₁ measurement**

Spirometry was performed by a single trained individual according to the guidelines for manoeuvres performance provided by the American Thoracic Society (1995). A single Welch Allyn PneumoCheck™ spirometer was used in all tests to ensure standardization of the measurements. Calibration of the equipment was performed with a 3 L syringe before each testing session, and readings were automatically corrected to BTPS (body temperature and pressure, saturated).

FEV₁ was the primary lung function measure used. FEV₁ is an extensively used index with good reproducibility (Pierce and Johns, 1995) and changes across a work shift have been described as useful response indices to measure acute airflow narrowing (Venables, 1994). All subjects were tested sitting straight up with their feet firmly on the floor, and without a nose clip. A minimum of three manoeuvres was undertaken to meet the ATS criteria for collection and to obtain reproducible tracings with the two highest FEV₁ within 5% of each other. Spirometric data were collected before entering and immediately after exiting the smoke chamber. The change in FEV₁ (ΔFEV₁) for each participant was measured by subtracting the baseline FEV₁ obtained before the exposure from the baseline FEV₁ measured before the exposure.

**SaO₂ measurement**

Arterial oxygen saturation of hemoglobin was measured in percentages (%) using a Datex-Ohmeda T DiffSat™ pulse oximeter. The change in SaO₂ (ΔSaO₂) for each participant was measured by subtracting the baseline SaO₂ measured before exposure from the baseline SaO₂ measured before the exposure.

**Air sampling inside the Masks**

Personal air samples from inside the masks were collected via sampling ports. In order to facilitate this, the masks were drilled and fitted with 60 cm Tygon tubing (6 mm ID). The tubing was connected to the air sampling pumps attached to the participants’ waist belts (Fig. 2). Air sampled from inside the mask was passed through a pre-weighted filter in a cassette and a charcoal/bonded silica sorbent tube connected in series using a calibrated air sampling pump (set at 1 L/min). Sampling lasted for the duration of the exposure period of 15 min, also the minimum period to ensure collection of sufficient sample volume (Rothbard, 2004). In addition, position air samples inside the smoke chamber were collected as controls.

Particles matter on the sample filters was analyzed gravimetrically as per Australian Standard AS 3640:2004 [Standards Australia, 2004]. Formaldehyde and acrolein were analyzed by high performance liquid chromatography.

*Figure 2.* Study participants were equipped with personal sampling equipment.
according to the National Institute for Occupational Safety
and Health Method 2016 [The National Institute for
Occupational Safety and Health, 2003]. Samples were
stored under refrigeration and transported in accordance
with established procedures to prevent sample degradation.
The Chemistry Centre (WA), Perth, Western Australia
performed all sampling procedures and laboratory
analyses.

**Statistical Analyses**

Data analyses were performed using SPSS for Windows
(Version 12.0) and Stata (Version 9.0). Kolmogorov–
Smirnov analyses were used to test dependent and indepen-
dent variables for violations of normal distribution.

Respiratory health outcomes were measured by symp-
tom scores. The differences in the respiratory health
symptoms before and after exposure were determined by
subtracting the before exposure score from the after exposure
score. Relationships between the differences in respiratory
health symptoms before and after exposure across the three
types of filters were tested with a χ²-test. Individual ΔFEV₁
and ΔASO₂ were assessed by paired t-tests.

A NOVA and linear regression were used to assess the
relationship between ΔFEV₁ and ΔASO₂ across the three
types of filters, while adjusting for potential confounders,
such as smoking history, years of service, and previous
exposure; and associations between the types of filter and
the results of the air sampling inside the masks. The
significance of respiratory health outcomes (better, no
difference, worse) were converted into dichotomous
variables by collapsing the “better” and the “no differ-
ence” variables into one new variable: “better/no differ-
ce.” By doing so we were able to use logistic regression to
determine differences in respiratory symptoms (new dichot-
omous variables: better/no difference and worse) across the
three types of filters. Models were adjusted for potential
confounding factors, including years in the Fire
and Emergency FESA, gender, smoking history, and asthma
history. Adjusted odds ratios were calculated to compare
the effectiveness of the filters based on the number of
participants reporting an increase in respiratory symptoms
following the exposure.

**RESULTS**

Sixty-four career urban fire fighters from 20 fire stations
in the Perth Metropolitan area participated in the six
controlled exposure trials. Sixty participants (93.7%) were
male and four (6.3%) were females. The largest proportion
was in the age group 40–49 years (Table 1).

Previous exposures were measured by attendance at
bushfires, and evaluated in relation to self-reported asso-
ciated symptoms from past bushfire exposures, including
coughing, wheezing, and shortness of breath. Thirty-two
participants reported symptoms after previous bushfires, with
29 indicating symptoms of cough, wheeze, or shortness of
breath. However, no consistent relationship could be
established between previous exposure to bushfire and
ΔFEV₁ or ΔASO₂ or the self-reported respiratory health
symptoms. In addition, no association was found between
age and FESA years and ΔFEV₁, ΔASO₂ or the self-reported
respiratory health symptoms.

The majority of the participants rated their overall
health as “very good” and none reported themselves to be in “fair”
or “poor” health, perhaps attributable to a strong “healthy
hiring effect” among firefighters due to stringent selection
criteria at the time of the recruitment [Cho, 2006]. Despite
these health ratings, a range of pre-existing medical
conditions were self-reported, including asthma, allergies
other than hay fever, regular production of sputum, and use of
bronchodilators (summarized in Table II). None of the pre-
exisiting medical conditions related to ΔFEV₁ or ΔASO₂.
However, 51.8% of the participants who reported an increase
in cough, wheeze, and shortness of breath following the
exposure suffered from pre-existing hay fever. Although
these findings were not statistically significant (P > 0.05),
they suggest that short-term exposure to bushfire smoke may
trigger the development of acute respiratory symptoms, such
as cough, wheeze, and shortness of breath in people with pre-
exisiting hay fever.

The measurements of pulmonary function before and
after exposure are presented in Table III. A mean decline of
0.01 L in FEV₁ was observed between the pre- and post-
exposure FEV₁ measurements. Multiple linear regression
analysis demonstrated that the declining trend in FEV₁ could
not be predicted from the type of filter used, after controlling
for years in FESA and smoking status.
TABLE II. Pre-Existing Medical Conditions in Selected Career Fire Fighters (n = 644). Part A: Presence/Absence

<table>
<thead>
<tr>
<th>Condition</th>
<th>Yes (%)</th>
<th>No (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cough</td>
<td>12</td>
<td>88.4</td>
</tr>
<tr>
<td>Wheeze</td>
<td>37</td>
<td>63</td>
</tr>
<tr>
<td>Shortness of breath</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>Asthma</td>
<td>76</td>
<td>24</td>
</tr>
<tr>
<td>No</td>
<td>58</td>
<td>42</td>
</tr>
<tr>
<td>Hay fever</td>
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<td>76</td>
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<tr>
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<td>63</td>
</tr>
<tr>
<td>No</td>
<td>54</td>
<td>46</td>
</tr>
<tr>
<td>Other symptoms</td>
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<tr>
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<td>47</td>
<td>53</td>
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<tr>
<td>No</td>
<td>54</td>
<td>46</td>
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<td>Regular use of aspirin</td>
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<tr>
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<td>21</td>
</tr>
<tr>
<td>No</td>
<td>57</td>
<td>43</td>
</tr>
<tr>
<td>Do not know</td>
<td>7</td>
<td>93</td>
</tr>
<tr>
<td>Common cold symptoms</td>
<td>5</td>
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<td>86</td>
<td>14</td>
</tr>
<tr>
<td>No</td>
<td>58</td>
<td>42</td>
</tr>
</tbody>
</table>

A statistically significant decline of 0.44% (P < 0.05) was observed between the pre- and post-exposure SaO2 measurements (Table II). The type of filter, years in FESSA, and smoking status did not significantly contribute to the regression model in which the SaO2 was used as the dependent variable. Although the paired difference (0.44%) was statistically significant, the effect was very small in clinical terms.

Acute respiratory health effects were measured by self-reported symptoms of cough, wheeze, and shortness of breath. After the 15-min exposure to bushfire smoke, 40 participants (62.5%) reported no difference in these symptoms, while 13 participants (20.3%) reported an increase in cough, wheeze, and shortness of breath (Fig. 3).

The relationship between differences in acute respiratory health symptoms and the three types of filters was analyzed using t-tests. The analysis showed that a significantly higher proportion of the participants in the P filter group (42%, n = 10) and the PBF group (4%, n = 3) reported an increase in respiratory symptoms following exposure compared to the POFV filter group (6%, n = 3) (P < 0.05). Further analysis using logistic regression demonstrated that the application of the P filter was a significant predictor for increases in acute respiratory outcomes, including cough, wheeze, and shortness of breath (P < 0.05). Potential confounders, such as years in FESSA, age, smoking history, and history of asthma did not significantly contribute to the model. Odds ratios comparing the effectiveness of the P filter with the POFV filter showed a statistically significant 10-fold reduction in respiratory symptoms following exposure for subjects who used the POFV filter (OR 0.062, 95% CI 0.005–0.775, P < 0.05). Results confirmed a statistically significant 10-fold reduction in respiratory symptoms following the exposure for subjects who used the POFV or P only filter (OR 0.091, 95% CI 0.009–0.931, P < 0.05) (Table IV).

In order to measure levels of particulate, formaldehyde, and acrolein inside the mask, air sampling was undertaken inside seven masks fitted with P filters, seven with POFV filters, and four masks fitted with POFV filters (Table V). Particulate levels inside the masks fitted with P and POFV filters were not significantly different. Levels for the POFV filter were not available.

Both formaldehyde and acrolein levels were significantly higher in the P filter group compared to the POFV filter and the POFV filter groups (Fig. 4). These findings suggested that the particulate only (P) filter is considerably less effective in filtering out volatile respiratory irritants, such as formaldehyde and acrolein in comparison to either the POFV or the POFV filter.

DISCUSSION

The present study indicated the occurrence of acute changes in pulmonary function and respiratory health symptoms in firefighters following controlled exposure to a light bushfire smoke situation for 15 min. These changes include physiological measures, such as declines in FEV1 and SaO2. These effects were not prevented by the use of face masks fitted with protective filters, which confirms earlier findings in an exposure study following fire fighter overhaul (Burgess et al., 2001). This likelihood of accumulation of carbon monoxide may play a role in these changes, however the adverse effects of this asphyxiant were not specifically examined in this study.
Testing the effectiveness of the P, POV, and POVF filters in a controlled light smoke situation demonstrated that the P filters were ineffective in filtering out bushfire smoke respiratory irritant components, such as formaldehyde and acrolein. Although the POV filter appeared to be reasonably effective, statistical analysis of the reported respiratory health symptoms across these three types of filters clearly demonstrated that the POVF filter was most effective in preventing acute respiratory health symptoms. Unlike other filters, none of the individuals wearing the POVF filter reported an increase in cough, wheeze, and/or shortness of breath.

The study revealed an apparent discrepancy between the chemical analysis of agents in the mask and the reported respiratory health outcomes. Results indicated that measured levels of particulates, formaldehyde, and acrolein were comparable in masks fitted with POV and POVF filters, yet a significantly lower proportion of the participants in the POVF filter group reported an increase in respiratory symptoms after the exposure. There are two possible explanations for this apparent anomaly between the similarity of measured chemicals and differences in respiratory effects across the two filters. Firstly, a number of volatile compounds have recently been detected in Western Australian bushfire smoke, for example, naphthalene, xylenes, and other organic by-products of vegetation smoke (Wilkinson et al., 2004; Brown et al., 2005). Many of these compounds were present at levels below occupational limits and were not separately measured in the main study. However, such individual components of the smoke—many of which are known respiratory irritants—may have exerted a synergistic effect on the respiratory health of the participants even though being present at low levels. Although not specifically examined in the chemical analysis during the experiment (which focused on particulates, formaldehyde, and acrolein), the POVF filter may interact and have been more effective in removing many other volatile compounds, thereby reducing the possibility of synergistic toxic effects and, consequently, the risk of reported respiratory symptoms. Such combined irritant effects are poorly recognized in the literature and existing standards, and we acknowledge that the full synergistic toxicity is probably impossible to measure due to the complexity of the smoke composition. Another explanation for the discrepancy relates to inadequate seals of the masks. Inadequate sealing of the mask against the user’s face may, in some cases, have resulted in movement of toxic compounds leaking into the mask, thereby causing adverse respiratory health effects. Although the fire fighters were instructed to perform a positive pressure

<table>
<thead>
<tr>
<th>Filters</th>
<th>Median</th>
<th>P-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>P vs. POVF filter</td>
<td>0.582</td>
<td>0.025</td>
<td>0.009–1.75</td>
</tr>
<tr>
<td>P vs. POV filter</td>
<td>0.911</td>
<td>0.001</td>
<td>0.000–10.37</td>
</tr>
<tr>
<td>POV vs. POVF filter</td>
<td>0.165</td>
<td>0.007</td>
<td>0.000–13.60</td>
</tr>
</tbody>
</table>

*ns = Difference not significant.
TABLE IX. Filter Types and Air Sampling Results

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Particulates mg/m³</th>
<th>Formaldehyde µg/m³ (STEL 2.5 mg/m³)</th>
<th>Acetone µg/m³ (STEL 0.5 mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate filter (PF) (n = 7)</td>
<td>0.7</td>
<td>600</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>1082</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>824</td>
<td>194</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>672</td>
<td>320</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>1402</td>
<td>190</td>
</tr>
<tr>
<td>Particulate/gas/vapor filter (FOV) (n = 7)</td>
<td>2.2</td>
<td>73</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>58</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
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<td>0</td>
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<td></td>
<td>*</td>
<td>39</td>
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<td></td>
<td>*</td>
<td>104</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>87</td>
<td>1</td>
</tr>
<tr>
<td>Particulate/gas/vapor/formaldehyde filter (FOV) (n = 4)</td>
<td>*</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>189</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>87</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: STEL: short-term exposure limit; STEL for total particulates is not available; STEL for total particulates 5 = Venl/h².

Fit Check in accordance with Australian/New Zealand Standard 1715:1994 [Standards Australia, 1994] to ensure an appropriate seal, leakage may have occurred due to perspiration, helmet pushing the mask downwards, and movements of the head and neck by participants unintentionally causing displacement.

A major potential impact on the validity of this study is the influence of self-reporting bias. Although self-reporting
on occupational exposures is generally valid [Pope et al., 2002; Tocchini et al., 2002]. It was found that validity and reliability estimates with regard to self-reporting vary greatly from study to study, and also within studies. Participants may have inaccurately reported information regarding their health, either intentionally or unintentionally. For example, the occurrence of asthma may have been under-reported given that not all fire firefighters admitted to have asthma or seek medical attention for asthma symptoms, perhaps from self-deception or fear of job loss.

The strategy of blinding the participants and investigators to the time of allocation of the three filters was used to prevent the fire firefighters from identifying the different filters, thereby ensuring that the health outcomes were not affected by the participants’ perception of wearing a particular type of filter.

Another limitation of the study was the initial selection of the most appropriate filters for comparison. Defining an optimal filter may be problematic, if not impossible, due to the complex mixture of products of combustion present in bushfire smoke. In this study, it was decided to use the particular and the POV filter, because these were the two types of filter that were currently used among fire firefighters in Western Australia. A POV filter was added to the study after smoke analysis during preliminary burns demonstrated elevated levels of formaldehyde—a Class 1 carcinogen [International Agency for Research on Cancer, 2004]—in the smoke. It must be noted however that levels of formaldehyde were measured within short-term exposure limits [National Occupational Health and Safety Commission, 1995], ensuring that none of the participating fire firefighters— with or without formaldehyde filters—were exposed to unacceptably high levels of formaldehyde during the course of this study. Finally, the present study attempted to compare three types of filters in an experimental setting and did not incorporate the impact of the face mask on the stresses and strains of the fire fighters, and their work capacity, as described for example by Budd et al. (1997a).

Although the research design and methodology can be applied for similar purposes elsewhere, the findings of this study should be considered specific in regard to exposure to Western Australian bushfire smoke. The respiratory health effects are highly dependent on the composition of the bushfire smoke, which is in turn determined by the fuel properties, such as the type and amount of vegetation, and the meteorological conditions, such as the presence of clearing winds or inversions [Luke and McArthur, 1978; Gill et al., 1981; Bear and Meyer, 1999]. In addition, given that the findings from this research are based on 15 min testing in a light smoke situation under controlled conditions, the recommendations for a particular type of filter should be considered within this context.

The mixing safety recommendations with regard to management of bushfire smoke in Western Australia are regulated by the Bushfire Smoke Management Standard Operational Procedures 51 [Fire and Emergency Services Authority Western Australia, 2003]. These procedures require FESA career fire fighters to use half face-piece masks with particulate filters while fighting bushfires. These demonstrate that particulate filters become ineffective in filtering out bushfire smoke components—including respiratory irritants, such as formaldehyde and acrolein—after 15 min use in light smoke conditions. The present study also showed that the POV filter was more effective in filtering out formaldehyde and acrolein under the stated conditions. However, compared to the number of participants wearing a POV filter a significant higher number of participants wearing the POV filter reported an increase in respiratory symptoms following the 15 min exposure. This suggests that POV Filter is the most effective option amongst the three in the prevention of acute respiratory symptoms, such as cough, wheeze, and shortness of breath in the stated conditions. Therefore, it is recommended that a review of the current Bushfire Smoke Management Standard Operational Procedures 51 should consider the findings of this study when determining the range of risk mitigation strategies available to reduce the harmful exposure of fire fighters to bushfire smoke. Further testing in field situations is needed to determine the efficacy of the filters in real bushfire situations and for prolonged periods of time. It is anticipated that these issues will be addressed in the follow-up phase of this study.

In conclusion, testing of the effectiveness of three different filters demonstrated that the POV Filter provided statistically significant better protection for the fire fighters’ respiratory health under these conditions. It must be acknowledged that future recommendations for fire fighter protection measures can only be based on the findings of additional exposure trials under a variety of conditions. Therefore, further research is needed to determine the breakthrough times of the filters and the efficacy of the filters over longer time periods, and in more realistic situations. It is anticipated, however, that these issues will be addressed in the follow-up phase of this study, which will be conducted during prescribed burns and real bushfire situations.

ACKNOWLEDGMENTS

We thank the fire fighters from the Fire and Emergency Services Authority of Western Australia, who participated in the present study. Special thanks to Respiratory Health of Fire Fighters Steering Group for their recommendations and invaluable assistance in completing the study. We acknowledge the support for the current study from the Chemistry Centre (WA). Perth, Western Australia. The research was funded by the Bushfire Cooperative Research Centre (grant no. 55011000).
REFERENCES


Appendix 5: Archives of Environmental Contamination and Toxicology
Respiratory Irritants in Australian Bushfire Smoke: Air Toxics Sampling in a Smoke Chamber and During Prescribed Burns

Annamarie J. B. M. De Vos · Fadhelme Reisea · Angus Cook · Brian Devine · Phillip Weinstein

Received: 5 December 2007 / Accepted: 21 July 2008
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Abstract Bushfire smoke contains an array of organic and inorganic compounds, including respirable and insoluble particles, aldehydes, and carbon monoxide. These compounds have been found to be a health hazard for firefighters in the United States. Despite the high frequency of bushfires in Australia, analysis of bushfire smoke components are scarce. As part of an occupational health study investigating the respiratory health effects of bushfire smoke in firefighters, air toxics sampling was undertaken in a smoke chamber and during prescribed burns. Levels of formaldehyde and acrolein were demonstrated at respectively 60% and 80% of the Short Term Exposure Limit in the smoke chamber. Carbon monoxide levels exceeded the peak limit of 400 ppm significantly. Although concentrations were lower during the prescribed burns, the study shows that Australian bushfire smoke contains air toxics of concern and provides justification for further research into the levels of air toxics measured at bushfires and the associated health impacts.

Introduction

Bushfire smoke is the evident product of bushfires. It contains a range of organic and inorganic compounds original to the combusted material or formed during the combustion process (Gill et al. 1981; Luus 1995). Combustion is a chemical-physical process in which the fuel properties, the temperature, the moisture, and the ventilation affect the type and amount of the combustion products present in the smoke (Brow and Meyer 1996; Bhendi-Reau et al. 1988; Gill et al. 1981; Tremil et al. 1978). Approximately 200 different compounds have been identified in wood smoke, including respirable and insoluble particles, carbon monoxide, nitrogen, and sulphur-based compounds, aldehydes, volatile and semi-volatile organics, compounds, polycyclic aromatic hydrocarbons, dioxins, organic acids, free radicals, and ozone (Doust 1991; Mailly 1990; Reise and Brown 2006; Ward 1967, 1999). Given that the emissions vary with fuel type and combustion conditions, the chemical basis for acute smoke toxicity is not adequately known. The majority of the findings are based on analyses from United States wildland fire smoke, and it is not clear whether these findings are applicable in the Australian environment, as vegetation types, soils, combustion conditions, and fire-fighting methods differ. Analysis of smoke components pertaining to Australian bushfires are limited. Obtaining the relevant data is complicated by the variation of the vegetation types, changing weather conditions, and often difficult access to the fire ground. (Flenwood et al. 2002). Reise (et al. 2006) conducted a method evaluation for the burning of various forest fuels selected from across Australia. Under controlled conditions, set amounts of these fuels were burned in a burn chamber, and air sampling was undertaken. The main identified toxic compounds were respirable particles, aldehydes (formaldehyde, acetaldehyde, acrolein, 3 formyldehydr.), volatile organic compounds (VOCs: benzene, toluene, xylenes, phenol), and carbon monoxide (Table 1). Of these compounds, respirable particles, carbon
monoxide, and acrolein exceeded the Exposure Standards for Atmospheric Contaminants in the Occupational Environment (Australian Safety and Compensation Council 1995). This was a preliminary evaluation conducted to identify toxicants of interest, and concentrations in the burn chamber could not be directly related to exposure levels at real bushfires.

During prescribed and experimental burns across Australia, Reisen et al. (2006a) identified carbon monoxide, respirable particles, formaldehyde, acrolein, benzene, and toluene from firefighter personal air sampling. The carbon monoxide exposure standard of 50 ppm was exceeded for one firefighter (30-min sample), with two additional exposure levels monitored at 26 ppm (15-min and 305-min samples). Respirable particle levels exceeded 13 mg/m³ at least once over the sampling period for 80% of the samples. It was noted that smoke exposure levels were influenced by a number of factors, including work activities, burn locations, fuel types, and meteorological variables. The findings were consistent with the results of other studies that have identified formaldehyde, acrolein, respirable particles, and carbon monoxide as a smoke hazard for firefighters (Reinhardt and Ottmar 2000; Reisen et al. 2006b; Sharkey 1997).

Formaldehyde is a colorless, strong-smelling, highly flammable gas that occurs naturally in plants and is released through biomass combustion during bushfires (Reinhardt and Ottmar 2000). The human health effects of inhalation of formaldehyde are well documented. There is consistent evidence of respiratory as well as skin and eye irritation after exposure to formaldehyde (Australian Government—Department of Health and Ageing 2005; Hauptmann 2004; International Agency for Research on Cancer 2004a; National Environment Protection Council 2003; World Health Organization 2002b). Epidemiological evidence demonstrates associations between occupational exposure to formaldehyde and nasopharyngeal and sinonasal cancers (McLaughlin 1994; Partee 1991; Vaughan et al. 2000). Based on these findings, the International Agency for Research on Cancer (IARC) classifies formaldehyde as a Class 1 carcinogen (i.e., carcinogenic for humans) (International Agency for Research on Cancer 2004a, 2004b). The Australian occupational exposure standards for formaldehyde are 1.0 ppm for an 8-h time-weighted average (TWA) and 2.0 ppm for a 15-min short-term exposure limit (STEL). The 15-min TWA is defined as the concentration for a normal 8-h workday and a 40-h workweek to which workers can be exposed, day after day, without adverse effect. The 15-min STEL is defined as the concentration to which workers can be exposed without adverse effect. Exposures should not be longer than 15 min and should not occur more than four times per day, and there should be at least 60 min between successive exposures. The National Industrial Chemicals Notification and Assessment Scheme recommends lowering standards to 0.3 ppm (TWA) and 0.6 ppm (STEL) (Australian Government—Department of Health and Ageing 2005). In the United States, the American Conference of Governmental Industrial Hygienists’ Threshold Limit Values for formaldehyde are 1.0 ppm (TWA) and 0.3 ppm (ceiling limit). The National Institute for Occupational Safety and Health recommends lowering occupational standards for formaldehyde from 0.75 to 0.16 ppm (TWA) and from 2.0 to 0.1 ppm (STEL).

Monitoring data during wildfires in the United States indicates that firefighters can be exposed to formaldehyde levels up to 0.34 ppm while controlling wildfires. Exposure levels for formaldehyde depend on the work activity being undertaken (Reinhardt and Ottmar 2000). Average formaldehyde levels varied from 0.015 ppm for "holding" compared to 0.098 ppm for “ mop-up.” These variations in formaldehyde exposure levels were confirmed in a smoke exposure study during prescribed burns by Reinhardt et al. (2000). Similarly, in Australia, Reisen et al. (2006a) measured different personal exposure levels of formaldehyde depending on work activities. Exposure levels for formaldehyde were highest for firefighters who were "pawing/ suppressing with a hose and/or a rake hoe" (up to 0.6 ppm).
compared to firefighters who were “fighting” and “supervising” (both up to 0.2 ppm).

Acrolein is a clear, colorless to straw-colored liquid with a pungent, suffocating odor. Forest fires emit acrolein as a product of incomplete combustion of organic matter. Acrolein is an upper-respiratory-tract irritant, causing increased airway resistance and a decreased respiratory rate. Severe respiratory symptoms, including bronchitis or pulmonary edema occur at concentrations of 10-20 ppm (Boklad-Johnson et al. 2000). Eye irritation can occur at concentrations of 0.01-2.0 ppm and irritation of the nose and throat can occur at 1.0-3.0 ppm (World Health Organization 2002a). Current occupational exposure limits in Australia are 0.1 ppm (TWA) and 0.3 ppm (STEL) (Australian Safety and Compensation Council 1995). Data on the emissions of acrolein from burning vegetation suggest a wide range of possible concentrations in smoke. Reinhardt et al. (2009) found shift averages for acrolein of 0.009 ppm for fire fighters, with the highest exposure averaging 0.06 ppm during the work shift. During the time on the fireline, the firefighters’ exposure to acrolein averaged 0.015 ppm, ranging up to 0.098 ppm (Reinhardt et al. 2000). In another study, Reinhardt and Ottmar (2000) found average acrolein exposures of 0.005 ppm during initial attack operations and 0.001 ppm over a work shift. In a study investigating the short-term health effects of exposure to smoke from prescribed burns, Slaughter et al. (2004) found mean levels of acrolein at 0.01 ppm. However, other studies have found acrolein concentrations in smoke as high as 0.1–10 ppm near fires (1997).

Carbon monoxide is a colorless, odorless, tasteless, nonirritant, highly toxic gas of the same density as air. It is extremely flammable and is present in virtually all fire environments (Lees 1995). It is produced abundantly through the incomplete combustion of biomass fuels, particularly in the smoldering phase, when temperatures are lower. Carbon monoxide has a well-established mechanism of action in humans. It displaces oxygen from hemoglobin in the blood to form carboxyhemoglobin, which leads to a reduction in both oxygen transport and release, resulting in a range of health effects (Bizovi and Leikin 1995; Ellenborn 1997; Mallory 1999; Townsend and Maynard 2002). Current occupational exposure limits set by the Australian Safety and Compensation Council (1995) are 30 ppm (TWA) for an 8-h workday, 200 ppm (STEL) for 15 min, and a peak limit of 400 ppm, which should not be exceeded at any time. At a concentration of 200 ppm, a healthy individual at rest starts experiencing mild headaches after 2–3 h. At 400 ppm exposure, the individual may experience nausea, headache, and dizziness after 1 or 2 h. With an exposure concentration of 800 ppm and higher, confusion, ataxia, coma, and seizures may develop. At high work levels, these symptoms can be expected to appear at lower exposure levels. Carbon monoxide is present in all fire environments and has been described as the most common and serious acute hazards for firefighters (Treichman et al. 1980). Although firefighters at bushfires infrequently encounter carbon monoxide levels that are capable of causing incapacitation and death within minutes, they are often exposed to levels that can compromise their judgment, psychomotor efficiency, visual vigilance, performance, and safety (Burgess et al. 1979; Hathaway and Proctor 2004; Matticks et al. 1992). Average carbon monoxide concentrations were measured at 14.4 ppm (TWA) (Table 2) and ranged from 1.4 to 38 ppm in 46 samples collected during fireline mop-up and a prescribed burn (Materns et al. 1992). The highest exposures, up to 300 ppm on an instantaneous basis, were associated with operators of gasoline-powered pumping engines. During prescribed burns, TWA levels were measured within occupational exposure limits (i.e., shift average was 38 ppm), and at the fireline, 58 ppm (TWA) was measured (Reinhardt et al. 2000). Smoke exposure measurements among firefighters at wildland fires undertaken between 1992 and 1995 showed that carbon monoxide levels occasionally exceeded full-shift permissible exposure limits (Reinhardt and Ottmar 2000). The average exposures to carbon monoxide at project wildland fires (i.e., eight multiday wildland fires) averaged 2.8 ppm over the work shift, with a maximum TWA exposure to carbon monoxide of 30.5 ppm over the work shift. During initial attack...

| Table 2 Carbon monoxide levels during fire fighting |
|----------------------------------|--------|-------|
|                                  | TWA   | STEL  |
| Structural fire fighting         |        |       |
| Treichman et al. (1980)          | 320    | >260  |
| Boklad-Johnson et al. (2000)     | 26.9   | 26.0  |
|        |        |       |
| Bulldozer fire fighting          |        |       |
| Brotherhood et al. (1990)         | 179    |       |
| Materns et al. (1992)             | 14.4   | 360   |
| Busen et al. (1990)               | 25     | 76.5  |
| Reinhardt et al. (2000)           |        |       |
| Shift average                     | 38     | 179   |
| At the fireline                   | 58     |       |
| Reinhardt and Ottmar (2000)       |        |       |
| Project wildfires                 |        |       |
| Shift average                     | 2.8    |        |
| Fireline                         | 4.9    |        |
| Initial attack wildfires          |        |       |
| Shift average                     | 1.6    |        |
| Fireline                         | 7.4    |        |
| Slaughter et al. (2004)           | 7.19   |       |

* Non-smokers/smokers

Source: Australian Safety and Compensation Council (1995)
wildfires (i.e., fires that were successfully controlled by initial attack forces), carbon monoxide levels averaged 15 ppm, with a maximum of 13.1 ppm, during the work shift. Smoke levels of carbon monoxide were found in a study investigating the association between lung function and exposure to prescribed burn smoke (Slaughter et al. 2004).

Particulate matter (PM) represents a complex mixture of organic and inorganic substances and consists primarily of condensed hydrocarbon, tar materials, and fragments of vegetation and ash (Ward and Hardy 1991). PM is abundantly produced during bushfires, is highly visible, affects ambient air quality, and has various health effects. The size of PM tends to divide into three groups: coarse particles, 2.5–10 μm; fine particles, 0.1–2.5 μm; and ultrafine particles, smaller than 0.1 μm. The chemical composition and size of the PM in bushfire smoke depend on the combustion conditions and the amount and type of biomass fuels. For example, a low-efficiency fire yields considerably more fine PM (72% of the total PM) than a high-efficiency fire (21% of the total PM), and incomplete combustion, due to a lack of oxygen, produces more toxic PM compared to complete combustion (Beer and Meyer 1999; Sharkey 1997). The fine particles account for up to 90% to nearly 100% of the mass of PM (Ward 1997).

Inhalation is the most important route of exposure during bushfires, and when particles are in the ambient air, there is a significant likelihood that firefighters will inhale them. It is extremely complex to determine the health effects of PM in smoke, as the damage causing properties of particles not only depend on the chemical and toxic characteristics but also on their size, shape, and density (Duest 1991; Naeher et al. 2007; Schwela 2001). Currently, there is no occupational exposure limit available for PM from smoke. In the United States, exposure levels are generally assessed against the occupational exposure levels for nuisance dust (i.e., 5 mg/m³ for the respirable fraction and 15 mg/m³ for the total dust fraction). In Australia, the recommended occupational exposure level for respirable non-toxic dust is 10 mg/m³ (Australian Safety and Compensation Council 1995). However, this general exposure standard should only be applied where the PM contains no substances that might themselves be toxic or cause physiological impairment at lower concentrations; for example, where a dust contains asbestos, the exposure to these materials should not exceed the appropriate value for these substances. For specific dusts, including coal dust, graphite dust, and hardwood dust, the occupational exposure levels for specific respirable particles vary from 1.6 to 6 mg/m³. During bushfire fighting, firefighters are exposed to considerable levels of particles produced by the combustion of biomass. Reinhart and Ottmar (2000) found maximum PM₁₀ (PM less than 10 μm aerodynamic diameter) levels of 2.5 mg/m³ on the fireline. The complex mixtures of the toxic compounds, which are adhered to the surface of the PM, and associated health effects are largely unknown. Moreover, exposure levels might vary with the specific toxic within a job that are being undertaken. Reinhart and Ottmar (2000) found that the PM₁₀ concentration was highest for firefighters during holding and mop up. These results were expected, as this task involves digging and stirring of ash and dirt, which causes particles to become airborne. Reinoso et al. (2005a) reported similar findings in particulate sampling during prescribed burns in Australia. Although the average work shift concentrations of particles ranged from 0.2 to 9 mg/m³, the particles reached levels above 20 mg/m³ during periods of low hoing.

This project was carried out to determine and quantify the air toxins in Western Australian bushfire smoke. Static and personal sampling was undertaken as part of an occupational health study investigating the effectiveness of protective filters on firefighter respiratory health during simulated bushfire smoke exposure (De Vos et al. 2006).

Methods

Experimental smoke trials were undertaken in two contexts: a smoke chamber and during prescribed burns. Personal sampling was undertaken in the breathing zone of the participating firefighters.

Smoke Chamber

The smoke chamber used for the study was a modified sea container (12.2 m × 2.4 m × 2.4 m) that was commonly used by the Fire and Emergency Services Authority of Western Australia (FESA) for education and training purposes. The sea container had two doors, which could be opened to regulate the smoke behavior and density during the trials. A pedestal fan was used inside the smoke chamber to ensure a consistent distribution of the smoke.

A standard drum-type incinerator of 243 L capacity was used to generate the smoke. The incinerator was placed outside the smoke chamber. A ventilation opening on the incinerator was used to manage the combustion process. The incinerator had a flue (diameter: 170 mm) at 1.76 m above floor level, which directed the smoke into the smoke chamber. There was no loss of smoke, as the flue was sealed into the wall of the smoke chamber.

The weight of the fuel used during each 1.5-h trial was ~25 kg. The fuel was a mixture of barkwood and coastal heath, which was typical of the fuel type that the firefighters would encounter in a bushfire situation. Based on workplace reports, these vegetation types were known to create substantial smoke levels during bushfires. The collected
vegetation was analyzed for moisture content, which was recorded at 9.4% during the period of the smoke chamber trials (Wilkinson, personal communication, 2004).

A light-smoke situation was produced, defined in the Bush Fire Somoce Exposure Standard Operational Procedures 51 (Fire and Emergency Services Authority Western Australia 2007) as a density of smoke producing a white to light gray color with reasonable visibility of at least 15 m.

Visual assessment of the smoke was undertaken by a single observer, using the usual smoke exposure classification as described by Reinhardt and Ottmar (2000). To assist with the assessment of the smoke density, five white circles with a diameter of 30 cm were spray-painted on the rear panel of the smoke chamber as indicators for visibility.

Prescribed Burns

Prescribed burns are low-intensity fires used to reduce the buildup of leaves and twigs on the forest floor. This procedure has proven to be an effective and environmentally sound way of reducing the future risks of destructive, high-intensity bushfires. The frequency of prescribed burns is given areas variable, with intervals between burns ranging from 5 to 15 years. The preferred seasons are usually during spring and autumn months. The method used to burn is based on the size of the area to be burned, prevailing weather conditions, and the availability of resources.

Before burns are conducted, firefighters ensure that control lines are established around the area to be burned. Control lines might be natural features, such as streams and existing roads, or can be tracks of vegetation cleared by hand tools or machinery. The most common method of ignition is to use a hand-held drip torch, which is a container of flammable liquid fitted with a wick and a bumer head. The trials were conducted during four prescribed burns in the Yanchep and two Rockingham area, which is located on the outer fringe of the Perth Metropolitan area in Western Australia. The prescribed burn was undertaken and managed by the Western Australian Department of Environment and Conservation. Table 3 shows the collected field data and predicted conditions for the scheduled days.

Air Sampling

The Chemistry Centre Western Australia, Perth, was commissioned to perform the monitoring and analysis of the bushfire smoke compounds of interest, including PM, formaldehyde, acrolein, carbon monoxide, and VOCs.

During the smoke chamber burns, static sampling of PM, formaldehyde, acrolein, VOCS, and carbon monoxide as well as personal sampling of VOCs were undertaken (Table 4). PM was measured by gravimetric sampling. The samples were collected on preweighed 25-mm acrylic filters (pore size 1 μm; sample rate 2 L/min). Formaldehyde and acrolein were sampled actively with two sectioned 2,4-dinitrophenyhydrazine SGC® sorbent tubes and analyzed by high-performance liquid chromatography (HPLC), as per National Institute for Occupational Safety and Health (NIOSH) Method No. 2460 (Schlecht and O'Conner 2003). Carbon monoxide and VOC monitoring was performed using the monitor from FMK-500-SP™. This is a portable monitor with photo-ionization detection, which determines the total level of VOCs. The Hipse™ field-portable gas chromatograph/mass spectrometer was used to identify and quantify the various VOCs. Personal VOC sampling was conducted on eight firefighters by using 3 M™ organic vapor monitors. This particular sampling was undertaken as part of another study investigating the effectiveness of protective filters on firefighter respiratory health during simulated bushfire smoke exposure (De Vos et al. 2006). The 3 M organic vapor monitors are devices that collect contaminants through the principle of diffusion and the purpose of the use of personal sampling devices was to measure the specific individual exposure, thereby assisting in the determination of the type of respiratory equipment appropriate to the contaminants. Passive personal sampling of organic vapors was conducted as per Australian Standard 2962.2—2003 (Standards Australia 2003). The monitors were attached near the participant's breathing zone (i.e., on the lipel of the jacket). Sampling lasted for 15 min, the minimum required period to obtain sufficient material for analysis (Standards Australia 2003). The organic vapor monitors were desorbed with 1.5 mL carbon disulfide and analyzed by gas chromatography/mass spectrometry with flame ionization detection, as per NIOSH Method No. 1501 (Schlecht and O'Conner 2003).

During the field trials, personal active sampling of formaldehyde was undertaken. The active 2-h sampling was done with 2,4-dinitrophenyhydrazine SGC sorbent tubes (i.e., similar methodology as in the smoke chamber). Analysis was performed by HPLC, as per National Institute for Occupational Safety and Health (NIOSH) Method No. 2460 (Schlecht and O'Conner 2003). No measurements of carbon monoxide, particles, acrolein, and VOCs were conducted during the prescribed burns.

Results

Static sampling was undertaken to characterize and quantify levels of air pollutants in the smoke chamber and in the field during the prescribed burns. Formaldehyde, acrolein, particles, carbon monoxide, and VOC levels were measured for 15 min in the smoke chamber. During the field trial, only formaldehyde was sampled, as a result of logistic limitations due to unsuitable weather conditions at the time.
Table 3  Prescribed burns environmental and meteorological data

<table>
<thead>
<tr>
<th>Location</th>
<th>17 and 20 October 2005</th>
<th>10 and 24 November 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Carnmen State Forest Block Prescribed Burn (415 057a) — approx. 10 km E of Two Rocks/Yanchep</td>
<td>Carnmen State Forest Block Prescribed Burn (415 055) — approx. 5 km E of Yanchep</td>
</tr>
<tr>
<td>Area burned</td>
<td>20–30 hectares per day were burned to provide smoke for the trial</td>
<td>20–30 hectares per day were burned to provide smoke for the trial</td>
</tr>
<tr>
<td>Total burn area</td>
<td>418 hectares</td>
<td>210 hectares</td>
</tr>
<tr>
<td>Vegetation type</td>
<td>Predominantly Banksia Low Forest A (LAc) with small areas of Diynamia</td>
<td>Predominantly Banksia Dense Low Forest A (LAd) with some emergent Diynamia</td>
</tr>
<tr>
<td>Associated plant species</td>
<td>B. grandis, Banksia robusta, Arctostaphylos pectinata, Diynamia</td>
<td>B. grandis, B. robusta, Arctostaphylos pectinata, Diynamia, Banksia robusta,</td>
</tr>
<tr>
<td></td>
<td>1 (LAc) with small areas of Diynamia</td>
<td>Banksia robusta, D. pelta, Banksia robusta, Banksia robusta, D. pelta,</td>
</tr>
<tr>
<td></td>
<td>Melaleuca spp., Eucalyptus todiata</td>
<td>Banksia robusta, Banksia robusta, Banksia robusta, D. pelta,</td>
</tr>
<tr>
<td></td>
<td>Eucalyptus marginata, E. gomphocephala</td>
<td>Banksia robusta, Banksia robusta, Banksia robusta, D. pelta,</td>
</tr>
<tr>
<td></td>
<td>Melaleuca spp., Eucalyptus todiata</td>
<td>Banksia robusta, Banksia robusta, Banksia robusta, D. pelta,</td>
</tr>
<tr>
<td></td>
<td>Melaleuca spp., Eucalyptus todiata</td>
<td>Banksia robusta, Banksia robusta, Banksia robusta, D. pelta,</td>
</tr>
<tr>
<td>Fire behavior</td>
<td>Surface moisture content (SMC) = 8–12%</td>
<td>SMC = 10–12%</td>
</tr>
<tr>
<td>Rate of Spread</td>
<td>~35 m/h</td>
<td>~35 m/h</td>
</tr>
<tr>
<td>Predictive conditions</td>
<td>Fire intensity: low to medium</td>
<td>Fire intensity: low to medium</td>
</tr>
<tr>
<td>Date</td>
<td>17 October 2005</td>
<td>10 November 2005</td>
</tr>
<tr>
<td>Fire Danger Index (FDI)</td>
<td>DFT 100 m/h and very high</td>
<td>DFT 100 m/h and very high</td>
</tr>
<tr>
<td>Windy mostly W to 25 km/h</td>
<td>Temp 21°C and fine</td>
<td>Windy mostly W to 25 km/h</td>
</tr>
<tr>
<td>Temp 21°C and fine</td>
<td>24 November 2005</td>
<td>24 November 2005</td>
</tr>
<tr>
<td>Windy mostly W to 25 km/h</td>
<td>Temp 21°C and fine</td>
<td>Windy mostly W to 25 km/h</td>
</tr>
<tr>
<td>Temp 21°C and fine</td>
<td>Windy and lean showers</td>
<td>Windy and lean showers</td>
</tr>
</tbody>
</table>

Source: L. Tsege (personal communication, 2006)

Table 4  Sampling methodology

<table>
<thead>
<tr>
<th>Smokes chamber burns</th>
<th>Prescribed burns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>Gernetic sampling</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>Sorbet tubes: static sampling</td>
</tr>
<tr>
<td>Acrolein</td>
<td>Sorbet tubes: personal sampling</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>Sorbet tubes: static sampling</td>
</tr>
<tr>
<td>VOCs</td>
<td>Sorbet tubes: personal sampling</td>
</tr>
<tr>
<td>Mixed gases</td>
<td>Portable GC/MS: static sampling</td>
</tr>
<tr>
<td>Methane</td>
<td>Mixed gases: static sampling</td>
</tr>
<tr>
<td>3 M³/m² organic vapour moniters</td>
<td>n/a</td>
</tr>
</tbody>
</table>

The narrow time window only allowed for an extremely limited preparation period for the researchers involved. Table 5 presents an overview of the results of the static sampling. Formaldehyde levels ranged from 1.16 to 2.54 mg/m³ during the three trials in the smoke chamber. Although the STEL level was exceeded slightly in one sample, it must be noted that these are positional or static samples in contrast to personal samples and, thus, personal exposure might have been higher or lower. Formaldehyde levels during the prescribed burns ranged from 0.46 to 0.75 mg/m³, which is well within the occupational exposure limits of 2.5 mg/m³ (STEL) and 1.2 mg/m³ (TWA). The mean formaldehyde level in the smoke chamber was approximately three times
Table 5: Results: Static sampling

<table>
<thead>
<tr>
<th>Air toxic</th>
<th>15-min sampling</th>
<th>2-h sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Smoke chamber</td>
<td>Pencilled burn</td>
</tr>
<tr>
<td>n (mg/m³)</td>
<td>Mean ± SD</td>
<td>n (mg/m³)</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>4.15 ± 0.39</td>
<td>4.17 ± 0.09</td>
</tr>
<tr>
<td>TWA 1.1 mg/m³</td>
<td>STEL 0.25 mg/m³</td>
<td></td>
</tr>
<tr>
<td>Acrolein</td>
<td>0.05 ± 0.04</td>
<td>0.05 ± 0.04</td>
</tr>
<tr>
<td>TWA 0.75 mg/m³</td>
<td>STEL 0.09 mg/m³</td>
<td></td>
</tr>
<tr>
<td>Particulate</td>
<td>n/a</td>
<td>0.05 ± 0.04</td>
</tr>
<tr>
<td>TWA 10 mg/m³</td>
<td>STEL na</td>
<td></td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>27 ppm</td>
<td>131 ppm</td>
</tr>
<tr>
<td>TWA 30 ppm</td>
<td>Range: 2-130 ppm</td>
<td>Range: 5-742 ppm</td>
</tr>
<tr>
<td>STEL 80 ppm</td>
<td>Range: n/a</td>
<td>Range: n/a</td>
</tr>
<tr>
<td>VOCs</td>
<td>2.1 ppm</td>
<td>2.1 ppm</td>
</tr>
<tr>
<td>Total</td>
<td>Range: 0.12 ppm</td>
<td>Range: 0.22 ppm</td>
</tr>
</tbody>
</table>

* Not detected
* Recommended TWA for inspirable non-toxic particles
* Geometric sampling

Source: Australian Safety and Compensation Council (1995)

higher compared to the mean level of formaldehyde during the prescribed burns (1.76 vs. 0.62 mg/m³). This discrepancy might be explained by the confinement and the limited airflow through the smoke chamber.

Acrolein levels were measured in the smoke chamber only and varied from 0 to 0.69 mg/m³ (mean: 0.58 mg/m³). The measured concentrations in the second trial reached the STEL of 0.69 mg/m³ and were significantly higher compared to the levels in the first and third trials. Although the trials were set up in a standard way to ensure consistency of the measurements, the variation in these findings might be explained by uncontrollable factors, including weather conditions, which might have resulted in an increased airflow in the smoke chamber.

Levels of particles in the smoke chamber ranged from 27 to 133 µg/m³, with a mean of 10 mg/m³, and exceeded the TWA of 10 mg/m³ for non-toxic particles on three occasions. Due to the toxic nature of bushfire smoke, it would be more appropriate to compare these results to occupational standards for toxic particles. However, such standards are not available, and no other existing guideline values capture the unknown synergistic and additive health effects of the individual compounds.

Carbon monoxide levels varied considerably among the three trials in the smoke chamber. The mean values ranged from 27 to 257 ppm. Peak levels were measured at 130 ppm, 742 ppm, and 932 ppm, which exceed the peak limit of 400 ppm on two occasions significantly. Carbon monoxide levels for the field trials were not available.

The mean level of VOCs determined by the multigas monitor was 2.1 ppm (TWA 0.2 ppm, range: 0.1-11.5 ppm). The major VOCs identified by the Haplos gas chromatograph/MS spectrometer were benzene, toluene, ethylbenzene, xylene, styrene, benzaldehyde, benzotate, phenol, benzofuran, allanes, indene, and naphthalene. It was not possible to accurately quantify individual levels because many of the identified compounds were present only in trace amounts and were poorly resolved by the gas chromatograph (Wilkinson, personal communication, 2005).

Personal sampling in the breathing zone of eight participants was undertaken with 3 M organic vapor monitors during one of the smoke chamber trials. These clip-on monitors make it possible to measure personal exposure levels to VOCs. The monitors were analyzed for N-heptane, benzene, toluene, ethyl benzene, M & P xylene, O-xylene, and total C2 benzenes (Table 5). The presence of these organic vapors was demonstrated at extremely low levels compared to the established occupational standards (Australian Safety and Compensation Council 1995). The mean toluene level was measured at 53.91 mg/m³, with the maximum level of 103.96 mg/m³, which is ~ 20% of the STEL (565 mg/m³).
Table 6 Results: Personal sampling volatile organic compounds

<table>
<thead>
<tr>
<th>VOC 1.5-metre sampling</th>
<th>Mean (mg/m³)</th>
<th>Range (mg/m³)</th>
<th>STEL (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methylene</td>
<td>2.11</td>
<td>1.3–4.14</td>
<td>–</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.48</td>
<td>0.14–1.91</td>
<td>–</td>
</tr>
<tr>
<td>Toluene</td>
<td>53.91</td>
<td>24.17–693.96</td>
<td>566</td>
</tr>
<tr>
<td>Dibutyl phthalate</td>
<td>0.06</td>
<td>0.05–1.07</td>
<td>–</td>
</tr>
<tr>
<td>Diethyl phthalate</td>
<td>0.05</td>
<td>0.02–0.13</td>
<td>–</td>
</tr>
<tr>
<td>Di-n-octyl phthalate</td>
<td>0.05</td>
<td>0.02–0.13</td>
<td>–</td>
</tr>
<tr>
<td>Total C2 aldehydes</td>
<td>0.24</td>
<td>0.10–0.28</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Source: Australian Safety and Compensation Council (1995)

Discussion

Bushfire smoke is the combustion product of biomass fuels and contains a range of organic and inorganic compounds, including respiratory irritants such as PM, formaldehyde, acrolein, and carbon monoxide. The health effects of PM depend on the size and characteristics of the adsorbed compounds. Consequently, there is no single description available of the health effects of particles of smoke. Formaldehyde is a known human carcinogen and causes direct irritation of both the skin and the respiratory tract. Acrolein is an irritant and adverse health effects associated with exposure are mostly confined to the tissue of first contact, which is often the respiratory tract due to inhalation of smoke. Carbon monoxide has acute effects on the body, ranging from slightly diminished work capacity to acute nausea, severe headache, disorientation, and impaired judgment. Death can occur during extreme exposure levels, but these levels are unlikely to exist during bushfire fighting.

The systematic sampling of particulate matter, formaldehyde, acrolein and carbon monoxide has demonstrated the presence of these toxic compounds in Western Australian bushfire smoke. Formaldehyde concentrations in the smoke chamber reached up to 60% of the STEL and exceeded the STEL on one occasion. Formaldehyde levels in the field reached 50% of the TWA. Acrolein concentrations in the smoke chamber reached up to 50% of the STEL and reached the STEL on one occasion. Carbon monoxide monitoring with real-time data loggers in the smoke chamber showed peak levels that exceeded the peak limit significantly. It is assumed that the high levels of particles and carbon monoxide might have been caused by the confinement and the limited ventilation in the smoke chamber.

It is acknowledged that conditions during the trials, in particular in the smoke chamber, do not exactly replicate real bushfire fighting situations due to the nature of the burning process, ventilation, humidity, and variance in meteorological conditions. Therefore, the concentrations of air toxics measured cannot be directly related to concentrations that firefighters will be exposed to during bushfire fighting activities. Nonetheless, exposure studies in the United States and in other Australian states have found similar results from smoke sampling during prescribed burns. Reliaabdit (2000) showed that during wildfires, occupational exposure standards were exceeded for up to 14% of firefighters’ exposures to respirable particles, formaldehyde, and acrolein, and 8% of exposure to carbon monoxide. In Australia, Reiser et al. (2001) found during prescribed burns in Victoria, South Australia, and the Northern Territory that respirable particle levels frequently exceeded the STEL of 10 mg/m³, and carbon monoxide levels exceeded occupational exposure levels in a small (not specified) number of cases related to specific trials. Furthermore, a strong correlation was found between levels of carbon monoxide and respirable particles and between levels of carbon monoxide and formaldehyde.

The findings of this study demonstrate that Western Australian bushfire smoke contains air toxics of concern and provide a justification for further research into the levels of air toxics measured at bushfires and associated health impacts. Identifying the acute respiratory health effects of occupational exposure to bushfire smoke is relatively straightforward, but quantifying them under actual field conditions is more difficult. Identification and quantification of long-term health effects requires further research.

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Appendix 6: American Journal of Industrial Medicine
Effect of Protective Filters on Fire Fighter Respiratory Health: Field Validation During Prescribed Burns

Annemarie J.B.M. De Vos, MPH, RN, ICN;1 Angus Cook, PhD, MCHERZ, MATER;1 Brian Devine, BSc;1 Philip J. Thompson, MBB, FRAC, FFCO, MEMAC;3 and Philip Weinstein, MD, MBB, MAPP, FESC, FFPM.4

Background: Bushfire smoke contains a range of air toxics. To prevent inhalation of these toxics, fire fighters use respiratory equipment. Yet, little is known about the effectiveness of the equipment on the fire ground. Experimental trials in a smoke chamber demonstrated that the particulate/organic vapor/ formaldehyde (POVF) filter performed best under simulated conditions. This article reports on the field validation trials during prescribed burns in Western Australia.

Methods: Sixty-seven career fire fighters from the Fire and Emergency Services Authority of Western Australia were allocated one of the three types of filters: Sporex, P95, or P100. Sampling was conducted before, during, and after exposure to bushfire smoke from prescribed burns.

Results: Exposures to PAH and SO2 were demonstrated after 60 and 120 min exposure. A significant number of participants in both the P95 and P100 filter groups reported increases in respiratory symptoms after the exposure. Air sampling inside the respirators demonstrated formaldehyde levels significantly higher in the P95 and P100 filter group compared to the POVF and the POVF filter group.

Conclusions: The field validation trials during prescribed burns supported the findings from the controlled exposure trials in the smoke chamber. Testing the effectiveness of three types of different filters under bushfire smoke conditions in the field for up to 2 hr demonstrated that the P95 filter is ineffective in filtering out respirable irritants. The performance of the POVF and the POVF filter appears to be equally effective after 2 hr bushfire smoke exposure in the field. Am J Ind Med. 2008 © 2008 Wiley-Liss, Inc.

KEY WORDS: prescribed burns; bushfire smoke exposure; fire fighters; respiratory health; respiratory protection

INTRODUCTION

Bushfires are a naturally occurring element on the Australian continent. Due to climatic variation across the continent, at any time of the year some part of Australia experiences bushfire events. The likelihood of an increase in bushfire risk in Australia resulting from climate change is very high (Petersen et al., 2007). Therefore, it is likely that Australia's fire fighters will be more frequently and severely exposed to bushfire smoke in the future.

For decades fire fighters and their managers have demonstrated anecdotal evidence of the health effects of
ilating bushfire smoke. Since the mid-1970s these health effects have been systematically investigated recognized. Toxic exposures are generally lighter in structural fire fighting, and declines in FVC, FEV₁, and FEF₂₅₋₇₅ have been well documented in urban and structural fire fighters. Peters et al. (1974; Mink et al., 1977a, b, 1979, 1982; Unger et al., 1980; Sheppard et al., 1986; Brandt-Rauf et al., 1988; Sherman et al., 1989; Lege et al., 1980; Guidotti and Cough, 1992). Yet, bushfire fighters tend to have longer periods of smoke exposure, which can range from hours to several days with limited respite periods. In addition, situational factors beyond the bushfire fighters' control, such as the wind speed, the terrain, the type of fuel, the fire behavior, and the urgency of the work task, determine the intensity and the time period of the smoke exposure. Bushfire smoke produces a diverse mix of chemicals that are not easily characterized, and published health effects are not available for many of these chemical contaminants.

Research conducted in the United States in the 1970s on the health effects of wildland fire smoke exposure was largely inconclusive, and a 1985 survey of the fire community indicated that studying the health effects of smoke was not a high priority for fire managers (Sharkey, 1997). This position changed with the 1987 fires in California and the 1988 fires in Wyoming, when thousands of fire fighters experienced respiratory problems. During the Wyoming fires, 40% of the approximately 30,000 medical visits made by wildland fire fighters were for respiratory problems [National Institute for Occupational Safety and Health, 2004].

Since the 1990s occupational health studies of United States wildland fire fighters have shown significant declines in respiratory function associated with increasing exposure over work shifts and fire seasons. Rothman et al. (1991) reported significant increases in symptoms of cough, phlegm production, and wheezing in a cross-sectional study of pulmonary function and respiratory symptoms. Mean cross-season decreases in FEV₁ (−1.2%) and FVC (−0.3%) were observed, with cumulative hours of fire fighting associated with a decline in FEV₁. Liu et al. (1992) studied sixty-three wildland fire fighters from five United States Department of Agriculture and Forest Service crew in Northern California and Montana across the 1989 fire season. Significant individual declines of 0.09 L, 0.15 L, and 0.44 Ls in post-season values of FVC, FEV₁, and FEF₂₅₋₇₅ respectively (Table 1). No consistent relationship was found between declines of FVC or FEV₁ and any of the covariates investigated, including smoking status, history of asthma or allergies, full-time or seasonal employment status, or history of respiratory tract symptoms. In a cross-sectional study in Sardinia, 92 firemen showed a significant reduction in lung function compared to the control group (pollen-free) (Berra et al., 1996). No significant correlation was found among years of service, number of fires extinguished, and respiratory data. In addition, there was no significant correlation between respiratory changes and hobbies or previous professional experiences, or involvement in non-urban fire fighting (Table 1). Fifty-three wildland fire fighters from USDAFS and Bureau of Land Management Crews in Washington and Oregon underwent pre-season and post-season spirometry across the 1992 fire season (Buchley et al., 1997) (Table 1). In addition, cross-shift spirometry was

<table>
<thead>
<tr>
<th>Study</th>
<th>Subjects</th>
<th>Location</th>
<th>Exposure period</th>
<th>Measured endpoints</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klimas et al. (1981)</td>
<td>52</td>
<td>North California</td>
<td>Season</td>
<td>Spirometry, pulmonary symptoms</td>
<td>Significant increases in symptoms of nose irritation, cough, phlegm production, and wheezing, decline in FEF₂₅₋₇₅, −12%, FVC, −0.3%</td>
</tr>
<tr>
<td>Liu et al. (1992)</td>
<td>63</td>
<td>Northern California, Montana</td>
<td>Season</td>
<td>Spirometry, sputum</td>
<td>Significant decrease in FVC, FEV₁, and FEF₂₅₋₇₅</td>
</tr>
<tr>
<td>Serra et al. (1996)</td>
<td>82</td>
<td>Sardinia</td>
<td>Cross-sectional study</td>
<td>Spirometry</td>
<td>Significant decrease in FEV₁, vs. 0.44 L</td>
</tr>
<tr>
<td>Buchley et al. (1997)</td>
<td>76</td>
<td>Washington and Oregon/Cascade Mountains</td>
<td>Shift 1</td>
<td>Spirometry</td>
<td>Significant decrease in FVC, 0.085 L, FEV₁, 0.150 L, FEF₂₅₋₇₅, 0.48 L</td>
</tr>
<tr>
<td>Shiokawa et al. (2004)</td>
<td>53</td>
<td>Western United States</td>
<td>Season</td>
<td>Spirometry</td>
<td>Significant decrease in FEV₁, 0.25 L, decrease in FVC, 0.45 L</td>
</tr>
</tbody>
</table>
obtained on 76 individuals during both prescribed burns and wildfires. Significant cross-shift declines in FVC (0.065 L), FEV1 (0.156 L), and FEF25-75 (0.496 L/s) were seen and remained significant after adjustment for covariates, including respiratory infection, smoking status, history of asthma or allergies. A significant cross-seasonal decline was observed for FEV1 and FEF25-75 (0.104 L/s and 0.275 L/s respectively). Slagheffer et al. [2004] measured the short-term effects of smoke exposures on lung function in a group of fire fighters performing prescribed burns (Table I). The study also measured several inhalable compounds such as, respirable particulate matter, carbon monoxide, formaldehyde, and acrolein. Spirometric measurements were made at the beginning, mid-point, and at the end of the work shift, while exposure was measured over the entire day. The cross-shift analysis showed a significant decline in FEV1 (0.125 L), a decline in FVC (0.067 L), and a decline in FEF25-75 (0.451 L/s). The investigators could not establish a link between the individual toxic components and any of the changes in lung function.

The relationship between bushfire smoke and health impacts in the Australian context has not been clearly established, even though bushfires are a naturally occurring element on the Australian continent, and at any time of the year some part of Australia experiences bushfire events. In the 1980s, one Australian study reported that the respiratory health effects of cigarette smoking among Sydney fire fighters far outweighed any contribution from occupational exposure to bushfire smoke (Young et al., 1980). Although anecdotal evidence is available, there is a lack of reliable occupational disease data and in particular, respiratory disease data associated with occupational exposure to bushfire smoke in the Australian environment.

Community studies of Australian bushfire smoke and asthma incidence have been undertaken, but show conflicting results (Churches and Corbett, 1991; Cooper et al., 1994; Smith et al., 1996; Johnston et al., 2002; Bowman and Johnson, 2005; Chen, 2006). More recently, Chen et al. [2006] showed a statistically significant association between the presence of bushfire smoke and hospital admissions for asthma in Brisbane. In summary, there is limited and conflicting information about the respiratory health effects of exposure to Australian bushfire smoke, in particular in the occupational context.

The study identified the need for appropriate and effective respiratory protective equipment for bushfire fighters. In Western Australia, the 1,000 career firefighters employed by the Fire and Emergency Services Authority of Western Australia are issued with respirators and P filters for use during bushfire suppression. A wide range of different respirators and filters is available, each with their own specific features. Yet, it is not clear, which is the most effective from a health and safety perspective. In Phase 1 of this study, reported elsewhere, an experimental investigation compared the effect of three different types of protective filters on the fire fighters' respiratory health [De Vos et al., 2006a]. The three types of filters tested were (1) particulate (P) filter; (2) particulate/organic vapor (POV) filter, and (3) particulate/organic vapor/formaldehyde (POVF) filter. The study demonstrated acute changes in reported respiratory health symptoms in fire fighters following controlled exposure to a light bushfire smoke situation for 15 min in a smoke Chamber. The changes also included physiological measures, such as declines in FEV1 and SaO2, which were not prevented by the use of respirators and any of the tested filters. The active sampling of air toxins inside the respirators indicated that the P filter was only effective in filtering out particles, and was ineffective in filtering out respiratory irritants, such as formaldehyde and acrolein. Although the POVF filter was effective in filtering out these compounds, the POVF filter was most effective in preventing acute respiratory health symptoms. After adjusting for possible confounders such as FESA service years, age, and history of tobacco smoking, a significant 12-fold reduction was found in the number of participants with respiratory symptoms following the smoke exposure with the POVF filter compared with the P filter. Phase 1 of the study demonstrated that the POVF filter provided statistically significant better protection for the fire fighters' airways in a simulated bushfire exposure chamber.

Phase 2 of the study, a field validation of the previously reported experimental observations, is reported here.

METHODS

The study used a double-blind randomized experimental design, to ensure that the intervention groups were initially comparable, and that any differences observed between the exposure groups would be related only to the actual differences between the different interventions [Savitz, 2003]. Random allocation of the intervention maximized the likelihood that each intervention would be allocated to similar proportions of the participants [Ahrens and Piggot, 2005]. Double blinding ensured that both the participants and the researchers did not have any knowledge of which intervention (i.e., which filter type) the individual participants were using during the trials. The aim of this method was to help prevent influences on the study outcomes as a result of participants' perceptions of using a particular type of filter [Nicholson, 1994]. All participants were provided with an informed consent sheet and signed an informed consent form.

Study Population

The source population consisted of the 1,000 male and female FESA career fire fighters in Western Australia. Study participants were defined as currently active career fire
fighters based in Perth Metropolitan fire stations. Individuals with unstable asthma, current acute or chronic respiratory illness, or any other chronic or severe illnesses were excluded from the study. Participants were randomly selected from the FESA Staff Deployment System, and participated on a voluntary basis. Sample size calculation showed that to detect at least a 20% variation in baseline respiratory status (with 55% confidence; power 80%) in any of the respiratory outcomes (as identified by the questionnaire and/or spirometry) across the three classifications of filter status, approximately 140 participants would be required. Approval for the study was obtained from the Human Research Ethics Committee, The University of Western Australia.

The researchers determined the random allocation of the intervention after completion of the participant register. This ensured that the decision to participate in the study was made regardless of which intervention group the participant would be allocated. In addition, this precluded that particular filters were allocated to specific participants, and discouraged "guessting" systems, in which participants attempt to find out which intervention was allocated to them, which, which would lead to "unblinding" of the study.

The Phase 1 controlled exposure trials in the smoke chamber demonstrated that the P filter was the least effective in filtering out bushfire smoke components. Therefore, it was decided to under-sample this type of filter during these held validation trials. Sixty-seven (67) career fire fighters from Perth Metropolitan fire stations participated in four field trials during prescribed burns. Thirteen subjects were randomly allocated to the F filter group, 27 to the P filter group, and 27 to the OFV filter group.

Test Filters

The three filters to be tested were:

1. Particulate filter (P) (3M™ 6025). This is a filter intended for use against both mechanically and thermally generated particles. The P filter was selected as the baseline filter in the trials, as this filter is issued to FESA career fire fighters in Western Australia, as per Standard Operational Procedures 51 (Fire and Emergency Services Authority Western Australia, 2007).

2. Organic Vapor/Organic Formaldehyde (OVF) filter (3M™ 6057A/BE1) with attached P filter. This OVF filter is for use against certain organic and inorganic gases, sulfur dioxide, acid gases and vapors, and against particles when combined with the P filter. A group of FESA career fire fighters had previously elected to purchase their own OVF filters. These fire fighters have advocated the use of these filters within FESA, as their perception was that they experienced considerably less respiratory symptoms following bushfire emergencies. In order to establish scientific evidence for these perceptions, and thus to determine which device was more effective in protecting the fire fighters’ respiratory health, this combination of filters (P/OFV) was included in the trials.

3. Organic Vapor/Formaldehyde (OVF) filter (3M™ 6057A/BE1) with attached P filter. This filter is for use against organic gases and formaldehyde vapor, and against particles when combined with a P filter (Fig. 1). The OVF filter was selected for the trials, because initial air sampling in the smoke chamber indicated the presence of formaldehyde concentrations in the smoke [De Vos et al., 2008]. Although levels detected in the experimental burns were well within STEL, formaldehyde is a compound of concern as it is a known carcinogen to humans [International Agency for Research on Cancer, 2004]. It was therefore considered relevant to include the combined P/OFV filter in the project to be tested against the P and the OFV filter.

For the purpose of the trials, the filters were made similar in appearance, in order to conceal the identity of the allocated filter. Before the trials, the researchers resolved packages, consisting of an information sheet, a consent form, and a questionnaire. Every package was tagged with a number, which corresponded with one of the similarity-numerated study filters. The researchers maintained a register of the three types of filters and its coding. On the day of the trial, the researchers handed out the administration packages randomly to the participants. This ensured that the researchers and the participants were unaware of what type of filter the participants used during the trials.

The 3M™ 6000 Series Standard Half Face respirators were selected to be used during the trials since these are the
respirators, which are issued to FESA career firefighters in Western Australia for bushfire fighting. The respirators had a soft lightweight elastomeric face piece with a cradle head harness and neck strap. The respirators were compatible with the selected study filters, and were available in three sizes (small, medium, large) to fit various face sizes. During the exposure trial, the participating firefighters were required to wear their personally issued respirator as part of their "turn-out gear."

Test Site and Conditions

The Phase 2 field validation trials were conducted during four prescribed burns in the Yanchep and Two Rocks areas on the outer fringe of the Perth Metropolitan area. The prescribed burns were selected for the experimental field trials, because these conditions are similar to bushfire conditions with regard to bushfire smoke density.

Prescribed burning involves the controlled setting of fires, carried out to reduce the build-up of leaves and twigs on the forest floor. In Western Australia, prescribed burns are managed and controlled by the Department of Environment and Conservation (DEC). The environmental conditions and smoke behavior during the prescribed burns were monitored and recorded throughout the process of the exposure trials. The density of the smoke was reported as light to medium.

Table 1 summarises these recordings.

The field validation trials were conducted utilising exposure methods similar to the methods used in the Phase 1 exposure trials in the smoke chamber (De Vos et al., 2005a). On arrival at the site of the prescribed burns, the participants were informed about the aims of the study, the procedures, and safety issues during the trials. All participants were provided with an information sheet and signed an informed consent form. Next they completed the first part of the questionnaire and underwent the baseline spirometry and oximetry testing.

As part of the study requirements, the participating firefighters wore their “turn-out gear” and used their own 3M™ 6000 Series Standard Half Face respirators during the exposure trials. After the researchers attached the study filters to the participants’ respirator, they were asked to perform a Positive Pressure Fit Check in accordance with Australian/New Zealand Standard 1715 [Standards Australia, 1994]. The participants were transported to the smoke area in the field, once the prescribed area had burnt sufficiently to produce light smoke conditions (i.e., bushfire smoke with a white to light gray color with a visibility of more than 15 m). The participants were requested to stay in the field for two subsequent periods of 60 min. During the exposure period, the subjects were not required to fight the prescribed fire. They were encouraged to walk around in the field to ensure exposure to a representative sample of the smoke (Fig. 2). After the first exposure period of 60 min, the firefighters were brought out of the smoke zone and transported to base where the second set of measurements was taken. After approximately 10 min break estimated total time between the two exposure periods was 15 min), they were returned to the smoke zone for a further 60 min. After the second period of exposure, they were returned to base where final measurements were taken.

During the trials the participants were assured that they could remove themselves from the smoke at any time if they experienced any adverse health effects both physically, for example, shortness of breath, wheezing, or dizziness. In addition, the participants were under the observation of a Registered Nurse. First aid facilities were available at the test site, and an emergency protocol was in place.

Data Collection

The difference in effectiveness of the three types of filters was assessed by measuring the respiratory health outcomes in the participants before (baseline) and after the

<table>
<thead>
<tr>
<th>TABLE 1. Environmental Conditions and Smoke Behavior During the Prescribed Burns</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observation</strong></td>
</tr>
<tr>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Vegetation type: Scrub, low bushes, trees</td>
</tr>
<tr>
<td>Vegetation height: 1-4 m</td>
</tr>
<tr>
<td>Vegetation density: Moderate, dry, very dry</td>
</tr>
<tr>
<td>Slope terrain: Level, gentle slope 5°</td>
</tr>
<tr>
<td>Wind Direction: South, South-West</td>
</tr>
<tr>
<td>Wind Speed: 15-20 km/h</td>
</tr>
<tr>
<td>Smoke density: Light, medium</td>
</tr>
<tr>
<td>Smoke behavior: Consistent, stable</td>
</tr>
<tr>
<td>Firefighter's position in the smoke: Downwind, peripheral, central</td>
</tr>
<tr>
<td>Other observations: Light smoke, not from intense but fine, thick smoke at the end</td>
</tr>
</tbody>
</table>

No smoke. Light smoke density: white to light gray color with a visibility of more than 15 m; medium smoke density: dark gray to black color with a visibility of 8-15 m; heavy smoke density: black to opaque/brown color with a visibility of 3-8 m.
two periods of smoke exposure. Respiratory health outcomes were measured by means of a respiratory symptom questionnaire, spirometry, and oxygen saturation measurement. Active sampling of air toxics inside the fire fighters' respirators completed the assessment of the effectiveness of the three types of filters.

**Respiratory symptom questionnaire**

The self-completed respiratory symptom questionnaire was designed to obtain information about the participants' perception of respiratory symptoms before and after exposure to combustion products of Australian bushfire smoke. The questionnaire was based on the Medical Research Council questionnaire, a validated instrument designed to elicit details about symptoms and factors associated with pulmonary diseases and smoking history (Medical Research Council, 1986). The respiratory symptom list included questions pertaining to intensity and frequency of cough, wheeze, shortness of breath, tightness in the chest, and sore throat. Participants were classified as either non-smokers, past smokers or current smokers, and cigarette consumption was estimated in standard pack-years. Additional questions were included to obtain information about the participants' risk perceptions in relation to the acute respiratory health effects of bushfire smoke exposure. The questionnaires were designed in three sections, relevant to the stage of the exposure process, that is, at baseline, after 60 min exposure, and after 120 min exposure.

**Spirometry**

Pulmonary function testing was used to detect and quantify abnormal lung function. Forced expiratory volume in 1 second (FEV₁) was selected, and is known as one of the most valuable and reliable of all pulmonary parameters. FEV₁ is an extensively used index with good reproducibility [Pierce and Johns, 1995], and provides the best method of detecting the presence and severity of airway obstruction. Changes in FEV₁ across a work shift have been described as useful work-related response indices to measure impaired lung function [Vernbles, 1994]. In a fire-fighting context, reduction of spirometry measurements has been shown to relate to combined smoke inhalation injury and burns [Haponik and Munster, 1990]. Spirometry was performed by a single trained individual according to the recommendations for manoeuvre performance provided by the American Thoracic Society [American Thoracic Society, 1995]. A single Welch Allyn PneumoCheck™ Spirometer was used in all tests to ensure standardization of the measurements. A minimum of three manoeuvres was undertaken to meet the ATS recommendations for collection and to obtain reproducible tracings with the two highest FEV₁ within 5% of each other [American Thoracic Society, 1995]. All participants were tested sitting straight up with their feet firmly on the floor, and without a nose clip. Spirometric data were collected at baseline and after two subsequent intervals of 60 min exposure to bushfire smoke in the field. The change in FEV₁ (Δ FEV₁) for each participant was measured by subtracting the FEV₁ obtained after the exposure from the baseline FEV₁.

**Oximetry**

Oximetry was performed to measure arterial oxygen saturation. Arterial hypoxemia and reduced hemoglobin oxygen saturation have been shown to accompany smoke inhalation and cutaneous burn injury, either separately or in combination [Whitener et al., 1980; Haponik and Munster, 1990]. Transient hypoxemia has been documented following the exposure of 21 fire fighters to dense smoke [Girosi et al., 1977]. The arterial oxygen saturation of hemoglobin was measured in percentages (%) using a Datex-Ohmeda Telfa® pulse oximeter. The change in SaO₂ (Δ SaO₂) for each participant was measured by subtracting the SaO₂ obtained after the exposure from the baseline SaO₂ measured before the exposure.

**Personal air sampling inside the respirators**

Levels of formaldehyde were sampled inside the respirators to assess and compare the filtering properties of the three types of study filters. Personal air samples from inside the respirators were collected via sampling ports, according to a method described and validated by Johnson et al. [1992]. Similar to Johnson’s method, the respirators were drilled and fitted with 60 cm Tygon™ tubing (6 mm) [Johnson et al., 1992]. The tubing was connected to the air sampling pump attached to the waist belts worn by the participants (Fig. 3). Air sampled from inside the respirator was passed through a carbonyl compound sorption tube.
connected in series using a calibrated air sampling pump (set at 1 L/min). The sampling lasted for 120 min, broken into two periods of 60 min.

Chemical analysis of air toxics

The Chemistry Centre of Western Australia performed all sampling procedures and laboratory analyses. Formaldehyde was analyzed by High Performance Liquid Chromatography in accordance with the National Institute for Occupational Safety and Health Method 2016 (The National Institute for Occupational Safety and Health, 2003). Samples were stored under refrigeration and transported in accordance with established procedures to prevent sample degradation.

Statistical Analyses

The data analysis were performed utilizing the statistical packages SPSS (Version 12.0) and STATA (Version 9.0). For consistency reasons, the data analysis was conducted following a similar strategy as used in Phase I of the study (De Vos et al., 2006b). Kolmogorov–Smirnov analyses were used to test dependent and independent variables for violation of normal distribution. Relationships between the differences in respiratory health symptoms before and after the exposure across the three types of filters were tested with a $t$-test. Individual $\Delta FEV_1$ and $\Delta SaO_2$ were assessed by paired $t$-tests. ANOVA and linear regression was used to assess: (i) the relationship between $\Delta FEV_1$ and $\Delta SaO_2$ across the three types of filters, while adjusting for potential confounders such as smoking history, years of service, and previous exposures; and (ii) associations between the types of filter and the results of the air sampling inside the respirators. Differences in respiratory health outcomes after the exposure were converted into dichotomous variables (i.e., no difference/better and worse) and assessed using logistic regression to compare differences in respiratory symptoms across the three types of filters. Models were adjusted for potential confounding factors, including years in FESSA, gender, smoking history, and asthma history. Adjacent odds ratios were calculated to compare the effectiveness of the filters based on the number of participants reporting an increase in respiratory symptoms following the exposure.

RESULTS

Description of Test Subjects

General description

Forty-five percent ($n = 30$) of the 67 study participants were 30–59 years old. Sixty-four were male, and 3 were female. The mean number of years employed at FESSA was 11 years. Seventy percent ($n = 47$) had never smoked, 25% ($n = 17$) were past smokers, and 2% ($n = 3$) were current smokers.

At baseline, 83% of the participants ($n = 57$) reported to be in “very good” to “excellent” health, 15% ($n = 10$) stated that they were in “good” health. Three percent ($n = 2$) of the participants reported suffering from asthma, and 2% ($n = 17$) reported having hay fever. Twenty-two percent of the participants ($n = 15$) reported to have slight to moderate coughing, wheezing, shortness of breath, with 10% ($n = 11$) reporting to have a cold, influenza or chest infection less than 2 weeks prior to the commencement of the study.

Respirator use prior to the study

Twenty-five percent ($n = 17$) reported to “always” wearing a respirator while fighting bushfires. While the remaining 75% reported to “sometimes” or “mostly” wearing a respirator during the bushfire fighting activities. Figure 4 shows the types of protective filter that the participating FESSA career fire fighters reported to use for bushfire fighting. The P95 filter was mostly used (72%, $n = 48$), followed by the P100 filter (9%, $n = 6$). A total of 3% ($n = 2$) reported using another unspecified type of filter, and 16% ($n = 11$) of the participants could not recall what they used.

Respiratory symptoms prior to the study

Approximately 40% of the participants ($n = 26$) reported experiencing respiratory symptoms after bushfire fighting, such as coughing, wheezing, shortness of breath. One participant reported having watery eyes after bushfire fighting.
Perceptions of respirator usefulness prior to the study

Forty-three percent of subjects (n = 20) stated that they agreed that the respirator issued to fight bushfires prior to the study was useful. Of these, 63% (n = 13) reported "sometimes" or "mostly" wearing a respirator, and 35% (n = 10) reported "always" wearing a respirator.

In contrast, 56% (n = 24) thought that the respirator issued to fight bushfires prior to the study was not useful. Of these, 79% (n = 19) reported "sometimes" or "mostly" wearing them, while 21% (n = 5) reported "always" wearing them despite their negative perceptions of their utility. Amongst those who thought the respirator was not useful, nearly half of them (46%, n = 11) indicated that the respirator/filter made breathing more difficult, and the remainder (54%, n = 13) thought that the respirator/filter made no difference or made it easier to breathe.

Field Test Results

Formaldehyde levels

As expected, inside-mask formaldehyde levels were significantly higher in the P filter group (0.44 mg/m³, n = 2) compared to the POV and POVF filter group both in the first and second hour of smoke exposure (P < 0.05) (Table II). Overall, the mean inside-mask formaldehyde level was higher for the POVF filter group (0.024 mg/m³).

<table>
<thead>
<tr>
<th>Filter type on respirator</th>
<th>Formaldehyde mg/m³ (mean ± SD) After 60 min</th>
<th>Formaldehyde mg/m³ (mean ± SD) After 120 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Filter (n = 2)</td>
<td>0.44 ± 0.044</td>
<td>0.26 ± 0.023</td>
</tr>
<tr>
<td>POV Filter (n = 6)</td>
<td>0.02 ± 0.003</td>
<td>0.02 ± 0.009</td>
</tr>
<tr>
<td>POVF Filter (n = 6)</td>
<td>0.01 ± 0.004</td>
<td>0.01 ± 0.004</td>
</tr>
</tbody>
</table>

*45% (n = 15) of subjects reporting a headache were in the P filter group.

Hemoglobin oxygen saturation

A decline in SaO₂ was measured across the study population both after 60 min (12%, P < 0.05) and 120 min (18%, P < 0.05) compared to baseline measurements. Although the SaO₂ declines were statistically significant, the effect is small in clinical terms, and was not associated with the type of filter used (Table IV).

<table>
<thead>
<tr>
<th>Health effects</th>
<th>60 min exposure</th>
<th>120 min exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quite short—extremely short</td>
<td>15% (n = 6)</td>
<td>14% (n = 5)</td>
</tr>
<tr>
<td>Slightly—moderately short</td>
<td>63% (n = 23)</td>
<td>23% (n = 9)</td>
</tr>
<tr>
<td>Lethargic</td>
<td>22% (n = 8)</td>
<td>23% (n = 9)</td>
</tr>
<tr>
<td>Headache</td>
<td>16% (n = 6)</td>
<td>8% (n = 3)</td>
</tr>
<tr>
<td>FEV₁</td>
<td>0.001 (P &lt; 0.05)</td>
<td>0.01 (P &lt; 0.05)</td>
</tr>
<tr>
<td>SaO₂</td>
<td>1.2% (P &lt; 0.05)</td>
<td>1.4% (P &lt; 0.05)</td>
</tr>
</tbody>
</table>

*45% (n = 15) of subjects reporting a headache were in the P filter group.

**Table IV.** Reported Health Effects After 60 and 120 min Bushfire Smoke Exposure

**Footnote:**

Source: American Conference of Governmental Industrial Hygienists (2007).

*45% (n = 15) of subjects reporting a headache were in the P filter group.

**Footnote:**

67% (n = 11) of subjects reporting a headache were in the P filter group.
Thirst

After the first 60 min smoke exposure, 15% of the participants (n=10) reported to be "quite a bit" to "extremely" thirsty, 63% (n=42) reported to be "slightly" to "moderately" thirsty, and 22% (n=15) was "not thirsty at all." After 120 min exposure, 13% (n=9) reported to be "quite a bit" to "extremely" thirsty, and 58% (n=39) reported to be "slightly" to "moderately" thirsty. Twenty-eight percent (n=19) were "not thirsty at all" after 120 min smoke exposure (Table IV).

Headache

Sixteen percent of the subjects (n=11) reported experiencing headaches at the first 60 min of smoke exposure; five (45%) of these belonged to the P filter group. Six individuals still reported headaches following 120 min of smoke exposure. Four of these (67%) belonged to the P filter group (Table IV).

Respiratory symptoms following 60 min smoke exposure

Thirteen percent of the subjects (n=9) reported increased coughing, wheezing, and shortness of breath following 60 min of smoke exposure while wearing a respirator (Fig. 6). A significantly higher proportion of these subjects were to the P filter (67%, n=6) group compared to the POV filter (22%, n=2) and the POV filter (11%, n=1) (P < 0.05) groups.

Respiratory symptoms following 120 min smoke exposure

Eighteen percent of the subjects (n=12) reported increased coughing, wheezing, and shortness of breath following 120 min of smoke exposure while wearing a respirator. A significantly higher proportion of subjects were in the P filter (64%, n=8) group compared to the POV filter (16%, n=2) and the POVF filter (18%, n=2) (P < 0.05) groups.

The odds ratios for increases in respiratory symptoms across the three types of filters were similar following 60 and 120 min of exposure (Table IV). However, there was no statistically significant difference observed between the POV and POVF groups.

Confounders

Potential confounders such as years in FESA, gender, smoking history, and asthma did not significantly contribute to the model.

DISCUSSION

In Phase 1 of this study, the effectiveness of these types of protective filters was investigated under controlled bushfire smoke conditions in a chamber (De Vos et al., 2006a). The study demonstrated that the POVF filter provided clinically and statistically significant better protection for the "fighters" respiratory health after 15 min controlled bushfire smoke exposure under described conditions. The present paper reports on the field validation under prescribed burn conditions (Phase 2).

Firefighters use the filters of interest on their respirator during bushfire fighting to prevent the inhalation of air toxics present in bushfire smoke. The Phase 2 measurements during the prescribed burns demonstrated that after 60 and 120 min bushfire smoke exposure, a significantly higher number of participants in the P filter group reported an increase in respiratory symptoms, such as coughing, wheezing and shortness of breath, compared to the other two filter groups. The failure to observe a statistically significant difference in respiratory symptoms between the POV and the POVF filter groups is consistent with the small differences in

![Figure 6](image-url)  
*Figure 6. Number of subjects with increased coughing, wheezing, or shortness of breath following 60 and 120 min of exposure to high levels of smoke while wearing a PVO, POVF, or P filter respirator.*

<p>| Table V. Odds Ratios for Increases in Respiratory Symptoms Across the Three Types of Filters |
|-----------------|--------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Comparison of Filters</th>
<th>OR (95% CI)</th>
<th>P-value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-60 min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P filter vs POV filter</td>
<td>0.55</td>
<td>0.02</td>
<td>0.004-0.057</td>
</tr>
<tr>
<td>P filter vs POVF filter</td>
<td>0.23</td>
<td>0.02</td>
<td>0.008-0.076</td>
</tr>
<tr>
<td>POV filter vs POVF filter</td>
<td>0.48</td>
<td>n.s.</td>
<td>0.36-0.66</td>
</tr>
<tr>
<td>0-120 min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P filter vs POV filter</td>
<td>0.43</td>
<td>0.00</td>
<td>0.05-0.358</td>
</tr>
<tr>
<td>P filter vs POVF filter</td>
<td>0.27</td>
<td>0.00</td>
<td>0.002-0.061</td>
</tr>
<tr>
<td>POV filter vs POVF filter</td>
<td>0.39</td>
<td>n.s.</td>
<td>0.14-0.59</td>
</tr>
</tbody>
</table>

*OR adjusted for FESA use, age group, pack years.

n.s. not statistically significant.
formaldehyde levels measured inside these two types of masks. It should be noted that those subjects who prior to the study "mostly" or "always" used a respirator while fighting bushfires, but who experienced an increase in respiratory symptoms while using a respirator during the study, could be individuals who were more sensitive to the effects of smoke exposure.

Declines in both FEV₁ and S_{aO₂} were observed after 69 and 120 min. However, these were not associated with a particular type of filter. It is also important to note that arterial oxygen measurements must be interpreted not absolutely, but in relation to the inspired oxygen concentration. A decline in S_{aO₂} may indicate the presence of high levels of carbon monoxide in the bushfire smoke. This is also important, given that prolonged exposure to high carbon monoxide concentrations may affect fire fighters' safety and cognitive functioning (Broekhoven et al., 1990).

Formaldehyde sampling inside the respirators demonstrated that the mean levels of formaldehyde inside the respirators fitted with P filters (0.44 mg/m³) exceeded the ceiling value of 0.26 mg/m³ (American Conference of Governmental Industrial Hygienists, 2007). The ceiling value is the concentration that should not be exceeded during any part of the working exposure. In addition, formaldehyde levels inside the respirators fitted with the P filters (0.44 mg/m³) were significantly higher than formaldehyde levels inside respirators fitted with P_{OV} (0.24 mg/m³) and the P_{OVF} filter (0.16 mg/m³). This may have explained the increase in respiratory symptoms for the P filter group.

There is conflicting evidence concerning the contribution of cigarette smoking to symptoms of airways obstruction in firefighters (Yoong et al., 1999; Lin et al., 1992). Although two smokers in the P filter group exited the field trial early due to shortness of breath and coughing, the numbers are too small to conclude from the current study that smokers are more vulnerable than non-smokers to the effects of bushfire smoke.

The study showed a discrepancy between some of the results from the smoke chamber compared to the field trials. In the smoke chamber, the number of participants reporting an increase in respiratory symptoms was significantly lower in the P_{OVF} filter group. Yet, in the field trials the number of participants reporting an increase in symptoms was comparable in the P_{OV} and the P_{OVF} filter group. A possible explanation for the variation in these findings may be related to the performance of P_{OVF} filter at higher exercise rates, which causes the peak airflow to increase. As a result, the residence time in the filter bed may not be sufficient long. In addition, there may be some channeling in the filter bed, thus exacerbating the problem (Kaufman and Hastings, 2001). The sorbent in the OVF filter may be more sensitive to this problem than the sorbent in the UV filter. Another possible explanation is that the OVF filter had exceeded its breakthrough time, since the same filter was used for the two consecutive exposure periods of 90 min.

A further explanation for the variation in the findings is the apparent dilution of the smoke in the field trials. The data suggest that the formaldehyde levels were three to five times lower than the prescribed values compared to the formaldehyde levels in the smoke chamber. In addition, carbon monoxide levels in the smoke chamber exceeded the STEL considerably during two trials. The reason for the high levels recorded in the smoke chamber is most likely due to the confined space in the chamber where pathways for ventilation were reduced, thus concentrating the various compounds. In the field trials, the dilution effect due to wind would account for lower values. This variability may in turn have resulted in smaller differences in respiratory outcomes between the P_{OV} and the P_{OVF} filter group in the field trials.

Combination filters are available to protect against particulates, as well as vapors and gases. The ability of sorbents to remove gases and vapors decreases as the sorbent becomes saturated with the contaminant, allowing additional chemicals to pass without being absorbed. If the sorbent is not replaced, 'breakthrough' occurs, and protection is diminished. The wearer may sense a odor, taste, or irritation from the contaminant penetrating the sorbents. Yet, this warning may not occur for some substances until undesirable concentrations have been reached in the inhaled air. Therefore, it would be extremely useful for fire fighters to have a reliable indicator to signal the breakthrough of the toxic gases and vapors. Although, various studies have developed predictive mathematical models to calculate breakthrough times for individual contaminants (Foutz, 1994; Wood, 1994, 2005; Yoon et al., 1996), it is extremely difficult to estimate accurate breakthrough times for complex mixtures (Yoon et al., 1996). This is complicated by numerous external factors, such as contaminant's chemical properties, contaminant concentration, humidity, temperature, breathing rate of the respirator user, and the variability of respirator filters between manufacturers. As a result, the service life of gas filters is a 'rule of thumb'; filters are replaced when the user senses an odor, taste, or irritation from the contaminates penetrating the filter.

The findings of this study may have been influenced by selection bias. This may occur when exposed and non-exposed individuals are selected in a way that leads to an inaccurate measurement of the association between exposure and disease (Choi, 2008). In the present study, selection bias may have arisen because of at least two major dynamics: (1) the selection process may have favored those who are healthier, and therefore attended, or conversely, those who are concerned about the health effects of smoke exposure, and therefore have chosen to participate; and (2) the fire fighters pre-conceptions regarding the efficacy of particulate filters. In order to minimize potential self-reporting bias caused by the participants' prior perceptions of the superiority of one of the three filters, the study filters were
as similar in appearance as possible, thereby effectively blinding the participants to the type of filter used.

The present study did not address workload factors such as job tasks, heat and physical exertion. In addition, the study did not incorporate the combined impact of stress of fire fighting and wearing respirators [Budd et al., 1997; Sharkey, 1997; Barnes, 1999] nor did it deal with the health effects associated with wearing respirators [Bollinger and Schutz, 1987]. Therefore, it has to be emphasized that the findings can only be interpreted only within the context of the experimental setting. This justifies the need for further research under more realistic conditions and for longer exposure periods, for example over a bushfire season or for a number of years. Personal factors such as fatigue and stress could therefore be taken into consideration, and the findings could be generalized to the broader fire fighting community.

Although a carbon monoxide filter is technically feasible, manufacturers have not thus far seen an adequate market to develop such a device for bushfire fighting. Bushfire fighters should be informed of the hazards of carbon monoxide and cautioned that currently available respirators will not filter this substance. Furthermore, they may expose themselves to higher levels of smoke when wearing a respirator than they would otherwise, thereby increasing their carbon monoxide exposure. It may be advisable, therefore, to use some form of carbon monoxide exposure monitoring in conjunction with POVF respirators.

In conclusion, testing the effectiveness of 37 F, 50 FOV, and 44 POVF filters under controlled and semi-controlled bushfire smoke conditions from 15 min up to 2 hr demonstrated that the FOV and POVF filter provides clinically and statistically significant better protection for the fire fighters’ eyes. Given these findings, and the fact that bushfire smoke may contain considerable levels of formaldehyde, it is suggested that FESA career fire fighters’ respiratory health would be best protected by the provision of the POVF filter. The filters are mainly used for high intensity short duration urban interface bushfires (Patto L, personal communications, 2007). The use of these filters is voluntary, yet most of the fire fighters choose to use them. FESA is currently considering whether or not to make the use of respirators and filters mandatory for all career fire fighters and is developing criteria to ensure distribution for volunteer fire fighters working in similar conditions.

ACKNOWLEDGMENTS

We thank the Fire and Emergency Services Authority of Western Australia, in particular the 67 fire fighters who participated in the exposure trials. Thanks to Respiratory Health of Fire Fighters Steering Group for their support and assistance in completing the research. We acknowledge the support from the Chemistry Centre Western Australia, Perth.

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Appendix 7: Media Statement
16 May 2007

Research shows new ways to reduce firefighters’ exposure to bushfire smoke

As bushfires burn throughout Australia virtually all year round, the role of the firefighter remains a difficult one. With an ever expanding rural-urban interface, firefighters are often involved in protecting property and apart from the intense heat and physical demands, firefighters may also be exposed to bushfire smoke that contains a cocktail of volatile compounds.

Research by Annmarie De Vos from the Bushfire Cooperative Research Centre (Bushfire CRC) has found that the types of face masks available for those at the fire-front vary greatly in their ability to shield the firefighter from particulate matter and the gases present in bushfire smoke.

A featured highlight at 2007 Cooperative Research Centres Association Conference Early Career Scientist Presentation, her research, conducted with the Fire and Emergency Services Authority (FESA) of Western Australia, assessed the effectiveness of a range of protective respiratory filters worn by firefighters required to remain in smokelogged conditions while protecting properties from fire.

“This study has resulted in FESA endorsing the use of a type of filter (a particulate/organic vapour/formaldehyde filter) for its career firefighters,” Annmarie said.

“There is evidence the presence of toxic compounds in bushfire smoke may pose occupational risks for firefighters. In particular, acute and chronic lung function impairment after exposure to bushfire smoke has been documented in the United States and Europe.”

This study involved controlled exposure trials in a smoke chamber for up to 15 minutes, followed by trials in the field during fuel reduction burns for up to two hours. A total of 131 FESA career firefighters participated in the trials – 37 wore particulate filters (P2), 59 particulate/organic vapour filters and 44 particulate/organic vapour/formaldehyde filters. Lung function and respiratory health symptoms were assessed by a questionnaire, lung function test and oxygen measurements. Personal air sampling was also conducted inside the masks.

Withdrawal from smoke conditions is always the best action but when firefighters cannot withdraw and need to remain in bushfire smoke to protect structures, Annmarie’s research showed that the particulate/organic vapour/formaldehyde filter allowed firefighters to work with a higher degree of comfort in smoke logged conditions.

Further research is now needed to determine the effectiveness of the filters over longer periods, such as a longer working shift or even for a full bushfire season. Annmarie’s study is part of a group of Bushfire CRC projects looking at the overall health and safety aspects of fighting bushfires.

Annmarie is conducting her Bushfire CRC research at the School of Population Health at the University of Western Australia.

Bushfire CRC was established in 2003 to improve understanding of the complex social, economic and environmental aspects of bushfires. Its partners include fire and land management agencies across Australia and New Zealand, universities, and government agencies including the CSIRO, Emergency Management Australia and the Australian Bureau of Meteorology.

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