



**OUTCOME:** 18. Increased Fire Fighter Health, safety and Well-Being

**OUTPUT:** 18.2. Capabilities for measurement and control of the exposure of fire fighters to air toxics

**MILESTONES:** 18.2.1. Results of field trials of air analysis procedures and personal sampling rig available

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# **Manual of Methods and Procedures for Measuring Personal Exposures of Bushfire Firefighters to Air Toxics.**

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## EXECUTIVE SUMMARY

The Bushfire CRC project D2.2 aims at measuring, evaluating and controlling the personal exposures of firefighters to air toxics that are present in bushfire smoke. Field measurements are required in order to better understand the frequency and magnitude of exposure to air toxics, to identify situations with high exposure risks and to determine the key factors that lead to high exposure levels. The objective of this manual is to provide information on the personal sampling devices used to collect data, how monitoring procedures are set up to take into account the various key factors that are likely to affect exposure levels and how exposure levels are assessed.

The personal sampling devices that will be used for field measurements are:

- A Draeger PAC IIIIE carbon monoxide datalogging device, which will be used on 3-5 firefighters over full work-shifts, supplemented in some situations (e.g. accidental fires where data can be collected for up to 20 firefighters) by Gastec CO colorimetric tubes and the micro Smokerlyzer<sup>®</sup> or pico Smokerlyzer<sup>®</sup>.
- A UMEx passive sampling badge for aldehyde measurements.
- A PAS-500 Micro Air sampler which is fitted with a charcoal tube holder for Perkin-Elmer preppacked sorbent tubes. The VOC samples are collected at 10-15 ml/min, followed by thermal desorption on a GC/MS/FID for analysis.
- pDR passive light scattering particle monitor, which will be used to measure respirable particles on 2 firefighters over full work-shifts, supplemented by gravimetric sampling with programmable AirCheck pump for approximately 2 hours of shift. PAH analysis of the particles will be carried out on the gravimetric filter samples to estimate BaP levels and assess the carcinogenicity of the bushfire smoke particle.
- TSI SidePak, a laser photometer with an in-built pump for active respirable particle sampling. The SidePak will only be used in areas away from the fire field (e.g. staging area or downwind areas).

For each fire event, the aim is to monitor 3-6 firefighters, who will be asked to wear the above mentioned personal sampling devices. The personal exposure measurements will take into account work activities, fuel characteristics (fuel type, load and moisture) and meteorology.

Personal air monitoring data will be assessed relative to legislative requirements using an occupational hygiene approach which aims to control the exposures to bushfire air toxics to acceptable levels within Australian legislative framework. The exposure standards are presented as time-weighted average (TWA) concentration, which is the average airborne concentration of a particular substance when calculated over a normal eight hour working day for a five day working week; short-term exposure limit (STEL) which is a 15 minute average exposure which should not be exceeded any time during the working day, even if the TWA is not exceeded; excursion limit concentration, used where peak or STEL concentrations are not specified and the TWA exposure is not exceeded. These exposure standards need to be adjusted to take into account the longer workshifts and harder workloads of bushfire firefighters as well as the complex nature of bushfire smoke.

## **1 Introduction**

Bushfire firefighters face a range of hazards in their occupation, and procedures are generally in place to manage these hazards. However, one hazard for which there is little control is their exposure to toxic air pollutants that are released during bushfires. A review of Australian and international literature has determined the key air toxic species to which bushfire firefighters may be exposed to, being; carbon monoxide, volatile organic compounds (VOCs), and a range of respiratory irritants, including aldehydes and respirable particles. Acute exposure to high levels of these toxic gases and respirable particles may affect the immediate performance and decision-making of bushfire firefighters. Additionally, long-term health effects may be observed due to the ongoing exposures of firefighters to carcinogens and lung irritants present in the bushfire smoke. In order to develop control strategies to minimize their exposure to air toxics, it is essential to measure and evaluate their exposures. The measurements need to be carried out within the breathing zone of the firefighters, so as to monitor the air the firefighters breathe. Therefore sampling devices that measure the various toxicants need to be worn by the firefighters during their work shift. .

Personal measurements of bushfire firefighters to air toxics have been primarily carried out in the United States in the 1990s (Kelly, 1992a; Kelly, 1992b; Reh and Deitchman, 1992; Reh et al., 1994; Reinhardt and Ottmar, 2000; Reinhardt et al., 2000). Only a few Australian studies looked at the exposure of bushfire firefighters to carbon monoxide (Brotherhood et al., 1990). Since those studies, newer and more reliable sampling devices have become available.

## **2 Objective**

The first part of this manual describes and assesses a range of personal sampling devices that are commercially available and monitor the air toxics of interest. It discusses the advantages and disadvantages of the various sampling devices and the final choice for a particular sampling device depended on several criteria which were:

- Comfortable, easy to wear, lightweight and non obstructive
- Robust to withstand harsh field conditions (heat, dust, smoke)
- Specific to selected air toxics
- Supported by reliable analysis methods.

The second part of the manual describes the procedures of measuring personal exposures. The aim is to monitor air toxics so that exposure levels can be assessed according to exposure determinants, which include work task, fuel characteristics, meteorology and fire characteristics. Additionally area sampling will also be carried out, which will help to assess exposure levels of fire fighters if they potentially stay in smoke-logged areas (eg staging areas, base camps, or motels)

### 3 Personal sampling devices

#### 3.1 Carbon monoxide

Carbon monoxide is a toxic gas that is commonly measured in bushfire smoke. Adverse health effects that are observed include headaches, dizziness, nausea, impaired exercise capability and judgement and potentially exacerbation of respiratory and cardiac diseases. The concern about acute overexposure to CO is not so much due to lethal exposure levels, but rather a concern about the previous-mentioned CO-induced symptoms, which may lead to inappropriate work behaviour and potentially increased risk accident frequency. Therefore it is essential to monitor firefighters exposure in order to minimize their intake of CO. Furthermore, exposure of pregnant women to elevated levels of CO may affect foetal development.

##### 3.1.1 Draeger PAC III E



The Draeger PAC III E is a battery-operated, pocket-size data-logger, which is equipped with an **electrochemical sensor** measuring CO levels in air up to 2000 ppm. It has alarm capabilities which can be set to a specified concentration. It can calculate and display the time-weighted average (TWA) and the Short-term exposure level (STEL). The device continuously logs data for approximately 20 hours at a logging interval of 10 seconds. The data is stored for subsequent analysis on a computer. The Draeger data logger has been used to measure personal CO exposure of firefighters in wildfires in the US (Reinhardt and Ottmar, 2000; Reinhardt et al., 1999; Reinhardt et al., 2000). They tested the Draeger data logger to Method 128, which used inert gas sampling bags to collect CO (Lodge, 1989). Their results showed that the data logger was very precise, but underestimated CO levels by about 20%. This negative bias could be overcome through more frequent calibration and quality assurance checks. Therefore it is recommended to perform quality control checks prior to and after sampling to ensure the validity of the data. Prior to sampling, it is also recommended to let the device warm-up for at least 30 min and if the battery is changed for at least 10 hours.

Furthermore they noticed that the data logger was sensitive to direct sunlight, resulting in false readings of 5 ppm CO. Keeping the data logger out of direct sunlight corrected the problem. Even though the sensor operates at temperatures of -20°C to 55°C, at elevated temperatures (40°C-50°C) the probability of measurement error increases. Again frequent calibration and quality control checks can overcome this problem.

Calibration of Draeger PAC IIIs should be carried out for each series of site measurements and at least weekly.

##### 3.1.2 Gastec CO Colour Dosimeter tubes



The dosimeter tubes are easy-to-use diffusion samplers, and are lightweight, economical and provide direct-reading of exposure levels. Concentration range: 50-2000 ppm-h for sampling time 0.5-48 hours. For a 4 hour shift sample a concentration of 12 ppm is measurable; for 8 hours, 6 ppm. The air diffuses into the tube



which contains a palladium salt that reacts with CO resulting in a colour change.

The dosimeter tubes have been tested in experimental burns of forest fuels in CSIRO burn chambers. The results showed good agreement between the average CO concentration measured with a TSI QTrak CO monitor and the TWA determined on the CO Colour Dosimeter tube (Appendix Table 2). CO dosimeter tubes were also used by NIOSH investigators to measure personal CO exposure levels of firefighters during wildfires in Wyoming (Reh and Deitchman, 1992), California (Reh et al., 1994), Montana (Kelly, 1992a) and West Virginia (Kelly, 1992b).

### 3.1.3 Smokerlyzer



The Smokerlyzer is a small and lightweight battery-operated breath CO monitor, which can be used to measure the CO inhalation dose from bushfire smoke as well as from cigarette smoke (if applicable). The CO ppm reading that is displayed can be easily converted to % carboxyhemoglobin (COHb). Hence it provides on-the-spot CO levels in blood, and could potentially determine whether it is safe to send a firefighter back into the smoke. The half-life of CO in the body is about 4-5 hours. Smokers are at higher risk for reaching critical levels of %COHb. One of these instruments - Ecolyzer 2000 -

was the instrument used by Brotherhood (Brotherhood et al., 1990), and was also used in one of the NIOSH investigations (Reh et al., 1994).

A disadvantage of the smokerlyzer to a CO datalogger is that for the post-shift measurement, time is critical for a proper evaluation of COHb levels. In fact CO has a half-life time of about 4-5 hours, which means that COHb is metabolized at a fairly rapid rate. Therefore it is critical to minimize the time between the end of the shift on the fireline and the measurement. It frequently happens that the staging area, where crews are returning after their shift and where COHb reading will be done, can be 1-2 hours away from the fireline. During that time some of the COHb may already have been metabolized, resulting in a lower reading to what the exposure might have been at the fireline

### 3.1.4 Choice

The Draeger datalogger provides essential information as it continuously measures and logs the CO concentrations relative to time of exposure. Furthermore it provides average and peak exposure levels. The results, which can be stored, analysed and graphed on a computer, present an essential tool to recognize hazardous exposure levels and could potentially be used later on to assess effectiveness of control strategies. The TWA can be used by fire managers to decide whether it's safe to send a firefighter back into the smoke, whereas the graph could be useful in identifying scenarios or job tasks that result in hazardous CO exposure levels. It could be a tool for firefighter training to recognize under what conditions (which could be task or weather related) hazardous levels would be reached and help them minimize their exposure.

Even though the dosimeter tubes are only able to provide TWA measurements, they are very useful to determine on-the-spot a person's exposure levels. The tubes are cheap, lightweight, non-obstructive, requiring no special training or analysis and hence could be easily clipped on each firefighter.

The smokerlyzer could also be an essential tool to be used on the fire ground. In fact it would provide additional information to the Draeger data logger and be useful in preventing hazardous smoke exposure. Since the device is not worn by the firefighter, potentially (time dependent) each firefighter returning from the fire ground could be tested for CO inhalation. The smokerlyzer provides on-the-spot measurements which could be used in making safe decisions on the fire ground as to whether to send a firefighter back into the smoke or not. Base-camps are often located in smoke-logged areas, where CO concentrations can be quite elevated. Therefore checking the COHb levels of firefighters indicates whether their rest time was sufficient to metabolize CO.

The smokerlyzer could also be very useful during accidental fires where the wearing of sampling devices may not be easily accepted by firefighters. Having their CO exposure checked before they head out to the fire ground and after they come back, enables us to get an evaluation of their exposure levels while working on the fireground. However, it is essential to be aware that depending on the travel time between the staging area and the fire ground, CO readings may not be reliable to evaluate a fire fighters exposure to CO on the fire ground.

US studies have shown that CO correlates well with the other pollutants. If the same holds true for Australian bushfires, checking CO exposure levels may be used in evaluating exposure levels to the remaining pollutants.

### **3.2 Aldehydes**

The major aldehydes that have been measured in bushfire smoke are formaldehyde, acetaldehyde and acrolein. They are primarily responsible for eye, nose and throat irritation at the fire ground, and, if present at elevated levels, could aggravate existing respiratory conditions including asthma. Furthermore, formaldehyde has been classified by the IARC as a known human nasal carcinogen and acetaldehyde is a probable human carcinogen. The sampling devices considered for measuring personal exposures to aldehydes are listed below.

#### **3.2.1 Active DNPH filter cassettes**

The air is sampled onto a 37 mm glass-fibre filter impregnated with 2,4-dinitrophenylhydrazine (DNPH) at a sampling rate of about 0.5 L/min. The recommended maximum air volume sampled is 120 L. This technique requires a personal sampling pump and it is likely that problems of filter blockage by smoke particles may occur if used over an extended time. After sampling, the filters are sent to a laboratory for HPLC analysis of the aldehyde-DNPH adducts. The method is very specific for each aldehyde, but has the disadvantage of requiring a sampling pump and tubing which may hinder firefighters during their work tasks.

### 3.2.2 Passive sampling

A range of passive sampling methods have been considered:

#### - **UMEx 100 passive sampler**



The UMEx 100 passive sampler is a small badge made of tough polypropylene. Each badge includes a “blank” section in addition to the active sampling section. The air diffuses through the diffusion barrier onto the active sampling site, which includes a tape treated with 2,4-DNPH. The aldehydes react with 2,4-DNPH to form a stable derivative which is desorbed in acetonitrile and analysed by HPLC. The UMEx passive sampler has a wide concentration range from 5ppb-5ppm. It has been tested for HCHO uptake and performance tests have also been carried out for glutaraldehyde and acetaldehyde. It is easy to use, requires no technical training or sampling pumps. The average uptake rate for formaldehyde is 28.6 ( $\pm 18\%$ ) ml/min if sampling occurs for 15 min to 24 hours. The average uptake rate drops down to 20.4 ml/min if sampling occurs over a one-week period. The uptake rate is reported to be independent of humidity (10-80%) and air velocity effects (0.05 -1.0 m/s). (Sampling rate determination: Mary Eide, Methods Development Team, Industrial Hygiene Chemistry Division, OSHA Salt Lake Technical Center, Sandy UT 84070-6406). HPLC detection per filter is  $\sim 0.5 \mu\text{g}$  and at the above sampling rates, the UMEx sampler should be capable of detecting aldehyde concentrations over 4 hours of  $70 \mu\text{g}/\text{m}^3$  (occupational exposure standards are usually 360-1200  $\mu\text{g}/\text{m}^3$ ). The badges require freezer storage before use and should be refrigerated after use for no longer than 3 weeks before being analysed.

#### - **Piezoptic personal dosimeter - formaldehyde**



Similar to the UMEx passive sampler, the piezoptic badge also relies on passive diffusion into the entry ports on the front of the badge. However, unlike the UMEx badge, the piezoptic badge does not require laboratory-based analysis. In fact, the formaldehyde that diffuses through the badge irreversibly reacts with a colour-forming chemical. The colour change is quantitated by the piezoptic analyser immediately after sampling. The badge is lightweight, simple to use and provides instantaneous results. The operation conditions for the badge are 10-35°C and 30-70% RH. It can analyse for formaldehyde only at a measuring range of 0.25-4.0 ppm. The badges have a 6 months lifetime when stored in the freezer. The badges should not be stored at room temperature or exposed to excessive heat. A calibration badge is measured with each batch of measurements and has a 1-2 year lifetime.

The badge needs to be read immediately before and after sampling to record the colour change. The badge commenced sampling immediately when removed from its sealed bag. The analyser has to be at the monitoring site, since the badges cannot be stored or mailed for later measurement.

#### – GasTec HCHO Colour Dosimeter Tube

The dosimeter tubes are easy-to-use, lightweight, economical and provide direct-reading exposure levels according to a yellow-reddish brown stain. Concentration range: 1-20 ppm-h, i.e. for a 4 hour sample, concentrations of 0.25-5ppm can be measured. Interfering species are acetaldehyde, MEK and furfural. Other aldehydes, ketones and acid gases can cause reddish brown stains.

The dosimeter was less sensitive than other methods when compared in the burn chamber tests. There was no clear reading of colour change for 1-2 hour exposure to ~0.1 ppm. In 2 experiments, a yellow streak was observed along the tube indicating some interferences from the other smoke constituents.

#### – SKC Formaldehyde passive sampler



The HCHO passive sampler relies on controlled diffusion of air onto a paper impregnated with sodium hydrogen sulfite. The HCHO reacts with the chemical to form a stable formaldehyde bisulfite, which is analysed in the laboratory by chromotropic acid analysis. There are two types of badges: the PEL and the STEL model differing by their membrane size, which is 2.7 times larger for the STEL sampler. The detection range for 8 hour exposure is 0.2-2 ppm for the PEL sampler and 0.5-6 ppm for the STEL sampler. The sampler has been validated by manufacturers and is reported to have

no known interferences from other substances. The badge is inexpensive, lightweight, small, easy-to-use with a shelf-life of 1 year.

#### 3.2.3 Choice

Preference is given to the passive sampling devices since there is no issue of potential filter blockage, and no personal pumps are required. The passive samplers are lightweight and non-obstructive to the firefighters. Since acrolein and acetaldehyde are present in the bushfire smoke and are likely to contribute to the irritant effect of bushfire smoke, it is preferable to use a sampling device which analyses for a range of aldehydes. Therefore the piezoptic badges and the formaldehyde passive samplers have not been considered for use.

We have tested the UMEx badge during experimental burns of forest fuels at the CSIRO burn chambers. The results have shown good agreement between active and passive sampling for formaldehyde and acrolein (Appendix Table 3). A slight decrease in concentrations was observed if sampled over 4 hours and therefore there may be an underestimation of formaldehyde and acrolein levels if measured over an 8-hour workshift. The acetaldehyde levels observed for the UMEx badge were about 5 times higher than those measured with the active sampling, leading to an overestimation of acetaldehyde exposure –we have no explanation for this discrepancy.

### 3.3 Volatile Organic Compounds (VOCs)

Incomplete combustion of vegetation litter releases a range of volatile organic compounds which may cause headaches, dizziness, fatigue and eye, nose and throat

irritation. Major VOCs that have been measured in bushfire smoke include benzene, a known human carcinogen, toluene, xylenes, phenol and furaldehyde.

### 3.3.1 PAS-500 Micro Air sampler



The PAS-500 Micro Air sampler is a battery-operated micro pump, with a flame retardant nylon case. It is fitted with a charcoal tube holder for Perkin-Elmer prepacked sorbent tubes, which are analysed by thermal desorption on a GC/MS. The sampler is lightweight, small, clips easily into a pocket and does not require any tubing. The flow ranges from 5-200 mL/min and is fully regulated between 20-150 mL/min. The operation temperature ranges from 0-50°C. The sampler requires minimal maintenance. However, since the VOC analysis is by GC/MS, it is essential to collect sufficient sample for analysis but not too large a sample that the GC/MS is overloaded (we aim for single VOC masses ~100-1000 ng to the MS, so with a 10% split the VOC collection per sorbent tube should be 1000-10,000 ng). If we assume a high end VOC concentration of 3000 µg/m<sup>3</sup>, then the volume of air sampled should be ~3000 mL and the flow rate over 8 hours ~10 mL/min. The PAS-500 Micro Air samplers have been modified with flow restrictors and operated for several hours to ensure that this low flow is achievable and stable over workshift periods for analysis by GC/MS.

### 3.3.2 Passive samplers

A range of passive samplers have been developed to collect organic compounds without the use of pumps and tubing. The passive samplers are small badges that collect organic vapours by molecular diffusion at a fixed rate.

#### – **SKC passive sampler for organic vapours (575 Series)**



The SKC passive samplers are solvent-based badges. The organic compounds diffuse at a fixed rate onto the sorbent, which can be charcoal, anasorb 747 or anasorb 727. The use of a selected sorbent is necessary to ensure that no reverse diffusion occurs for the adsorbed chemicals. Therefore it is critical to use a strong sorbent medium to assure complete capture and retention of organic compounds. Various factors such as concentration, time of exposure, sorbent strength and

capacity, environmental conditions (wind, temperature, humidity), interfering chemicals, reverse diffusion and sampler orientation affect complete sample uptake and retention. After sample collection, the organic vapours are removed from the sorbent by solvent extraction and then analysed by GC/MS. The detection limits are in the 200-500 ng range. The badges meet OSHA precision and accuracy requirements for passive samplers.

#### – **3M Organic Vapour Passive Air Monitoring Badges**

The 3M passive badges use a single charcoal wafer for collection of organic vapours.



Similar to the SKC passive sampler, the 3M samplers also require solvent extraction for analysis by GC/MS.



#### – SKC Ultra passive sampler (590 Series)

The Ultra passive sampler is a small badge that provides reliable and easy collection of low ppb-level VOCs. The VOCs diffuse at a fixed rate into the sampler, which is filled with 265 mg Tenax TA or 285 mg Chromosorb 106. Unlike the other passive badges, this sampler is a thermally desorbable badge. After sample collection, the sorbent is transferred to a tube, which is then thermally desorbed onto a GC/MS. Since it does not require solvent extraction, its detection limits are much lower, in the 1-2 ng range. The sampler has been tested by OSHA and found to be suitable for 8-hour sampling.

#### 3.3.3 SXC-20 VOC monitor



The SXC-20 VOC monitor is an active total VOC detector equipped with a quantitative sampler and data-logger. It weighs approximately 1 kg and detects up to 100 VOCs. The presence of a VOC will quantitatively change the electrical resistance and transmit a voltage signal. It is fitted with a colour bar display which immediately indicates hazardous levels and an alarm which can be set for a specified concentration of VOCs. The built-in data-logger records the duration and levels of VOCs present. The data can be graphed on the computer for analysis. When elevated VOC levels are measured, a second pump can be activated to take samples onto a charcoal sorbent tube. The tube can then be analysed for specific VOCs by GC/MS. The flow ranges from 40-200 cc/min and can be easily adjusted. Major problems with the device are that it also detects CO and the sorbent sampling pump will operate until the end of the shift and may overload the sorbent. These problems were considered severe making the instrument of no use for bushfire smoke measurements.

#### 3.3.4 Choice

We have opted for the active sampling micropump device, as the sorbent tubes can be thermally desorbed and therefore offer greater analytical sensitivity and lower detection limits. In fact the solvent extraction dilutes the collected sample and it is probable that the more volatile VOCs are lost during the extraction. The active sampling is also preferred to the ultra passive sampler badge, as it does not have to rely on diffusion rates and has no problems of face velocity and reverse diffusion, which may be of concern when using passive samplers. There may be some issues with the micro pump in regards of excessive sampling volumes for high VOC levels, though this may be further compensated in analyses with the Perkin Elmer ATD by modifying the desorption split ratio.

### 3.4 Respirable particles

Respirable particles can settle deeply in the gas exchange regions of the lungs and are not ejected by exhalation, sneezing or coughing, or removed by ciliary clearance. They may impair lung function and exacerbate cardiac and respiratory illnesses. Since only a fraction of the inhaled particles deposit in the lungs, respirable samplers are designed to mimic particle penetration. According to ACGIH, NIOSH, ISO and the European Standard Committee (CEN), a respirable collection efficiency curve has a 50% cut-out point of 4  $\mu\text{m}$ , which means that 50% of the 4  $\mu\text{m}$  particles are collected and the other

50% penetrate through the sampler. The following personal samplers are designed for collecting respirable particles.

#### 3.4.1 Gravimetric sampling

Gravimetric measurements require the use of a cyclone, which separates particles according to their size, and a personal sampling pump. Respirable particles are collected onto a filter, with a size cut-point depending on sampling rate, whereas larger particles fall into the grit pot.

##### Cyclones



The **SKC Aluminium Cyclone** is used with a 25 mm filter loaded into a 3-piece filter cassette. The cyclone is made of conductive aluminium to eliminate adverse electrostatic effects and collect particles more efficiently. The cyclone needs to be used at a flow rate of 2.5 L/min in order to match the respirable collection convention curve.



The filters used with the **SKC Conductive Plastic Cyclone** are loaded in reusable plastic filter cassettes, which are held securely in place within the plastic unit of the cyclone. The conductive plastic eliminates electrostatic problems. The flow rate is set at 2.2 L/min for a 50% cut-point of 4 µm. The filter cassettes are easy to transport and can be easily changed in the field without incurring the risk of dust contamination.

##### Respicon Particle Sampler



The respicon is a multi-stage, virtual impactor that collects particles onto 3 individual 37 mm glass fibre filters according to particle size. The first impactor separates out particles smaller than 4 µm (respirable fraction), the second filter collects particles below 10 µm (thoracic fraction) and the remaining particles (larger than 10 µm, inhalable fraction) are collected on the third filter. The particle size separation allows sampling for an extended period of time without encountering problems of overloading filters. The respicon is compact and lightweight (290 g) and permits gravimetric and chemical analysis of respirable particles. It requires a personal sampling pump that needs to operate at 3.11 L/min.

##### Filters

A range of filters are available for gravimetric measurements. The following filters have been tested in the chamber burns of forest fuels:

- Millipore Corporation FA Teflon membrane filters (nominal pore size 1 µm)
- Gelman Sciences GLA 5000 PVC membrane filters (nominal pore size 5 µm)
- Millipore Corporation glass microfibre filters (nominal pore size 1 µm)
- Pall Corporation Type A/E glass fibre filters (nominal pore size 1 µm)
- Pallflex Emfab filters, borosilicate glass microfibres reinforced with woven glass cloth and bonded with PTFE

The membrane filters became blocked at high smoke levels. The glass microfibre filters were very delicate and may not be reliably weight stable. The glass fibre filters were able

to collect up to 6 mg of particles before the sampling flows were affected (Appendix Table 4). This may be an issue when collecting personal gravimetric samples in the bushfire smoke. The use of a programmable pump (see below) would overcome this issue.

The gravimetric measurements have the advantage of providing a sample of the particles suitable for analysing composition, in particular determining the levels of PAHs present in the bushfire smoke. Worksafe Australia required that for certain complex coal-derived substances, classification as a carcinogen need not apply if it can be shown that the substance contains less than 0.005 % w/w benzo[a]pyrene. If this criterion is applied to bushfire smoke, the amount of smoke particles for this analysis can be estimated:

- Detection limit for BaP 0.25 µg per sample
- BaP content limit for carcinogen classification 50 ppm
- Minimum sample weight required = 5 mg.

Thus, it is feasible to determine BaP levels in the smoke gravimetric sample for the purpose of classifying the bushfire smoke as carcinogenic or not.

#### 3.4.2 Data-logging, light-scattering devices

The light-scattering devices measure respirable particles in real-time and are able to log the data for subsequent analysis. Their optimal response is for particles in the size range of 0.1-10 µm.

##### a. **Sidepak,**



The SidePak is a compact laser photometer with an in-built pump for active particle sampling. The flow can be easily adjusted, but should be run at a flow rate of 1.7 L/min for accurate measurements with a respirable 10 mm nylon Dorr-Oliver cyclone (50% cut-off at 4µm). It displays the real-time aerosol mass concentrations as well as the 8-hour time weighted average (TWA). It logs data at 10 second intervals for up to 3.5 days. Temperature range for operational status

is 0-50°C. It is recommended to do a zero calibration before each use and an annual factory clean and calibration.

The major disadvantage of the SidePak is that it measures particle concentrations up to only 20 mg/m<sup>3</sup>. These levels can easily be exceeded in bushfire smoke.

##### b. **pDR,** active and passive sampling device



The personal DataRAM (pDR) is a battery-operated light-scattering device which can be used for passive (pDR-1000AN) or active (pDR-1200) air sampling. It can measure real-time mass concentrations as high as 400 mg/m<sup>3</sup>. It is compact, lightweight (0.5 kg for passive device and 0.68 kg for active sampling device) and easy-to-use. The device logs the data for about 37 hours with a logging interval of 10 seconds. Zero calibration can be easily carried out in the field using the zeroing kit. It is essential to do a zero calibration particularly in settings where PM levels

are low. The sampler is equipped with alarms which can be set at specified



concentrations. The operating environmental conditions are -10 to 50°C and 10-95% relative humidity.

For the passive sampler, the air enters the sensing chamber by convection, diffusion and simple air motion. On the other hand, the active sampler requires a personal sampling pump, and includes a particle size-selective inlet cyclone. For accurate measurements of respirable particles with a 50% cut-point at 4 µm, the pump needs to be set at 2.7 L/min. Downstream of the sensing chamber, a 37-mm filter cassette can also be attached for gravimetric sampling and subsequent chemical analysis. A standard calibration, e.g. zeroing and span checking, should be performed before sampling. Maintenance requirements are minimal. The sensing chamber requires cleaning when a “Background high” message is displayed during the zeroing process.

We conducted tests in which we burned forest fuels in CSIRO burn chambers. The results showed that there was good agreement between the data obtained from the passive pDR sampler and the measurements received from the active TSI DustTrak particle monitor (Appendix Table 5). The readings often exceeded 20 mg/m<sup>3</sup> during the tests and therefore a comparison of the TSI SidePak to the TSI DustTrak monitor could not be achieved.

Several studies have evaluated the use of passive and active pDR as an indoor, outdoor and personal particle measurement device (Chakrabarti et al., 2004; Liu et al., 2002; Rea et al., 2001; Sioutas et al., 2000). Liu et al (2002) compared two light-scattering devices, the Radiance nephelometer (neph) and the personal DataRAM (pDR). They showed that at low concentrations, the pDR was not as precise as the neph. The passive pDR's precision however increased with higher PM concentrations. In a study conducted by Chakrabarti et al (2004), the precision of the active pDR was found to be very good (2.1%). It performed better at low relative humidities, and overestimated particle levels at high humidity. However using a correction factor for higher humidities remedied the problem. Similar findings were reported by Muraleedharan and Radojevic (Muraleedharan and Radojevic, 2000) where considerably higher levels were measured with the pDR compared to a tapered element oscillating microbalance (TEOM) PM<sub>10</sub> monitor. This discrepancy was related to the higher scattering coefficient at RH above 60%. Liu et al (2002) found that the pDR correlated well with the 24-hour integrated gravimetric measurements, but observed a general overestimation of PM readings. This overestimation was also reported by Quintana (Quintana et al., 2000) and Howard-Reed (Howard-Reed et al., 2000). High relative humidity seems to be partly responsible for affecting the performance of light-scattering devices, but only significantly at RH greater than 85% (Quintana observed a significant increase in particle readings at RH greater than 85%). In order to correct for RH issues, Sioutas et al (2000) modified the pDR by attaching a diffusion drying tube to the sampling line. Their results showed very good agreement between the DataRAM and MOUDI gravimetric measurements at low humidity and an increasing discrepancy at higher RH levels. Their measurements showed higher readings for the pDR compared to the MOUDI gravimetric measurements. This difference was independent of humidity effect or chemical composition of the particles. They observed that the particle size significantly affects the pDR readings. pDR has the most efficient light-scattering for particle ranging in size from 0.3-0.7 µm. Therefore the pDR underestimates particle levels when mass fraction of ultrafine particles is significant

and overestimates PM levels by 30-40% for particles of size ranging between 0.5-1.2  $\mu\text{m}$ . Similar findings were reported by Chakrabarti using the active pDR sampler. The gravimetric results from the filter attached to the pDR are in very good agreement to the gravimetric measurements using BAM (Beta Attenuation Monitor). However correlation was not very good between the gravimetric measurements by the back-up pDR filters compared to the continuous light-scattering measurements and this was primarily related to particle size. Lanki (Lanki et al., 2002) also observed that particle concentrations measured by similar photometers were on average 1.37 times higher than those measured gravimetrically.

The chamber burns have shown that the ratio of particle concentrations measured by photometers to those measured gravimetrically ranged from 1.6 to 7.9

In general, the studies concluded that there was a good correlation between pDR and gravimetric measurements, in particular with  $\text{PM}_{2.5}$  impactors. The integrated filter data was found to be similar to the continuous PM concentrations measured by light-scattering monitors (Rea et al., 2001). Chakrabarti et al (2004) also concluded in their study that the pDR would be sufficiently precise and accurate for use as a personal monitor.

The major advantage of laser-scattering devices is that they continuously monitor the personal exposures to respirable particles, unlike gravimetric sampling which measures only the total mass over a sampling period. Therefore laser-scattering devices can provide useful information about job activities that cause exposure to elevated levels of respirable particles. However gravimetric sampling is essential as well, as it will provide data by which to calibrate the response of the laser-scattering devices and it is the only way to provide a sample for determining particle composition.

### 3.4.3 Pumps



The AirChek 2000 Pump is a programmable pump which allows the user to set up a personal sampling schedule. Various flow rates and times at which the sampling pump is activated can be programmed. The data can be downloaded later on and provide a complete documentation of the sampling history. The pump has built-in sensors to automatically correct the flow rates for variations in temperature and pressure. The pump weighs 624 g and operates at a flow rate between 750 and 3250 ml/min. At a flow rate of 2 L/min, the water back pressure is 30 inches, dropping to 20 inches if flow rate is increased to 2.5 L/min. The pump operates on rechargeable batteries for up to 10 hours. If the filters block up and the flow drops by more than 5%, the pump will stop and attempt to restart every 5 min up to 10 times. It saves data which includes its run-time and this enables determination of when sampling was halted.

The programmable pump is considered to be useful for collecting personal gravimetric particle samples. The schedule could be set up to allow for a 2 hour sample collection over an 8-hour work shift. There is the risk that the pump may not capture the highest particle levels, but it would give a good overall average of personal exposures to respirable particles and their composition.



The Airlite pump is a battery-operated small, lightweight (340 g), and economical sampling pump, which operates at a flow rate ranging from 750-3000 ml/min with full back pressure compensation. The pump will stop if the flow is blocked for more than 10 seconds and will attempt up to 5 times to restart after 10 seconds. However, unlike the AirChek2000 pump, it will not show at what time the pump stopped working.

### 3.5 Summary

The CRC Bushfire Air Toxics Project (D2.2b) will use the following methods/procedures for measuring firefighter exposures to bushfire smoke:

- CO by Draeger PAC IIIE datalogging devices on 3-5 firefighters over full work-shifts, supplemented in some situations (e.g. accidental fires where we can collect data for up to 20 firefighters) by Gastec colorimetric tubes and the micro Smokerlyzer<sup>®</sup> or pico Smokerlyzer<sup>®</sup>
- Aldehydes by the UMEx passive sampling badge
- VOCs by micropump sampling onto Perkin-Elmer/Marques 'air toxics' sorbent tubes at 10-15mL/minute, followed by thermal desorption GC/MS/FID analysis
- Respirable particles by TSI Sidepaks for areas away from the fire field (e.g. staging area or downwind areas)
- Respirable particles by pDR passive sampler on 2 firefighters over full work-shifts, supplemented by gravimetric sampling with programmable AirChek pump for <2 hours of shift on 1 of these firefighters
- Respirable particles by gravimetric sampling with programmable AirChek pump for <2 hours of shift on 2 firefighters; PAH analysis of the particles to be carried out on these and above filter to estimate BaP levels.

### 3.6 Maintenance

Minimal maintenance is required for the majority of the sampling devices.

#### 3.6.1 Carbon monoxide

The datalogger requires little maintenance. The internal filter (order no. 68 10 378) should be replaced regularly. Its service life is approximately 5000 ppm × hours of contaminant gases (hydrogen, ethylene). Furthermore as mentioned previously a zero check and a quality control check should be carried out regularly, using a certified nitrogen or air gas tank and a certified standard calibration gas of 100 ppm CO, respectively. If 100 ppm is > 5% out, the device should be recalibrated. A log-sheet should be kept to register quality control checks for each fire or burn. Make sure that the batteries are replaced before they go totally flat, otherwise the sensor requires a 10 hour warm-up time.

#### 3.6.2 Aldehydes

No maintenance is required, the badges should be stored in the freezer. After sampling, the badges need to be stored in the fridge until analysis. The analysis can be carried out by Workcover NSW or CSIRO Marine and Atmospheric Research (Aspendale).

### 3.6.3 VOCs

The micropumps require minimal maintenance. The flows and batteries should be checked prior to each site investigation.

### 3.6.4 Respirable particles

The cyclones need to be cleaned after each use, especially just inside the inlet where liquid particles may build up.

The SidePak needs to be calibrated at least annually (it contains no filters and will be exposed to the full mass of smoke which can foul internal surfaces, so avoid using it in heavy smoke, which will overload it anyway); zero check should be carried out on each day of use.

pDR calibration should be done at least annually or more often if a fault message appears; zero check should be carried out on each day of use.

## 4 Monitoring procedure

On site, the aim is to carry out 2 different types of measurements, personal exposure measurements within the breathing zone of firefighters and area samples taken on the fireground, the staging areas or base camps or at downwind communities.

- For personal exposure sampling, the aim is to monitor from 3 to 6 firefighters, which will be randomly selected among all firefighters so as to guarantee a representative sample. The firefighters will be asked to wear up to 5 personal sampling devices with a max weight of 2 kg (Figure 1). The personal samplers can be fitted onto the clothing of the firefighter or the firefighters will be provided with a backpack which includes the samplers. A log sheet will be filled out for each firefighter to record information on the fire, firefighter work activities, sampling times and air toxics measured. An example of a log sheet is shown in Figure 2.



**Figure 1 Firefighters wearing personal monitoring devices**

Figure 2 Log sheet for personal sampling of firefighters

**1. ACTIVITY DIARY FOR FIELD FIRE FIGHTER** (fill in at end of shift when air samplers collected)

Pin Code: .....

Age: ..... y M / F ? (circle)

Fire Unit: .....CRC Job Class: volunteer/professional

Date(shift end):.... /...../20..... Time of day (24h):.....Shift Durn.....h

Cross Reference (Smoke Sig & Fire Desc): .....

Fire Type (circle): Accidental Prescribed Experimental

General Description of Your Main Tasks (please tick 1 or more):

- ☐ Fire suppression - hose
- ☐ Fire suppression – hand tools (back hoe, etc)
- ☐ Fire suppression – power tools (chainsaw, etc)
- ☐ Direct attack – fire line construction close to fire
- ☐ Indirect attack – fire line construction away from fire
- ☐ Repellers
- ☐ Machine operators (engine, pump)
- ☐ Driving fire tankers at suppression sites
- ☐ Driving small fire trucks at suppression sites
- ☐ Bulldozer driver
- ☐ Bulldozer driver immediately post-fire
- ☐ Supervising fire suppression crews at fire site
- ☐ Supervising fire suppression crews away from fire site
- ☐ Fire mop-up (same day fire suppressed)
- ☐ Fire mop-up (day or more after suppression)
- ☐ Fuel reduction burning/lighting
- ☐ Patrolling – includes putting out spotfires with hose or hand tools
- ☐ Other (specify .....)

Which of the above was the main task and for how many hours was it done?

- task .....
- duration of task .....

Percentage of shift at fire front (tick): <10% ( ) 10-50% ( ) >50% ( )

Which tasks (up to three) exposed you to the most smoke?

- task .....

Did any task cause you eye watering ?

Yes ☐

No ☐

- tasks .....

Did any task cause you coughing?

Yes ☐

No ☐

- tasks .....

Did any task cause you headache? Yes ☐ No ☐  
• tasks .....

Did any task cause you to feel sick or disoriented ? Yes ☐ No ☐  
• tasks .....

Did you wear any: Eye goggles Yes ☐ No ☐  
Dust mask Yes ☐ No ☐

Are you a smoker? Yes ☐ No ☐

Did you smoke while wearing the instruments? Yes ☐ No ☐

Describe any other ill-effects you experienced .....  
.....

Do you have any of these health complaints (please tick):

• asthma	Yes <input type="checkbox"/>	No <input type="checkbox"/>
• bronchitis	Yes <input type="checkbox"/>	No <input type="checkbox"/>
• hayfever	Yes <input type="checkbox"/>	No <input type="checkbox"/>
• other respiratory illness	Yes <input type="checkbox"/>	No <input type="checkbox"/>
• angina	Yes <input type="checkbox"/>	No <input type="checkbox"/>
• other heart ailments	Yes <input type="checkbox"/>	No <input type="checkbox"/>
• allergies (describe.....)	Yes <input type="checkbox"/>	No <input type="checkbox"/>
.....		

Do you suspect you will experience ill-effects in the next few days? If so, what?  
.....  
.....

Any comments on your participation in the air sampling program (e.g. bulky sampling equipment, how representative this day has been of what you normally experience)?  
.....  
.....  
.....

**THANKYOU FOR PARTICIPATING IN THE AIR TOXICS PROJECT – THESE MEASUREMENTS WILL BE PRESENTED (WITHOUT IDENTIFYING YOU) IN OUR PUBLICATIONS IN THE NEXT 1 TO 4 YEARS.**

## 2. AIR SAMPLING RECORD FOR FIELD FIRE FIGHTER (fill in at start and end of shift)

PIN CODE: \_\_\_\_\_ (ddmmyy-\_\_\_\_\_)

Pollutant	Aldehydes	Carbon Monoxide	Respirable particles Laser	Respirable particles Gravimetric	VOCs
Sample Code	PE-A-	PE-C-	PE-RL-	PE-RG-	PE-VOC-
Sample Method	UMEx badge	<input type="checkbox"/> Draeger <input type="checkbox"/> GASTEC <input type="checkbox"/> Smokerlyzer	<input type="checkbox"/> SidePak <input type="checkbox"/> pDR	<input type="checkbox"/> Glass filter <input type="checkbox"/> Teflon filter <input type="checkbox"/> PVC filter	<input type="checkbox"/> Micropump <input type="checkbox"/> Passive
Sample Unit	Badge #			Filter # Pump #	Tube # Pump #
Sample log rate					
Sampling date					
Start time					
End time					
Initial Flow rate					
Final Flow rate					
Air Volume sampled					

- Air toxics will be monitored at staging areas and/or basecamps, in case they are affected by bushfire smoke. Also depending on plume dispersion and accessibility, measurements at downwind communities will be taken. These area samples will complement personal exposure measurements, as the latter ones will only be taken during work activities. However depending on the situation, firefighters may remain in smoke-logged areas after their workshift, and it would be interesting to assess their overall exposures while being present at a fire. Additionally, if feasible, smoke signature samples will be taken, which are samples collected on the fireground. They will provide additional data on potential hazardous exposure levels during firefighting operations. Furthermore filters can be easily changed if necessary, and peak exposure measurements for dense smoke conditions can be carried out for VOCs and aldehydes, which are the 2 air toxics that are not monitored by dataloggers.

#### **4.1 Personal exposure measurements**

The sampling devices used for the personal exposure measurements are described in the previous section. The air toxics monitored include CO, aldehydes, VOCs and respirable particles, including particle composition.

##### **4.1.1 CO**

For CO measurements, each Draeger unit has an internal number which is recorded by the datalogger and is used in all the sampling records.

Draeger operating parameters:

- disable alarms
- set maximum range to 2000 ppm
- set logging interval to 10 sec.

At the start of shift, the logger is attached onto the firefighter's clothing, ensuring the chemical sensor is not obstructed and the time is recorded. The data-logger will record the CO exposure from when first turned on until when turned off, i.e. over the entire shift. At the end of shift, the device is removed and the time is recorded. Note any exposure to CO sources apart from bushfire smoke (eg. Vehicle exhaust, cigarette smoke). It is recommended to do quality control checks before and after sampling to ensure the validity of the data. The CO levels should read zero in a CO-free environment and should read 100 ppm when attached to a standard calibration gas of 100 ppm CO.

Alternatively, additional firefighters can be given a CO dose colorimeter tubes. At the beginning of the shift, the pre-scored end of the tube is snapped off, the tube is inserted into a tube holder, placed in the breathing zone of the firefighter and the time is recorded. At the end of the shift, the tube is removed and the TWA measurement is read immediately from the printed calibrated scale on the tube by dividing by the sampling time.

Upon return from their shift, the firefighters will be asked to breathe into the smokerlyzer which will provide their %COHb, and give an immediate indication of their smoke exposure. Alternatively the COHb levels of firefighters returning to the fireground can be tested using a smokerlyzer and determine whether their rest time was sufficient enough to metabolize their CO intake.



#### 4.1.2 Aldehydes

For aldehyde measurements, record the number on the UMEx badge. At the start of the shift, slide the cover open to expose inlet holes to the air. Clip onto the firefighter's clothing and record the time. At the end of shift, remove the badge, close the cover and keep cold until sent for analysis. Include a field blank for each batch of analyses.

#### 4.1.3 VOCs

VOC operating procedures:

- place a small plug of glass wool into the inlet of the sorbent tube to capture smoke particles and prevent fouling of the sorbent tube
- record the numbers of the micro pump and the sorbent tube
- turn on pump and measure flow rate into sorbent tube (generally it must be in the range 10-15 mL/min)
- place device onto firefighter and record the time
- at the end of the shift, re-measure the flow, switch the pump off and record the time.

If pump flow has dropped by >20% note this in the result. If flow has stopped, the tube can only be used qualitatively (e.g. to determine VOC species). The tubes will be analysed by thermal desorption using a GC/MS/FID in CMIT's laboratory.

#### 4.1.4 Respirable particles

For respirable particles, several devices will be used:

**SidePak:** for low smoke levels

- the sampling records are registered according to unit's serial number (also recorded by datalogger)
- set logging interval to 10 sec and averaging period to 5 sec
- check instrument zero (flow is prechecked in lab)
- start datalogging, clip the device onto the firefighter with cyclone in breathing zone and record time; the keypad can be locked to avoid any tampering if needed
- after the shift, recover the SidePak, record time and flow and switch the device off.

**pDR passive sampler:**

- the sampling records are registered according to unit's serial number (also recorded by datalogger)
- set logging interval to 10 sec and averaging period to 5 sec
- check instrument zero
- no flow check needed, but ensure the air can freely flow to the sensing chamber via opening slots on the front and/or back of the device
- start instrument ensuring that logging is initiated and record the time.
- at the end of the shift, remove the pDR, switch it off and record the time.

**Active gravimetric sampling:**

- to collect gravimetric samples, place the reusable filter cassette containing the pre-weighed filter (to 0.00001 g at 23°C and 50%RH) into the plastic conductive cyclone and record filter number
- attach the pump (programmable AirChek pump or Airlite pump) to the air outlet and measure the flow
- record the number of the pump and the time
- attach the cyclone and pump to the firefighter ensuring that the air inlet is not obstructed
- at the end of the shift, remove the cyclone and pump, record the time and re-measure the flow; if pump flow has dropped by >20% note this in the test result.
- remove the filter cassette and attach the transport clip
- condition filter at 23°C and 50%RH for 24 hours before reweighing to 0.00001 g.

**PAH:**

Send glass fibre filters (samples plus filter blank) to a lab for analysis of PAHs. A detection limit of 0.25 µg or better is necessary for a total particulate weight of 6 mg. Filters may need to be combined to achieve this weight of particulate.

**4.2 Area measurements**

Smoke signature, staging area and downwind community measurements will be conducted for CO, respirable particles, aldehydes and VOCs, as shown on Figure 3.



**Figure 3 Area measurements on fireground**

The sampling devices used in those measurements consist of:

- an electronic data-logging TSI Q-Trak for continuous measurements of CO, CO<sub>2</sub>, temperature and relative humidity
- a 2,4-DNPH impregnated filter cassette attached to an air sampling pump at 0.6 litre/minute for collection of aldehydes. The filters are sent to Work Cover NSW or CSIRO-MAR for analysis
- Envirochem multisorbent tubes for collection of VOCs. The tubes are analysed by thermal desorption by a Varian 3100 GC/FID/MS
- a data-logging, light-scattering active monitor (TSI Dust-Trak) with a 10 mm nylon Dorr-Oliver cyclone for continuous measurements of respirable particles
- a 25 mm glass fibre filter loaded in a filter cassette and used with a conductive plastic cyclone at 2.2 litre/minute for gravimetric sampling of respirable particles

### **4.3 Factors that affect exposure levels**

Exposure levels are likely to be affected by a range of factors, such as work activities, fuel characteristics, meteorology and fire characteristics. Monitoring procedures will be set up to take into account those exposure determinants.

#### **4.3.1 Work activities**

Fire fighters are involved in a range of work activities, which may influence their exposure levels. In fact the proximity and the duration of smoke exposure are likely to differ for various job tasks. Monitoring will take into account these differences by targeting various job tasks as shown in the log sheet in Figure 2 and observing as much as possible the firefighters on the fireground.

#### **4.3.2 Fuel characteristics**

Exposure levels are likely to differ for different vegetation types. The monitoring will be carried out across Australia, so that the various vegetation types can be taken into account. Furthermore, experimental burns of various vegetation litter types that will be gathered at the burn or fire (if access to the fireground is allowed) will be carried out in burn chambers to assess the amount and types of air toxics emitted.

Fuel moisture is also likely to play a critical part in smoke exposure levels by influencing fire behaviour. Low moisture fuel is likely to result in intense fire behaviour and higher risk of spot fire development. On the other hand in high moisture fuels, no strong columns develop to effectively disperse the smoke. Fuel moisture levels will be taken into consideration when possible, most likely feasible only during prescribed and experimental burns. Experimental burns of various vegetation types are also planned at different fuel moisture levels, ranging from 8% (accidental fire conditions) up to 15% (upper limit of prescribed burn conditions).

#### **4.3.3 Meteorology**

Smoke dispersion is strongly dependent upon wind speed and wind direction and will affect exposure levels. The vehicle is equipped with a small weather station, which will provide information on wind speed and direction, temperature and humidity. Incident

action plans will be used to assess weather conditions during accidental fires, where access to the fireground will be more difficult.

Inversions are likely to occur at night, which would result in pollutants being trapped close to the surface hence increasing exposure levels. Therefore night shifts may experience higher exposure levels if temperature inversions are present.

#### 4.3.4 Fire characteristics

During a fire event, different stages are observed which are likely to result in different emissions of air contaminants and therefore different exposure levels for the firefighters. The different periods in a fire event include:

- initial attack (flaming phase), such as building control lines, fire suppression using a hose or physical tools, conducting backburns,
- mop-up (smouldering phase), which is likely to result in higher smoke levels due to the conditions of incomplete combustion,
- patrolling

Fire types are also likely to affect exposure levels as they may involve different work tasks and different smoke levels that the firefighters have to work in. The types that will be attended for the purpose of this research project include:

- prescribed burns, which could be on activity or natural fuels, be conducted away or in close proximity to the urban interface,
- accidental fires, which can occur in parks or on public land, and may involve property and/or asset protection
- experimental burns, during which fuel characterization (type, loading and moisture) will be carried out.

## **5 Criteria for assessing firefighter exposures**

Fire fighting is an occupational activity and will be covered by OHS regulations relevant to any other workplace. However, there are specific features of fire fighting that differentiate it from most other workplaces, and so the Australian legislative requirements are reviewed in light of these features. Note that the criteria cannot be simply stated as a simple set of numbers for bushfire air toxics because of the unique features of fire fighting. Instead, the exposures should be assessed relative to legislative requirements using an occupational hygiene approach which aims to control the exposures to bushfire air toxics to acceptable levels within Australian legislative framework.

### **5.1 Australian legislation**

OHS standards are provided in Australia by the National Occupational Health & Safety Commission (NOHSC), but are only guidance documents to promote uniformity in regulations. Those relevant to workplace air contaminants are:

- the *National Model Regulations for the Control of Workplace Hazardous Substances* [NOHSC:1005(1994)] (the National Model Regulations)
- *Adopted National Exposure Standards for Atmospheric Contaminants in the Occupational Environment* [NOHSC:1003(1995)]

- [Guidance Note on the Interpretation of Exposure Standards for Atmospheric Contaminants in the Occupational Environment \[NOHSC:3008\(1995\)\]](#) (the NES Guidance Note)

These standards tend to follow those used in the USA and UK. The standards are generally called up by each State and Territory in a principal OHS Act which sets out requirements for ensuring that workplaces are safe and healthy. These requirements spell out the duties of different groups of people who play a role in workplace health and safety, and are known as the Duty of Care. Duty of care requires everything 'reasonably practicable' to be done to protect the health and safety of others at the workplace. This duty is placed on:

- all employers;
- their employees; and
- any others who have an influence on the hazards in a workplace.

'Reasonably practicable' means that the requirements of the law vary with the degree of risk in a particular activity or environment which must be balanced against the time, trouble and cost of taking measures to control the risk. It allows the duty holder to choose the most efficient means for controlling a particular risk from the range of feasible possibilities preferably in accordance with the 'hierarchy of control' (below). This qualification allows those responsible to meet their duty of care at the lowest cost. It also requires changes in technology and knowledge to be incorporated but only as and when it is efficient to do so. The duty holder must show that it was not reasonably practicable to do more than what was done or that they have taken 'reasonable precautions and exercised due diligence'.

Specific rights and duties logically flow from the duty of care. These are representative of the employer's specific duties in all Australian States and Territories:

- provision and maintenance of safe plant and systems of work;
- safe systems of work in connection with plant and substances;
- a safe working environment and adequate welfare facilities;
- information and instruction on workplace hazards and supervision of employees in safe work;
- monitoring the health of their employees and related records keeping;
- employment of qualified persons to provide health and safety advice;
- nomination of a senior employer representative; and
- monitoring conditions at any workplace under their control and management.

The 'hierarchy of control' refers to the range of feasible options for managing the risk to health and safety. The hierarchy normally ranges over the following controls: elimination of the hazard; its substitution with a less harmful version; its redesign; engineering controls; isolation of the hazard from people at the workplace; safe work practices; redesigning work systems; and the use of personal protective equipment by people at the workplace.

The National Commission sets OHS Standards for hazards common to many industries and workplaces across Australia. These standards do not become law until they are adopted as regulations in each of the states and Territories. The National Standard relevant to the bushfire air toxics research is [Exposure Standards for Atmospheric Contaminants in the Occupational Environment - Database \[NOHSC:3008\(1995\)\]](#). These standards are based on the concept that **the air inhaled at work should not contain chemical agents at concentrations that produce adverse effects on health, safety or well-being**. While supporting the concept that exposure to chemical agents should be kept as low as practicable, national exposure standards (NES) have been declared as guidance to assist in ensuring that workers are adequately protected from exposures to hazardous substances. Exposure standards represent airborne concentrations that, according to current knowledge, should neither impair the health of nor cause undue discomfort to nearly all workers. Additionally, the exposure standards are believed to guard against narcosis or irritation that could precipitate industrial accidents. **Exposure standards do not represent a ‘no-effect’ level, and are best used to assess the quality of the working environment and indicate where control measures are required.**

**The National Model Regulations for the Control of Workplace Hazardous Substances [NOHSC:1005(1994)] (the National Model Regulations)** is the regulation relevant to hazardous substances in workplaces. It states “3(1) These national model regulations shall apply to all hazardous substances, to all workplaces in which hazardous substances are used or produced and to all persons with potential for exposure to hazardous substances in those workplaces.” The regulation contains requirements that have little relevance to a bushfire site, e.g. provision of MSDS, labelling, packaging etc, but if bushfires produce hazardous substances (see later discussion) then:

**“11(1) An employer shall ensure that a suitable and sufficient assessment is made of the risks to health created by work involving potential exposure to any hazardous substance.**

**(2)** For the purposes of sub-regulation 11(1), a suitable and sufficient assessment shall include:

- (a) the identification of any hazardous substance** used or produced in that work;
- (b)** a review of... the MSDS for each hazardous substance .. produced ... and
- (c) the identification of any risk of exposure to any hazardous substance** used or produced in that work.

....

**12(1)** Where an assessment under regulation 11 indicates that it is necessary, the employer shall ensure that exposure of employees to hazardous substances is either prevented or, where that is not practicable, adequately **controlled so as to minimise risks to health**.

**(2)** So far as practicable, the prevention or adequate control of exposure of employees to hazardous substances shall be secured by measures other than the provision of personal protective equipment.

**(3)** Where the measures taken in accordance with sub-regulation 12(2) do not prevent, nor provide adequate control of exposure of employees to hazardous substances, then, in addition to those measures, the employer shall provide those employees with such suitable personal protective equipment as will adequately control their exposure to



hazardous substances.

(4) Without limiting the requirements of sub-regulation 12(1), the employer shall ensure that **no employee is exposed to hazardous substances at levels above the appropriate (national) exposure standards for the relevant period of time**” (as listed in the *Adopted National Exposure Standards for Atmospheric Contaminants in the Occupational Environment* [NOHSC:1003(1995)] and declared amendments.

The [Guidance Note on the Interpretation of Exposure Standards for Atmospheric Contaminants in the Occupational Environment \[NOHSC:3008\(1995\)\]](#) (the NES Guidance Note) provides further information on the interpretation and application of NES. It states that the exposure standards are guides to be used in the control of occupational health hazards, and should not be used as fine dividing lines between safe and dangerous concentrations of chemicals or as measures of relative toxicity. **They should not be applied in the control of community air pollution.** Lastly, interpretation of the exposure standards should be undertaken by an appropriately qualified and experienced person.

## 5.2 Legislation/national exposure standards applied to bushfire fighting

The basis for determining whether a substance is hazardous, is the *Approved Criteria for Classifying Hazardous Substances 3rd Edition* [NOHSC(1008:2004)] (the Approved Criteria). The criteria included in the Approved Criteria were adopted from European Community (EC) legislation for classifying dangerous substances. From the perspective of bushfire air toxics:

- *Adopted National Exposure Standards for Atmospheric Contaminants in the Occupational Environment* [NOHSC(1003)] are referenced in relevant Commonwealth, State and Territory hazardous substances legislation, and hence the exposure standards are used as guides in the control of occupational health hazards
- Bushfire firefighters may work shifts much longer than 8 hours and endure heavy workloads, and NES should be adjusted for such scenarios
- Bushfire smoke is a complex mixture and while the National Exposure Standards are appropriate criteria for single substances:
  - some substances are not listed in the NES (e.g. smoke particles, see below)
  - complex mixtures of substances may need specific assessment if they have potential health impacts.

### 5.2.1 Application of adopted NES to bushfire air toxics

NOHSC has stated support for the concept that exposure to chemical agents should be kept as low as practicable, but recognises that, in practice, guidance in the form of exposure standards may be used by occupational health and safety practitioners, employers and employees or their representatives, and regulatory agencies to assist them in ensuring that workers are adequately protected from substances that may impair health

or cause undue annoyance. The exposure standards listed by NOHSC represent airborne concentrations of individual chemical substances which, according to current knowledge, should neither impair the health of nor cause undue discomfort to nearly all workers. They are presented as:

- time-weighted average (TWA) concentration, which is the average airborne concentration of a particular substance when calculated over a normal eight hour working day for a five day working week
- peak concentration, which is the concentration not to be exceeded and which is determined over the shortest possible time (not more than 15 minutes)
- short-term exposure limit (STEL) which is a 15 minute average exposure which should not be exceeded any time during the working day, even if the TWA is not exceeded; STEL exposures should not exceed 15 minutes, should not be repeated more than four times per day, and should be separated by at least 60 minutes
- excursion limit concentration, used where peak or STEL concentrations are not specified and the TWA exposure is not exceeded, by which short term exposure not exceeding a total of 30 minutes is allowable at up to 3 times the TWA level but in no case can 5 times the TWA level be exceeded.

NOHSC states that:

- The exposure standards do not represent 'no-effect' levels which guarantee protection to every worker. Given the nature of biological variation and the range of individual susceptibility, it is inevitable that a very small proportion of workers who are exposed to concentrations around or below the exposure standard may suffer mild and transitory discomfort. An even smaller number may exhibit symptoms of illness.
- The exposure standards are not fine dividing lines between satisfactory and unsatisfactory working conditions, but rather are best used to assess the quality of the working environment and indicate where appropriate control measures are required.
- For a few substances, usually the more potent probable and established human carcinogens, it is not currently possible to assign an appropriate exposure standard. For these substances, exposure should be controlled to the lowest practicable level.

#### 5.2.2 Adjusting NES for longer shifts and heavier workloads

NOHSC established an expert working group that produced Altered Workshifts: Amendments to the Guidance Note on the Interpretation of Exposure Standards for Atmospheric Contaminants in the Occupational Environment (June 1996). It was considered that exposure standards for conventional workshifts may be inappropriate where there are altered workshifts and that the 8-hour TWA exposure standard should be reduced by a suitable factor to provide an equivalent degree of protection. Application of this factor was considered part of an employer's duty of care. No adjustment was considered necessary for Peak Limitation and Short Term Exposure Limit (STEL) values since adverse effects due to acute over-exposure were already accounted for by existing



limitations. It was stated that 8-hour TWA exposure standards should not be adjusted upwards when considering shorter exposure periods or shifts (for example, exposure to 8 times the TWA for one hour and zero exposure for the remainder of the shift) because data on the mode of action of the substance, its target organ, absorption and excretion rates may not be fully understood for high exposures of short duration. In circumstances where short exposure periods or shifts were encountered the general excursion limitations described above would apply and adherence to these general limitations were recommended but these would not supersede any STEL or Peak Limitation value which may be assigned.

Several mathematical models exist for adjusting exposure standards for use during altered work shifts, and the expert group recommended use of the 'Brief and Scala Model' (Brief and Scala 1975) because it is simple to use, takes into account both increased hours of exposure and decreased exposure free time, is more conservative than other models and is suitable for the Australian NES. The Brief and Scala Model is based on the number of hours worked per 24 hour day and the period of time between exposures. This model is intended to ensure that the daily dose of the toxicant under an altered workshift is below that for a conventional shift to take account of the lessened time for elimination.

$$\text{Adjusted exposure standard (TWA)} = \frac{8 \times (24 - h) \times \text{Exposure Standard (8-hour TWA)}}{16 \times h}$$

where **h** = hours worked/day.

For example:

Substance: Bushfire smoke respirable particles  
 Exposure Standard: 3 mg/m<sup>3</sup>, 8 -hour TWA  
 Workshift: 12 hours

$$\text{Adjusted exposure standard for 12-hour workshift} = \frac{8 \times (24 - 12) \times 3}{16 \times 12} = 1.5 \text{ mg/m}^3 \text{ (12-hour TWA)}$$

Bushfire firefighters may work under heavy workloads in some circumstances. The exposure standards were established for an eight-hour exposure, during work of normal intensity, under normal climatic conditions and where there is a sixteen-hour period between shifts to permit elimination of any absorbed contaminants. Heavy or strenuous work increases lung ventilation, thereby increasing the uptake of airborne contaminants (Astrand 1983). Similarly, heavy physical work under adverse climatic conditions, such as excessive humidity or heat, or work at high altitudes, may lead to an increased uptake of contaminants. NOHSC provided no specific guidance on this factor but noted that any evaluation of the working environment must consider the lung ventilation rate where there is a significant airborne concentration of contaminant. Consideration of this factor for the Bushfire Air Toxics project will need to be made in the first instance on the basis of the levels of exposure determined and secondly in relation to workload findings from CRC Project D2a Firefighter safety, health and well-being.

### 5.2.3 Complex nature of bushfire smoke

While the list of NES is extensive and it lists several types of respirable particles (equivalent aerodynamic diameter below 10  $\mu\text{m}$ , all 8-hour TWA's), as follows, it does not provide NES for smoke particles from any source:

- Carbon black TWA 3  $\text{mg}/\text{m}^3$
- Graphite dust TWA 3  $\text{mg}/\text{m}^3$
- Talc dust TWA 2.5  $\text{mg}/\text{m}^3$
- Wood dust (hardwood) TWA 1  $\text{mg}/\text{m}^3$
- Fume (thermally generated, e.g. welding) TWA 2  $\text{mg}/\text{m}^3$
- Dusts not otherwise classifiable – where no NES has been assigned to a substance and it is both inherently low toxicity and free from toxic impurities, the recommended NES should be 10  $\text{mg}/\text{m}^3$  measured as inspirable (equivalent aerodynamic diameter below 185  $\mu\text{m}$ ) dust (note, the US ACGIH also recommends a respirable dust limit of 3  $\text{mg}/\text{m}^3$ ).

Based on the last NES above, depending on the constituents of bushfire smoke particles, a TWA of 3  $\text{mg}/\text{m}^3$  is considered appropriate if the smoke contains no toxic components. However, there is a possibility that it will contain polyaromatic hydrocarbons (PAH). NOHSC does not provide an NES for benzo(a) pyrene since it is a carcinogen and exposure should be reduced to the minimum practicable level. [\*Approved Criteria for Classifying Hazardous Substances \[NOHSC:1008\(2004\)\]\*](#) is the national standard for determining whether a substance is a hazardous substance, and for certain complex coal-derived substances it specifies that classification as a carcinogen need not apply if it can be shown that the substance contains less than 0.005 % w/w benzo[a]pyrene. It is considered reasonable then to apply this criteria to bushfire smoke to determine whether it should be classified as a carcinogen and thereby require a much lower TWA than 3  $\text{mg}/\text{m}^3$ .

Additionally, bushfire smoke consists of a large number of air contaminants and while each may individually be lower than NES values, there must be some consideration of interactive health effects for such mixtures. The NES are applicable to airborne concentrations of single pure substances, and when a working environment contains a number of airborne contaminants the exposure to these additional substances, either simultaneously or sequentially, could give rise to an increased hazard to health.

NOHSC provides the following general proposals to deal with mixtures but notes the need for considerable caution and assessment of each scenario by either toxicologists, occupational hygienists or physicians after specific toxicological consideration of all substances involved. Mixtures of air contaminants may cause:

- Independent effects
- Additive effects
- Synergistic/Potential effects

Independent effects arise where there is clear toxicological evidence that two or more contaminants have totally distinct mechanisms of effect on the body. For this scenario, each substance may be separately evaluated against its appropriate exposure standard. For example, since crystalline silica affects the lungs, and inhaled ethanol vapour acts upon the liver and central nervous system, each of these substances may be assessed individually against its appropriate exposure standard. If neither standard is exceeded, the atmosphere within the working environment is deemed to be satisfactory.

An additive effect is obtained when contaminants have the same target organ or the same mechanism of action. In this situation, the total effect upon the body equals the sum of effects from the individual substances. For substances which are purely additive, conformity with the standard results when

$$\frac{C_1}{L_1} + \frac{C_2}{L_2} + \dots + \frac{C_n}{L_n} \leq 1 \quad (1)$$

where  $C_1, C_2 \dots C_n$  are the average measured airborne concentrations of the particular substances 1, 2 ... n and  $L_1, L_2 \dots L_n$  are the appropriate exposure standards for the individual substances.

An example of an additive effect is the general effect of VOCs on the central nervous system (narcotic or anaesthetic effect), but the exposure standard for a number of VOCs, such as benzene and carbon tetrachloride, have been assigned on the basis of effects other than those on the central nervous system. Therefore, it is essential to refer to the documentation for the specific substances to ascertain the basis of the standard and any potential interactions.

Synergism and potentiation arise when the combined effect of multiple exposure is considerably greater than the sum of the effects from the individual components. Synergism occurs when both chemicals have an effect individually and a more than additive effect when together. Potentiation is when one chemical has an effect but the second chemical does not but enhances the effect of the former chemical on combined exposure. An example of a synergistic effect is the combined effect of solvents such as n-hexane and methyl ethyl ketone (MEK) on the nervous system (Holmburg and Lundberg 1985, Vouk 1987). In combination, the damage caused by simultaneous high concentrations of both these solvents is far greater than the sum of either of these substances acting alone. Interaction can also arise from exposures via routes other than inhalation. For example, imbibed alcohol increases the narcotic effects of inhaled trichloroethylene. Interaction effects may also occur in connection with exposure to entirely different environmental factors such as simultaneous exposure to chemical agents and physical factors, such as light, heat and noise (Fechter 1988, Paran'ko and Belitskaya 1988). Smoking of tobacco is known to have a synergistic effect in combination with, for example, inhaled particulates. NOHSC notes that the understanding of interaction effects is incomplete and that the knowledge that such effects can occur is reason to maintain the

concentrations of individual substances as low as is practicable under complex exposure conditions.

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## 7 Appendix

### 7.1 Burn Room Test Procedure

All the tests were carried out in a 33 m<sup>3</sup> burn chamber lined with insulation board. The chamber has air duct openings which are used to ventilate the room, but were closed during the experiments. The air leakage was approximately 0.15 air changes per hour as determined by previous experiments. A fan was used inside the chamber to ensure proper mixing of the combustion products. The sampling devices were placed on a table inside the room approximately 1 m off the ground and 1.5 m away from the fuel. The sampling equipment could be accessed via a small port in the wall. The vegetation litter was placed on an aluminium foil-lined stainless steel tray about 0.5 m off the ground in the centre of the room and was lit on several edges using a small gas flame. The fuels were conditioned at 23°C and 50% relative humidity. Weight loss was monitored during conditioning and once a stable mass was achieved the moisture content was determined by heating the material in an oven at 110°C until a stable mass was achieved, which generally took approx. 24 hours. The aim of the conditioning was to produce fuels with moisture contents from 9 -12% by weight, the range generally used for prescribed burns.

**Table 1 Chamber burn experiments**

Chamber burn #	Fuel type	Mass burned [g]	Chamber burn #	Fuel type	Mass burned [g]
CB-1	Sorghum grass	25	AT-1	WA Scrub	25
CB-2	Eucalypt	25	AT-2	Pine litter	25
CB-3	Sorghum grass	25	AT-3	WA Scrub	25
CB-4	Eucalypt	25	AT-4	WA Scrub	184
CB-5	Pine litter	25	AT-5	WA Scrub	125
CB-6	Eucalypt	25	AT-6	Pine litter	120
CB-7	Eucalypt	25	AT-7	Pine litter	25
CB-8	WA Scrub	25	AT-8	Eucalypt	50
CB-9	Pine litter	30	AT-11	WA Scrub	120
CB-10	Pine litter	30	AT-12	WA Scrub	20
CB-11	Pine litter	30	AT-13	Pine litter	25
CB-12	Pine litter	30			
CB-13	WA Scrub	25			
CB-14	WA Scrub	25			

### 7.2 Results and discussion

#### 7.2.1 Carbon monoxide

Carbon monoxide measurements were taken by a TSI QTrak monitor (Model 8551), which logged concentrations of CO and CO<sub>2</sub> as well as temperature and relative humidity every 10 seconds. The instrument was calibrated using a 100 ppm CO and 1000 ppm CO<sub>2</sub> calibration gas.

A Draeger data-logger (PacIII) was also logging CO concentrations during the test. Additionally a CO colour dosimeter Gastec tube was put into the chamber to determine the average CO concentration and compare it to the electrochemical sensor devices.

**Table 2 Carbon monoxide measurements during chamber burns**

Chamber burn #	Q-Trak	Draeger	Gastec Tube
AT-1	22 ppm	23 ppm	24.5 ppm
AT-2	11 ppm	N/A	10 ppm
AT-3	N/A	30 ppm	18 ppm

### 7.2.2 Aldehydes

The air was sampled onto a 37 mm glass-fibre filter impregnated with 2,4-dinitrophenylhydrazine (DNPH) at a sampling rate of about 0.5 L/min using a SKC Universal 224-44XR air sampling pump. The volume sampled was about 120 L. The filter cassette had front and back filters which enabled to take into account pollutant breakthrough. Additionally samples were also collected onto UMEx 100 passive samplers. The air diffused through the diffusion barrier onto the active sampling site, which includes a tape treated with 2,4-DNPH. Both filters and UMEx badges were sent to WorkCover NSW laboratory for analysis by HPLC.

**Table 3 Aldehyde measurements during chamber burns**

Chamber burn #	Formaldehyde		Acrolein		Acetaldehyde	
	DNPH filter	UMEx	DNPH filter	UMEx	DNPH filter	UMEx
AT-2 (3 hrs)	64 ppb	63 ppb	26 ppb	< 12 ppb	44 ppb	53 ppb
AT-3 (4 hrs)	42 ppb	95 ppb	18 ppb	9 ppb	20 ppb	60 ppb
AT-4 (2 hrs)	281 ppb	285 ppb	153 ppb	144 ppb	78 ppb	463 ppb
AT-4 (4 hrs)	265 ppb	202 ppb	153 ppb	109 ppb	73 ppb	423 ppb

### 7.2.3 Respirable particulates

Respirable particles were sampled by gravimetric and laser scattering methods.

**Gravimetric** measurements were carried out to assess a range of filter types and to determine the levels at which filters start to block up. The particles were collected using an SKC 25 mm aluminium cyclone operated by an air sampling pump at a flow rate of 2.5 litres per minute. The particulates were collected on pre-weighed 25mm diameter filters so that the amount captured was measured gravimetrically after sampling using a microbalance weighing to 0.01 mg. Filters were conditioned at a temperature of 22°C and RH 50% for 24 hours prior to all weighings.

The filters tested and the problems encountered during sampling are listed in Table 4.

**Table 4 Type of filters tested during chamber burns**

Filter Type	Problems encountered
Millipore Corporation FA <b>Teflon</b> membrane filters (nominal pore size 1 µm)	Appeared to leak around the outside, and blocked up quickly at higher fuel loads
Gelman Sciences GLA 5000 <b>PVC</b> membrane filters (nominal pore size 5 µm)	Blocked up at high particle loadings
Millipore Corporation glass microfibre filters (nominal pore size unknown) ( <b>GF</b> )	Due to the delicate nature of the filter media, the filters are unlikely to be reliably weight stable
Pall Corporation <b>Type A/E</b> glass fibre filters (nominal pore size 1 µm)	Performed well

Based on the tests, the Type A/E filters were chosen for future measurements and experiments were carried out to determine the concentrations at which filters tend to

block up. The results are displayed in Table 5 and have shown that a mass of approx 6 mg can be collected onto the Type A/E filters without resulting in pump stoppage.

**Table 5 Gravimetric measurements of respirable particles**

Chamber burn #	SKC pump		Aircheck pump		Airlite pump	
	Flow rate [L/min]	Mass [mg]	Flow rate [L/min]	Mass [mg]	Flow rate [L/min]	Mass [mg]
AT-5	2.44	0	2.39	0	2.5	0
	2.51	5.1	2.36	4.6	2.36	3.7
	2.24	6.1	pump stopped	5.4	2.05	5.1
AT-6	2.45	0	2.51	0	2.49	0
	2.51	9.3	2.54	6.0	2.42	4.9
	2.1	11.1	pump stopped	10.6	1.34	10.0
AT-7	2.46	0	2.51	0	2.49	0
	2.47	7.9	2.53	7.7	2.39	6.2
					pump stopped	7.7
AT-8	2.45	0	2.51	0	2.5	0
	2.51	5.5	2.56	5.7	2.41	3.8
					2.3	4.6

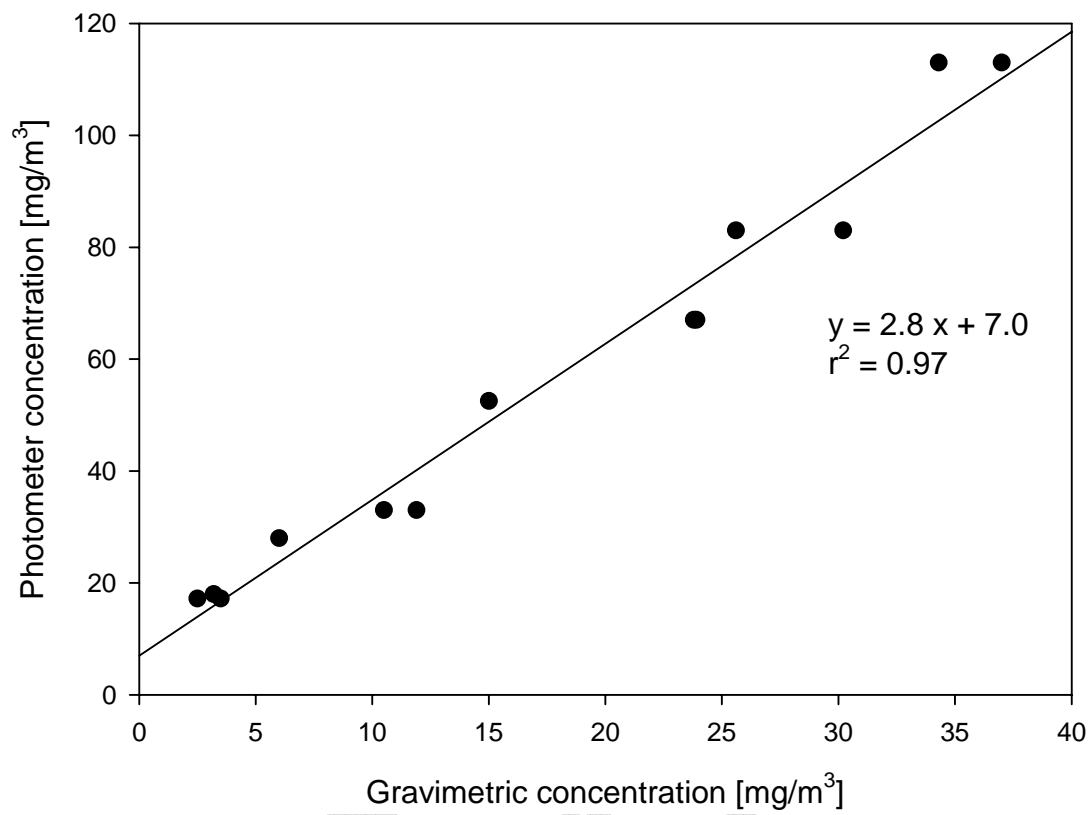
Chamber burn experiments were also carried out to assess the response of three different light scattering particle monitors to bushfire smoke and compare their response. The devices tested included a TSI DustTrak, a TSI SidePak and a passive personal DataRam (pDR) particle monitor. The TSI DustTrak and the TSI SidePak are laser photometers with an in-built pump for active sampling of respirable particles. Both instruments were operated with a 10 mm nylon Dorr-Oliver cyclone at a flow rate of 1.7 L/min to ensure accurate measurements of respirable particles (50% cut-off at 4 micron). The DustTrak monitor and the SidePak are calibrated against a standard dust material (Arizona Road Dust). The laser scattering devices can be recalibrated for various aerosols by comparing readings with respirable gravimetric measurements. The results are shown in Table 6 and the relationship between the gravimetric results collected on the glass microfibre filters/Type A/E glassfibre filters and the photometers is shown in Figure 4.

To compare the response of the TSI DustTrak, the TSI SidePak and the pDR to bushfire smoke, the instruments have been placed in a smoke atmosphere generated by 120 g and 20 g of Western Australian scrub and by 25 g of pine litter. The respirable particle concentrations generated during the burns were exceeding 20 mg/m<sup>3</sup>, which is the maximum response limit of the TSI SidePak. Therefore comparison of the DustTrak and the SidePak could not been carried out. At higher particle concentrations, there was very good agreement in the response to bushfire smoke between the active TSI DustTrak particle monitor and the passive pDR particle monitor (Table 6).



**Table 6 Measurements of respirable particles during chamber burns**

Chamber burn #	Gravimetric [mg/m <sup>3</sup> ]	Filter type	DustTrak [mg/m <sup>3</sup> ]	SidePak [mg/m <sup>3</sup> ]	pDR [mg/m <sup>3</sup> ]
CB-1	0.5	Teflon	3.5		
CB-2	2.4	Teflon	19		
CB-3	0.9	Teflon	2.3		
CB-4	5.0	Teflon	29		
CB-5	24	Teflon	120		
CB-6	5.5	PVC	28		
CB-7	9.0	PVC	26		
CB-8	4.8	PVC	15		
CB-9	37	GF	113		
	34.3				
CB-10	30.2	GF	83		
	25.6				
CB-11	23.9	GF	67		
	23.8				
CB-12	10.5	GF	33		
	11.9				
CB-13	6.0	A/E	28		
CB-14	34.6	A/E	140		
AT-2	2.5	A/E	17.2	> 15	N/A
	3.5	GF			
AT-3	3.2	A/E	N/A	> 17	N/A
AT-5	24	A/E	43	N/A	N/A
AT-6	62	A/E	101	N/A	N/A
AT-7	11	A/E	24	N/A	N/A
AT-8	6	A/E	17	N/A	N/A
AT-11	12	A/E	N/A	> 20	88
AT-12	N/A	A/E	18	17	9
AT-13	15	A/E	51	N/A	54



**Figure 4 Response of photometers to bushfire smoke**