

1 Introduction

1.1 History of the Project

In 1996, the Workers' Compensation Board of BC (WCB) convened two Regulation Review sub-committees representing the Live Performing Arts and the Motion Picture and Video industries. Both of these groups made independent recommendations that a study be performed on the use of theatrical smokes and fogs. SHAPE, a tripartite organization to promote Safety and Health in Arts, Production, and Entertainment, mirrors the Regulation Review committees and includes the unions, associations, guilds, and organizations that represent employers and workers in the motion picture, theatrical, and music industries in the province. In planning for the 1999 year, the members unanimously agreed that SHAPE should sponsor an application to the WCB Finding Solutions program for a study of this nature. Meetings were held with investigators from the University of British Columbia School of Occupational and Environmental Hygiene, an initiative that gave rise to successful research proposals to the WCB and the BC Lung Association and resulted in the studies described in this report.

1.2 The Issue

Personnel employed in the motion picture, theatrical, and music industries often work in fog or smoke filled environments purposely created for atmospheric effects. Whether the effect is provided for recording on film or for the benefit of a live audience, the products used and the manner of application are similar. Many industry employees, including musicians, actors, technicians, directors and other staff, are concerned about the safety of these environments.

The most common agents used to create special atmospheric effects are glycol-water mixtures and mineral oils. Other agents, less frequently used but reported in industry publications, include dry ice, petroleum distillates, zinc chloride, ammonium chloride, pressurized water, liquid nitrogen, and burning organic materials^{1,2}. Anecdotal reports from industry personnel indicate that other agents may also be used, including diatomaceous earth, flour, aluminum, naphthalene, fragrances, and dyes. The extent to which each of these compounds is used in the British Columbia entertainment industry has been undocumented; thus uncertainty about the agents used has been one of the issues of concern.

The most common effect-generating techniques create suspended liquid aerosols (fogs), using heat or mechanical methods². Heat-based methods involve propelling a fluid into a heat exchanger preset to the solution's boiling temperature. The vaporization produces the desired fog effect. The fog can then be gas-propelled to create a very fine droplet (0.5 to 4 microns in aerodynamic diameter) or pump propelled². Mechanical methods include atomizers and ultrasound. Atomizers (called 'crackers' in the industry) work by forcing air through a dispersion system with small holes submerged in the fogging solution. The air breaks the surface of the fluid and disperses small droplets (10 - 20 microns)². In ultrasonic techniques, a transducer is submerged in the solution. The extremely high vibration frequencies produce a smaller aerosol than the cracker method (1 - 10 microns)². From a health perspective there is an important distinction between the heat-based and mechanical methods. Heat-based methods have the potential to generate additional airborne contaminants in the form of thermal degradation compounds of the parent solution since the temperatures of the solutions may exceed 300°C.

Performers' and crews' exposures to the multiple components of theatrical fog will occur mainly through the inhalation route, but may also include dermal exposure and ingestion. Because of the small size of the fog droplets, once they are generated, exposures are likely to continue until the completion of work at that location on that day. The finest droplets can remain suspended in the air for hours to days,³ although the total mass concentration will decrease over time, as the larger aerosols settle.

1.3 Literature

In order to examine the published literature on theatrical smokes and fogs, a search was conducted using medical and occupational health data bases (Medline, 1966 to the present, and Silverplatter OSH ROM, 1995, which includes NIOSHTIC, HSELINE, CISDOC and MHIDAS) using terms related to the atmospheric effects (theatrical smoke, theatrical fog, theatrical, performing arts, pyrotechnics, and special effects) and terms related to the main agents used to create the effects (mineral oil, glycol, propylene glycol, ethylene glycol, diethylene glycol, triethylene glycol, and butylene glycol). The search revealed that research on the topic of theatrical fog exposures and health effects is very limited.

1.3.1 Previous research about theatrical fogs

A recent analysis of the US National Health and Nutrition Examination Survey (NHANES III) data, which examines all industries in a cross-sectional survey of a random sample of the US population, found that the entertainment industry was one of the main industries identified with self-reported work-related asthma and work-related wheezing³⁰. There have been three studies specifically examining the health effects of theatrical fogs. The US National Institute for Occupational Safety and Health (NIOSH) conducted a health hazard evaluation in theatrical productions in 1991, with a follow up in 1993⁴. Consultech Engineering (Omaha, Nebraska) conducted a mailed survey of actors in 1993⁷. From 1997 to 1999, the Mount Sinai School of Medicine and Environ International conducted a study of exposures and irritant health effects in performers in Broadway musical productions²³. Each of these is described in more detail below.

The NIOSH Health Hazard Evaluation quantified actors' 'smoke' exposure at four Broadway stage productions by collecting personal and area samples. The report does not explicitly identify the fog generation methods used at the time of sampling. The glycol sampling methodology used in the initial survey was inadequate (NIOSH method 5500)⁵, prompting development of a new sampling and analytical method for the 1993 survey of 3 theatrical productions (NIOSH Method 5523)⁶. Ethylene glycol, propylene glycol, triethylene glycol, and butylene glycol were then detected at most but not all sampling locations. Concentrations of all glycol components combined ranged from 0.053 mg/m³ to 7.59 mg/m³. Two of seven samples investigating potential thermal degradation products of glycols detected low levels of acrolein, formaldehyde, acetaldehyde, acetone, C₉₋₁₂ aliphatic hydrocarbons, and alkyl benzenes at low levels. Mineral oil was used at only one site; concentrations ranged from not detectable to 1.35 mg/m³ (NIOSH Method 5026)⁶.

The 1991 study compared symptom prevalences in four 'non-smoke' productions to those in five 'smoke' productions using a questionnaire addressing the frequency and severity of respiratory and irritant symptoms. 134 actors working in 'smoke' productions had a higher

prevalence of nasal, respiratory, and mucous membrane symptoms than 90 actors working in 'non smoke' productions.

The 1993 survey⁶ was designed to evaluate the relationship between occupational asthma symptoms and theatrical fog exposures among 37 actors who had reported symptoms consistent with asthma in 1991, and 68 asymptomatic controls. Participants were asked to submit peak flow measurements and complete questionnaires about medical and work histories. Only 65 subjects (62%) submitted complete or partial information. Five people met the case definition for asthma related to theatrical work, three of whom worked in 'smoke' productions at the time. Performers with asthma-like symptoms and bronchial lability were not more likely to have been exposed (OR = 1.0, 95% CI 0.1-13.1).

Consultech Engineering carried out a survey in 1993 to investigate perceived health problems reported by actors exposed to glycol fogs⁷. A questionnaire with 50 questions about health problems, exposure levels, impact of health effects on work attendance and performance quality, and confounders was published in a monthly publication distributed to approximately 14,000 people in the industry. Of these, 3,000 to 4,000 were believed to be working with glycol fogging products. 231 people returned questionnaires to Consultech. Almost all (98%) of the respondents had been exposed to fogs, and 77% reported being exposed to glycol fogs. Of those exposed to glycols, 40% reported respiratory and mucous membrane symptoms, 18% had missed a performance, and 33% had sought medical attention because of the symptom severity.

The **Mount Sinai and Environ** study²³ was conducted in three phases and examined performers in 16 Broadway musicals. The overall mean total glycol concentration was 0.73 mg/m³, with daily subject averages ranging from non-detectable to 7.2 mg/m³, and 15-second peaks ranging from 0.08 to 37 mg/m³. For mineral oils, the overall mean was almost identical at 0.74 mg/m³, but daily subject averages ranged from 0.001 to 68 mg/m³, and 15-second peaks ranged from 0.02 to 600 mg/m³. Among 218 actors with detailed exposure assignment, increases in respiratory, throat, and nasal symptoms were associated with higher peak, but not average, levels of exposure to glycols. Throat irritant symptoms were associated with high average exposures to mineral oil. No acute (cross-shift) changes in vocal cord or lung function were observed. In those with long-term exposures to high peak levels of glycols, increased inflammation of the vocal cords was observed, but there was no observed effect on lung function parameters. Actors with high chronic exposures to mineral oil had significant decrements in forced vital capacity, though lung volumes were still within the normal range.

Given the still limited nature of the studies conducted to date on theatrical smokes and fogs, it is reasonable to review what is known about potential health effects from the more common products used in these productions: glycols and mineral oils.

1.3.2 Glycols

The most common glycol components in theatrical fogs include ethylene glycol, diethylene glycol, triethylene glycol, propylene glycol, dipropylene glycol, butylene glycol, and glycerol^{2,8,9,10}.

Much of the available information about glycols is derived from toxicological experiments on animals. In general, the toxicity of glycols under normal exposure scenarios can be rated as low^{9,10}, that is, under normal exposure intensities encountered in common industrial environments, glycols are not expected to cause serious health outcomes. Since glycols are

polyfunctional alcohols, exposure to any of these substances may cause a drying of mucous membranes, resulting in irritation and drying of the eyes and respiratory tract.

The literature search did not reveal epidemiological studies that have investigated the irritant properties of the various glycols, even though glycols are commonly reported as being responsible for respiratory, eye and skin irritation^{9,10}. Table 1.1 provides a brief summary of the health effects that might be expected due to either inhalation or dermal exposure to glycols, as listed by the International Chemical Safety Cards¹¹. More serious health effects due to exposure to glycols such as central nervous system depression and renal failure were observed with ingestion of diethylene glycol¹². Spermatogenic disorders were reported in humans with a urinary metabolite indicative of ethylene glycol exposure, although the route of exposure was not specified¹³. Teratogenesis was reported in an epidemiological study looking at occupational factors and solvent exposure (parents of subjects exposed to both methyl cellosolve and ethylene glycol)¹⁴. Dermatitis has been documented as a result of exposure to butylene glycol¹⁵ and propylene glycol¹⁶.

Table 1.1 Expected health effects due to inhalation and dermal exposure to glycols

<i>Glycol</i>	<i>Types of health effects</i>
Ethylene glycol	Eye irritation, throat irritation, headache, respiratory irritant
Diethylene glycol	Eye irritation, skin irritation, respiratory irritant
Triethylene glycol	Headaches, eye irritation
Butylene glycol	Dermatitis, eye irritation
Propylene glycol	Eye irritation, skin irritation

1.3.3 Glycol thermal degradation products

The heating of organic compounds to high temperatures is well known to cause pyrolysis, generating decomposition products such as aldehydes (e.g., formaldehyde and acrolein), carbon monoxide, carbon dioxide, nitrogen oxides, and hydrogen cyanide. These products are generated during combustion and/or during prolonged heating of organic materials to high temperatures. Many of the products are asphyxiants and, at lower concentrations, respiratory irritants. In addition, polymerization products can be generated; these include the polycyclic aromatic hydrocarbons (PAHs) usually associated with combustion of biomass materials (wood, food, fuels). Exposure to this class of compounds was originally linked to scrotal cancer in chimney sweeps²⁴ and has now been linked to lung and other cancers as well²⁵. Benzo[a]pyrene is regarded as the most carcinogenic in this class of compounds. The International Agency for Research on Cancer (IARC, an agency of the World Health Organization) has classified it as probably carcinogenic (group 2a)²⁶. Naphthalene is the simplest of these ringed compounds with only two fused benzene rings. Its toxicity has recently been reviewed²⁸; the lungs (chronic inflammation) and eyes (cataract formation) appear to be the most sensitive organs. It does not appear to be carcinogenic²⁹.

Thermal degradation products of glycols that have been detected in field samples from heat-based fog generation or suggested in the literature include acrolein, acetaldehyde and formaldehyde, as well as other organic compounds^{4,7,17}. Acrolein is a very strong irritant that can cause rapid injury to the respiratory tract, eyes, and skin¹⁸. It is noted more for its acute than chronic toxicity, however dermatitis and skin sensitization have been reported¹⁷. Acetaldehyde is a mucous membrane irritant and has been demonstrated to cause eye irritation as well as dermatitis¹⁸. IARC has classified acetaldehyde¹⁹ as possibly carcinogenic (group 2b) based on animal evidence. Formaldehyde can cause irritation to the eyes, nose and respiratory tract, and asthma has also been reported¹⁸. It is classified as probably carcinogenic to humans (group 2a) by IARC²⁰.

It is important to note that the thermal decomposition products described here can also arise from other sources including off-gassing from furniture, tobacco smoke, and traffic pollution, a point raised by recent commentators on theatrical fogs²⁷.

1.3.4 Mineral oils

The literature does not indicate whether refined or unrefined mineral oils are used in fog generation. Unrefined mineral oils have been designated as carcinogenic to humans (group 1) by IARC²¹, however most mineral oils available on the market today are refined due to improvements in the manufacturing process. Refined mineral oils have not been shown to be carcinogenic. Exposure to mineral oil mist has been found to result in an increase in respiratory symptoms such as mucous membrane irritation and dyspnea²².

1.4 Rationale for the Study

The existing literature indicates that personnel in productions using glycol and mineral oil to produce fog effects are potentially highly exposed to the resulting aerosols⁴. The literature on the toxicity of these products indicates that they might be expected to produce mucous membrane irritation and other respiratory symptoms^{9-11,18}. These symptoms have been reported in actors working in these productions^{4,7}, though only a few studies have been conducted to date, mostly among theatrical performers. Some have suffered from small study sizes, poor participation rates and potential volunteer biases.

Much remains unknown. No survey has been conducted to document the proportions of the two main products which are used in the industry, and there is no documentation of the use of the many other ingredients that have been anecdotally reported by industry personnel. Almost all the measurements of exposures and response to date have been done in stage productions; how representative these are of the entertainment industry as a whole, which includes a wide range of music, theatre, film, television, and other show venues, is unknown. The studies to date have focused on actors, not the many other types of personnel who work in the industry. No measurements have examined the size distribution of the aerosols. Only one health effects study to date has included lung function measurements and examined exposure-response relationships.

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2 Research Objectives

The research reported here had several parts. The core was a cross-sectional study of exposures and health effects among employees of a wide range of entertainment industry productions using special atmospheric effects (Chapters 7 and 8, respectively). In addition, we conducted a survey of special effects technicians (Chapter 3), laboratory investigations of the products used (Chapter 4), and field testing of measurement methods which might allow industry personnel to easily monitor exposures (Chapters 5 and 6).

The research had the following specific objectives:

- To enumerate the special effects technicians in BC, and interview a sample of them about the materials and equipment they use to create atmospheric effects;
- To collect bulk samples of fluids used to generate fogs and smokes, and identify their constituents by gas chromatography/mass spectrometry;
- To heat the glycol fluids, in a laboratory setting, to the temperatures used in fogging machines to identify thermal degradation products which result;
- To select a sample of sites using atmospheric effects, for monitoring of aerosol concentrations on the set and in the breathing zones of personnel, and for assessing health outcomes among personnel;
- To measure area aerosol concentrations using a variety of direct-reading aerosol monitoring devices to allow selection of a simple-to-use instrument for on-site exposure monitoring by production staff;
- To determine whether self-reporting of exposure to visible fogs by production personnel is a feasible substitute for exposure monitoring;
- To select a representative sample of productions using atmospheric effects, and measure the area exposures to aerosols, specific glycols, aldehydes, and polycyclic aromatic hydrocarbons at the site;
- To measure the size distributions of the aerosols at these sites;
- To measure the personal exposures to aerosols and polycyclic aromatic hydrocarbons among cast, crew, musicians, and special effects technicians;
- To identify factors associated with increased and decreased personal exposure levels at these sites;
- To collect information about respiratory symptoms, mucous membrane irritation, other symptoms, and lung function among the staff whose exposures are measured, and to evaluate the association between fog exposure levels and these health symptoms; and
- To make recommendations about control measures based on the results of the study.

3 Survey of Special Effects Technicians

3.1 Methods

There is no comprehensive registry of special effects technicians in the province of British Columbia, however the International Alliance of Theatrical Stage Employees (IATSE) Local 891 includes all the unionized personnel in the greater Vancouver area. IATSE provided a list of all 133 members in the special effects division for the year 2000, and from these 65 were randomly selected to take part in the survey. In the late spring and summer of 2000, each selected member was sent a letter explaining our study and asking them to participate. Those who did not respond by telephone were sent an additional letter, then individually contacted by an employee of the union.

All willing subjects were subsequently contacted by study personnel to arrange an in-person interview about the chemicals and fog-generating equipment used and the effects created (see Appendix A for data collection form). Descriptive statistics (means for continuous data; counts and percentages for categorical) were used to summarize the data.

3.2 Results

Of the 65 IATSE Local 891 members randomly selected, 51 were contacted and 30 agreed to be interviewed. Because 10 'yes' respondents could not be reached subsequent to their original agreement to participate, only 20 of these members were interviewed, a participation rate of 31%. Interviews of 3 additional special effects technicians were conducted during the exposure monitoring and health study, providing a total of 23 interviews. The low rate of participation makes it possible that the sample is not representative.

Table 3.1 summarizes characteristics of the participating special effects technicians. Almost all worked primarily in the television and movie industry. They averaged about 9 years of experience in the job, and worked long work days and work weeks. About half owned their own fog machines, and about 40% on occasion formulated their own fluids.

Table 3.1 Characteristics of the special effects technicians interviewed, all subjects combined and stratified by specific job subcategory (results from all interviewees combined in bold)

	<i>All interviewees</i>	<i>Special effects technician/assistant</i>	<i>Special effects coordinator</i>	<i>Other classifications*</i>
n (%)	23	11 (48%)	9 (39%)	3 (13%)
Years of experience	8.9	5.8	11.7	12.3
Primary industry: TV/movie (%)	96	100	100	66
Primary industry: theatre (%)	4	0	0	33
Average shift length (hrs)	12.2	12.4	12.4	10.7
Average hours worked per week	62.0	60.0	65.0	60.0
% technicians owning fog machines	48	18	100	0
% technicians formulating fog fluid	39	27	67	0

* rigging coordinator, puppeteer, and electrician

Table 3.2 describes the machines owned and used by the interviewees. The most commonly used machines were LeMaitre and Rosco for glycol-based fluids, Hessa and IGEBA for either glycol- or mineral oil-based fluids, and bee-smokers. Although many of the technicians owned fog machines, they also used equipment that they did not own, providing a diversity of machines for their repertoire of effects.

Table 3.2 Percent of technicians who had used and/or owned the various fog machines and special effects devices, all subjects combined and stratified by specific job subcategory (results from all interviewees combined in bold)

	<i>All interviewees</i>		<i>Special effects technician/assistant</i>		<i>Special effects coordinator</i>		<i>Other classifications*</i>	
	<i>Used</i>	<i>Own</i>	<i>Used</i>	<i>Own</i>	<i>Used</i>	<i>Own</i>	<i>Used</i>	<i>Own</i>
<i>Glycol based fog machines</i>								
Corona Integrated Technology®	17	4	27	0	11	11	0	0
LeMaitre®	87	39	100	9	100	89	33	0
Lightwave & High End System®	17	4	9	0	22	11	33	0
Mole fogger/Madewill fogger	48	4	46	0	56	11	33	0
Radioshack® fogger	44	26	46	9	56	56	33	0
Rosco®	70	13	73	0	100	33	33	0
<i>Mineral oil based fog machines</i>								
Curtis fogger	9	0	9	0	11	0	0	0
Diffusion™ fogger	35	4	46	9	22	0	0	0
Navy fogger	13	0	18	0	11	0	0	0
<i>Glycol and mineral oil fog machines</i>								
Burgess® fogger	35	4	18	0	56	11	33	0
Crackers	30	4	27	0	44	11	0	0
Hessa	87	43	100	18	89	89	33	0
IGEBA®	87	4	100	0	89	11	33	0
MDG®	52	4	46	0	56	11	67	0
<i>Other</i>								
Bee-Smoker	83	22	82	0	100	56	33	0
Chill chamber	18	13	82	0	100	33	0	0
Dry ice barrel (chugger, rumble pot)	20	17	82	0	100	44	67	0
Nitrogen fogger	8	4	36	0	44	11	0	0
Smoke cookie	17	17	73	0	89	44	33	0
Steamers	13	9	64	0	67	22	0	0

Table 3.3 indicates the fluids or materials used and the types of effects created with each machine type, and the typical location of use. The glycol-using machines were typically used with the fluid supplied by the manufacturer, but this was rarely the case for any other type of machine or special effects device. Most machines were used in either indoor or outdoor locations, and many could be used to create diverse effects, including source smoke, large volume smoke, smoldering, atmospheric haze, low lying fog, and steam effects. Only smoke cookies were used to create coloured smoke. Mineral oil-based machines were limited to a more circumscribed set of effects, as were crackers, bee-smokers, and steamers.

Table 3.3 Fluids and materials used, location of use, and effect created for each fog machine type

	<i>Manufacturer supplied fluid used</i>	<i>Other fluids or materials used*</i>	<i>Used in indoor or outdoor environments</i>	<i>Effect created**</i>
<i>Glycol based fog machines</i>				
Corona Integrated Technology®	yes	no	in & out	1, 4
LeMaitre®	yes	no	in & out	1, 2, 3, 4, 5, 6
Lightwave & High End System®	yes	no	in & out	1, 2, 3, 4, 5, 6
Mole fogger/Madewill fogger	yes	2	in & out	1, 2, 3, 4, 5
Radioshack® fogger	yes	2	in & out	1, 2, 3, 4, 5, 6
Rosco®	yes	no	in & out	1, 2, 3, 4, 5, 6
<i>Mineral oil based fog machines</i>				
Curtis fogger	no	1	out	2, 5
Diffusion™ fogger	yes	no	in	4, 6
Navy fogger	no	1	out	2, 6
<i>Glycol and mineral oil fog machines</i>				
Burgess® fogger	no	1, 2, 3	out	1, 3, 4, 5
Crackers	no	1,2	in & out	1, 4
Hessy	no	1, 2, 3	in & out	1, 2, 3, 4, 5, 6
IGEBA®	no	1, 2	out	2, 4, 6
MDG®	yes	2	in & out	1, 2, 3, 4, 5, 6
<i>Other</i>				
Bee-Smoker	no	4	in & out	1, 3
Chill chamber	no	5, 7	in & out	1, 2, 6
Dry ice barrel (chugger, rumble pot)	no	5, 7	in & out	1, 2, 3, 4, 5
Nitrogen fogger	no	2, 6, 7	in & out	2, 5, 6
Smoke cookie	no	8	in & out	1, 3, 7
Steamers	no	2, 7	in & out	1, 6
		* 1. mineral/white oil 2. 'poly G' (glycol) 3. glycerin 4. bee gum burned 5. dry ice 6. nitrogen 7. water 8. cookie burned		
			** 1. source smoke 2. large volume smoke 3. smoldering effect 4. atmospheric haze 5. low lying fog 6. steam effect 7. coloured smoke	

4 Constituents and Thermal Products of Glycol Fluids

4.1 Introduction

There were two issues which inspired a series of laboratory-based tests investigating the constituents and products of the fluids. The first was the concern expressed by industry personnel that it was not clear which fluids were being used on a regular basis and to what extent the constituents of the fluids were accurately reflected in their Material Safety Data Sheets (MSDS). The latter concern arose because there were anecdotal reports that special effects technicians on occasion used additives with base fluids to create 'home brews' which produced unique effects.

The second concern arose because glycol-based fluids are heated to produce fogs, leading to the question of whether the temperatures are high enough to produce pyrolysis products. To address the issue in a better controlled environment than possible in field studies, an experimental procedure was developed to determine whether formaldehyde and other pyrolysis products might arise when commercially available or home-brewed glycol-based fluids are heated to produce fogs.

4.2 Methods

4.2.1 Sample acquisition

During field work, bulk samples of fifteen glycol-based fluids were collected from the special effects technicians. The samples were taken either from the fog machine itself or from opened bottles of fog fluid, to ensure that samples of actual fog fluids as typically used were obtained.

The fluids obtained are listed below:

- Antari™
- Atmospheres™
- CITI FCF100A™
- CITI FCF200B™
- home-brewed #1
- home-brewed #2
- LeMaitre Extra Quick Dissipating™
- LeMaitre Long Lasting™
- LeMaitre Maxi Fog™
- LeMaitre Molecular™
- LeMaitre Regular Haze™
- MBT®
- MDG Dense Fog™
- Rosco Scented-Pina Colada™
- Rosco Stage & Studio™ Unscented

4.2.2 Constituents of the fluids

A drop (25 µg) of each bulk sample was diluted with 25 mL of ethanol. The glycols in the sample were then quantified using a Varian 3400 gas chromatograph (Varian Inc., Palo Alto, CA, USA) equipped with Supelco SPB™-1000 column (Sigma-Aldrich, St. Louis, MO, USA) and a Varian Saturn II mass spectrometer, based on a revised version of NIOSH Method 5523⁴. The following 7 glycols from Acros® Organics (99% purity) were used as standards: propylene glycol; 1,3-butanediol; dipropylene glycol; diethylene glycol (2-hydroxyethyl ether); triethylene glycol; glycerin/glycerol; and tetraethylene glycol.

The measured constituents of the bulk samples were compared with the ingredients listed on the material safety data sheet (MSDS) to confirm the presence of a particular glycol and, if applicable, the percent of the glycol in the bulk fluid.

4.2.3 Thermal products of the glycol fluids

In order to identify whether heating of these fluids in fog-generating machines resulted in unknown and/or unwanted degradation products, these fluids were investigated in a pyrolysis experiment as outlined below. The method is identical to that used previously for the pyrolysis of aircraft jet engine oils and hydraulic fluids¹⁻³.

The experiment entailed heating the fluids in an environmentally controlled stainless steel chamber 54 cm wide x 64 cm long x 71 cm high (245.4 liters). A ceramic top hotplate was put at the bottom of this chamber and allowed to reach 343 °C while the top lid was open. A surface thermometer (Model 573C, Pacific Transducer Corporation) was placed on top of the hotplate to monitor the temperature. The selected temperature of 343 °C was based on the published literature and consultation with the fog machine manufacturers, who identified this as the upper operating range of the machines.

Air sampling instrumentation and sampling trains were then mounted to take air samples within the environmental chamber. A direct-reading data-logging multi-gas monitor (TMX-412, Industrial Scientific Corporation, Oakdale, PA) with sensors for NO₂, O₂, CO, and lower explosive limit (LEL; based on methane) and an indoor air quality meter (YES-204A, Young Environmental Systems, Richmond, BC) with sensors for temperature, humidity and CO₂ were suspended at the top inside of the chamber. Other sampling devices, each with its own calibrated constant-flow air sampling pump (SKC, Eighty-Four, PA, USA), were attached to the chamber sampling ports prior to each trial. These included:

- for measuring aerosol mass and PAHs, a 7-hole inhalable aerosol sampler (JS Holdings Ltd., Stevanage, UK) mounted with a 25-mm diameter, 0.45-micron pore size Teflon filter (Gelman Sciences, Ann Arbor, MI, USA) and Supelpak™ 20U Orbo43 XAD-2 tubes (Sigma-Aldrich, St. Louis, MO, USA), with air sampled at a rate of 2 L/min;
- for measuring glycols, XAD-7 OVS tubes (SKC) and midget impingers with 10 mL of ethanol; with air sampled at a rate of 2 L/min; and
- for measuring aldehydes, silica gel tubes impregnated with 2,4 DNPH (SKC), with sampled at a rate of 1 L/min.

When all instrumentation was in place and the direct reading instruments were turned on, a 0.5 mL sample of the fluid to be investigated was introduced onto a 5 cm x 5 cm piece of aluminum foil with the edges slightly curled up. This sample was put directly on top of the hot plate at

343 °C. The chamber lid was closed and, in order to prevent the direct reading instruments from thermal damage, the hot plate was kept at this temperature for 5 additional minutes, at which time it was allowed to cool off. Air sampling continued for a further 10 minutes, for a total of 15 minutes. In order to lower the limit of detection for PAHs and aldehydes, the process was repeated with a 1 mL sample of the fluid and using only the XAD-2 and silica gel tube sampling trains. After the lid of the chamber was closed, the hot plate was kept at 343 °C for a 5-minute period and sampling continued for another 40 minutes, for a total of 45 minutes. Prior to each experiment, a control sample was taken with the same procedure except no fog fluid was placed in the weighing boats. After each experiment, including the control samples, the insides of the chamber and hotplate were thoroughly cleaned with ethanol, then the chamber was aerated.

All filter air samples were quantified gravimetrically on a micro-balance (M3P, Sartorius, Germany). Prior to triplicate pre-sampling weighing, filters were equilibrated for at least 24 hours to a stable temperature and relative humidity ($22\text{ }^{\circ}\text{C} \pm 0.3\text{ }^{\circ}\text{C}$ and $45\% \pm 5\%$ relative humidity). Prior to triplicate post-sampling weighing, filters were desiccated for 24 hours, then equilibrated for at least 24 hours to the same stable temperature and relative humidity.

Glycols were extracted from the sorbent tubes using ethanol and quantified using the method described in section 4.2.2.

Aldehydes were extracted with acetonitrile and quantified using a Varian 9010 high performance liquid chromatograph using WCB Method 5270⁵. The following 14 aldehydes from Supelco® T1011/IP6A Carbonyl-DNPH Mix were used as standards: formaldehyde; acetaldehyde; acrolein (note that acrolein and acetone have the same retention time); propionaldehyde; crotonaldehyde; butylaldehyde; benzaldehyde; isovaleraldehyde; valeraldehyde; o-tolualdehyde; m-tolualdehyde; p-tolualdehyde; hexaldehyde; and 2,5-dimethylbenzaldehyde.

PAHs were extracted from both the Teflon filter (after weighing) and the XAD2 tubes with toluene and quantified using a Varian 3400 gas chromatograph with a flame ionization detector using NIOSH Method 5515⁶. This protocol was altered to decrease the detection limits by concentrating the filter and sorbent tube extracts four-fold to 1 mL using nitrogen gas and increasing the injection volume from 2 μL to 5 μL . The following 16 PAHs from Supelco® EPA 610 Polynuclear Aromatic Hydrocarbons Mix were used as standards: naphthalene; acenaphthylene; acenaphthene; fluorine; phenanthrene; anthracene; fluoranthene; pyrene; chrysene; benzo(a) anthracene; benzo(k)fluoranthene; benzo(b)fluoranthene; benzo(a)pyrene; indeno(1,2,3-cd)pyrene; dibenzo(a,h)anthracene; and benzo(ghi)perylene.

4.3 Results

4.3.1 Constituents of the glycol fluids

The results from the GC-MS analysis of bulk samples of various theatrical fog producing fluids that were collected at the time of aerosol sampling are summarized in Table 4.1. This table also provides a comparison to the ingredients reported on the MSDS for each product. While most fluids were found to have the same composition as reported on the MSDS, there were a number of inconsistencies between the reported ingredients and those actually present in the following fluids: LeMaitre Long Lasting; MDG Dense Fog; and the two Rosco fluids (highlighted in bold in Table 4.1). These differences may indicate that some fluids may have been contaminated with other fluids in the fog machines.

Table 4.1 Presence and composition (%) of bulk glycol-based fluid samples, based on Material Safety Data Sheets (MSDS) and gas chromatography-mass spectrometry (GC-MS) analysis (in bold where GC-MS results differed from MSDS)

	<i>Propylene glycol</i>		<i>1,3-butandiol</i>		<i>Dipropylene glycol</i>		<i>Diethylene glycol</i>		<i>Triethylene glycol</i>		<i>Glycerin/glycerol</i>		<i>Tetraethylene glycol</i>	
	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>
Antari™	√ *	√ (13)	X	ND	X	ND	√ *	ND	√ *	√ (21)	X	ND	X	ND
Atmospheres™	√	√ (28)	X	ND	X	ND	X	ND	√	√ (20)	X	ND	X	ND
CITI FCF100A™	n/a	√ (60)	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	ND
CITI FCF200B™	n/a	√ (28)	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	√ (34)	n/a	ND
home-brewed #1	n/a	√ (39)	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	√ (55)	n/a	ND
home-brewed #2	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	√ (21)	n/a	ND	n/a	√ (19)
LeMaitre Extra Quick Dissipating™	√ (<40)	√ (34)	X	ND	X	ND	X	ND	X	ND	X	ND	X	ND
LeMaitre Long Lasting™	X	√ (27)	X	ND	√ (<35)	ND	X	ND	√ (<35)	√ (18)	X	ND	X	ND
LeMaitre Maxi Fog™	X	ND	X	ND	√ (<25)	√ (19)	X	ND	√ (<25)	√ (17)	X	ND	X	ND
LeMaitre Molecular™	√ (<90)	√ (75)	X	ND	X	ND	X	ND	X	ND	X	ND	X	ND
LeMaitre Regular Haze™	X	ND	X	ND	X	ND	X	ND	X	ND	√ (<10)	ND	X	ND
MBT®	X	ND	X	ND	X	ND	X	√ (21)	X	ND	X	ND	X	ND
MDG Dense Fog™	X	√ (54)	X	ND	X	ND	X	ND	X	√ (7)	X	ND	X	ND
Rosco Scented Pina Colada™	X	√ (13)	X	√ (14)	X	ND	X	ND	X	√ (22)	X	ND	X	ND
Rosco Stage & Studio™ Unscented	X	√ (20)	X	√ (25)	X	ND	X	ND	X	√ (23)	X	ND	X	ND

√ = indicated on MSDS and/or detected on GC-MS (%)

* = MSDS indicates propylene glycol, glycerol or di- or tri- ethylene glycol

X = not indicated on MSDS

ND = not detected on GC-MS

n/a = MSDS not available

4.3.2 Thermal products of the glycol fluids

Table 4.2 reports simple gaseous constituents of the air and physical conditions inside the environmental chambers, during heating of 15 glycol-based fluids (listed in section 4.2.1) to 343 °C, and under control conditions with no fluid present. There is little difference between the results in control and fluid heating conditions for any of these parameters, indicating that the temperature to which the fluids were raised inside the chamber was not high enough to result in the generation of gases usually associated with the combustion of organic compounds. This is consistent with the normal oxygen concentration measured; it would have changed considerably had breakdown occurred. Only ‘home brewed #2’ appeared to generate some carbon monoxide indicating the degradation of one (or more) of its constituents at this temperature.

Table 4.2 Physical conditions and gaseous constituents of the air in glycol heating and control conditions, for 15 different glycol-based fluids

	<i>No fluid, control conditions</i>	<i>Heating of glycol-based fog fluids</i>
Temperature (°C) ^A	24-37	25-37
% Relative humidity ^A	52-68	52-67
CO ₂ (ppm) ^B	431-490	314-569
Temperature (°C) ^B	24-36	25-35
% Relative humidity ^B	25-48	25-44
CO (ppm) ^C	0.0	0.0-2.0*
O ₂ (%) ^C	20.8-21.5	20.7-21.2
LEL (%) ^C	0.0	0.0

^A From the top of the chamber at the location of the recording instrument

^B From YES-204A monitor

^C From TMX-412 monitor

* For only 1 of 15 glycol-based fog fluids (home-brewed #2)

Table 4.3 lists the mass concentrations of the aerosols generated during heating of the fluids in the environmental chamber. The clearly increased concentrations during fluid heating indicate that the fluid was being aerosolized.

Table 4.3 Mass concentration of aerosols in the chamber air during glycol heating and control conditions, from 15 different glycol-based fluids

	<i>No fluid, control conditions</i>	<i>Heating of glycol-based fog fluids</i>	<i>Heating of glycol-based fog fluids, blank corrected</i>
Minimum [mg/m ³]	0.011	0.052	0.04
Maximum [mg/m ³]	0.149	213	213
Arithmetic mean [mg/m ³]	0.075	56.9	56.9
Arithmetic SD [mg/m ³]	0.049	57.6	57.6

Table 4.4 summarizes the GC-MS analysis of the glycol air concentrations generated within the stainless steel chambers during heating. The glycol aerosols produced agreed well with the glycols reported in Table 4.1, i.e., the % composition of the bulk samples based on the GC-MS analyses. This result suggests no gross changes in composition on heating.

Table 4.4 GC-MS analysis of concentrations of glycols (in mg/m³) in the chamber air during glycol heating and comparison to MSDS data, from 15 different glycol-based fluids

	<i>Propylene glycol</i>		<i>1,3-butandiol</i>		<i>Dipropylene glycol</i>		<i>Diethylene glycol</i>		<i>Triethylene glycol</i>		<i>Glycerin/glycerol</i>		<i>Tetraethylene glycol</i>	
	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>	<i>MSDS</i>	<i>GC-MS</i>
Antari™	√ *	√ (8.2)	X	ND	X	ND	√ *	ND	√ *	√ (4.7)	X	ND	X	ND
Atmospheres™	√	√ (46.4)	X	ND	X	ND	X	ND	√	√ (11.2)	X	ND	X	ND
CITI FCF100A™	n/a	√ (45.5)	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	ND
CITI FCF200B™	n/a	√ (32.7)	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	√ (26.1)	n/a	ND
home-brewed #1	n/a	√ (26.8)	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	√ (21.0)	n/a	ND
home-brewed #2	n/a	ND	n/a	ND	n/a	ND	n/a	ND	n/a	√ (8.7)	n/a	ND	n/a	√ (8.0)
LeMaitre Extra Quick	√	√ (57.7)	X	ND	X	ND	X	ND	X	ND	X	ND	X	ND
Dissipating™														
LeMaitre Long Lasting™	X	√ (45.0)	X	ND	√	ND	X	ND	√	√ (11.4)	X	ND	X	ND
LeMaitre Maxi Fog™	X	ND	X	ND	√	√ (9.0)	X	ND	√	√ (5.9)	X	ND	X	ND
LeMaitre Molecular™	√	√ (53.0)	X	ND	X	ND	X	ND	X	ND	X	ND	X	ND
LeMaitre Regular Haze™	X	ND	X	ND	X	ND	X	ND	X	ND	√	ND	X	ND
MBT®	X	ND	X	ND	X	ND	X	√ (5.8)	X	ND	X	ND	X	ND
MDG Dense Fog™	X	√ (32.6)	X	ND	X	ND	X	ND	X	ND	X	ND	X	ND
Rosco Scented Pina Colada™	X	√ (10.6)	X	√ (6.0)	X	ND	X	ND	X	√ (8.3)	X	ND	X	ND
Rosco Stage & Studio™	X	√ (16.0)	X	√ (11.2)	X	ND	X	ND	X	√ (9.6)	X	ND	X	ND
Unscented														

√ = indicated on MSDS and/or detected on GC-MS (mg/m³)

* = MSDS indicates propylene glycol, glycerol or di- or tri- ethylene glycol

X = not indicated on MSDS

ND = not detected on GC-MS

n/a = MSDS not available

Table 4.5 reports the air concentrations of aldehydes detected in the chamber when the glycol-based fluids were heated. All fluids investigated released acetaldehyde and formaldehyde into the air. Propionaldehyde was released from 13 fluids and hexaldehyde from 8. Whether the heating of these fluids to 343°C resulted in the generation of these aldehydes or whether they were already present in the bulk fluids cannot be determined from these results. The former is likely the case, but would need to be verified with an aldehyde analysis of the bulk samples.

Table 4.5 Concentrations of aldehydes in the chamber air during glycol heating, from 15 different glycol-based fluids

	<i>Number of samples > LOD</i>	<i>Minimum > LOD [mg/m³]</i>	<i>Maximum [mg/m³]</i>	<i>Arithmetic mean [mg/m³]</i>	<i>Arithmetic SD [mg/m³]</i>
Acetaldehyde	15	0.022	0.878	0.367	0.313
Acrolein	0	-	-	-	-
Benzaldehyde	0	-	-	-	-
Butylaldehyde	0	-	-	-	-
Crotonaldehyde	0	-	-	-	-
2,5-Dimethylbenzaldehyde	0	-	-	-	-
Formaldehyde	15	0.079	1.436	0.391	0.373
Hexaldehyde	8	0.0005	0.0022	0.0012	0.0006
Isovaleraldehyde	0	-	-	-	-
Propionaldehyde	13	0.026	0.269	0.126	0.071
<i>m</i> -Tolualdehyde	0	-	-	-	-
<i>o</i> -Tolualdehyde	0	-	-	-	-
<i>p</i> -Tolualdehyde	0	-	-	-	-
Valeraldehyde	0	-	-	-	-

LOD = limit of detection
- = not detected

Table 4.6 reports the air concentrations of PAHs detected in the chamber when the glycol-based fluids were heated. One sample (Rosco, unscented) indicated the presence of naphthalene in the aerosol. (F-100 Atmospheres and LeMaitre Regular Haze) indicated acenaphthylene as an aerosol constituent. As before, whether these were already present in the bulk fluids or were generated upon heating needs to be verified.

Table 4.6 Concentrations of PAHs in the chamber air during glycol heating, from 15 different glycol-based fog fluids

	<i>Number of samples > LOD</i>	<i>Minimum > LOD [$\mu\text{g}/\text{m}^3$]</i>	<i>Maximum [$\mu\text{g}/\text{m}^3$]</i>	<i>Arithmetic mean [$\mu\text{g}/\text{m}^3$]</i>	<i>Arithmetic SD [$\mu\text{g}/\text{m}^3$]</i>
Acenaphthene	0	-	-	-	-
Acenaphthylene	2	0.057	0.072	0.063	0.008
Anthracene	0	-	-	-	-
Benzo(a)anthracene	0	-	-	-	-
Benzo(a)pyrene	0	-	-	-	-
Benzo(b)fluoranthene	0	-	-	-	-
Benzo(ghi)perylene	0	-	-	-	-
Benzo(k)fluoranthene	0	-	-	-	-
Chrysene	0	-	-	-	-
Dibenzo(a,h)anthracene	0	-	-	-	-
Fluoranthene	0	-	-	-	-
Fluorine	0	-	-	-	-
Indeno(1,2,3-cd)pyrene	0	-	-	-	-
Naphthalene	1	0.098	0.098	0.098	-
Phenanthrene	0	-	-	-	-
Pyrene	0	-	-	-	-

LOD = limit of detection

- = not detected

4.4 Conclusions

The constituents of the glycol based fluids was found in most cases to conform well with the ingredients listed on the Material Safety Data Sheets.

Heating of the glycol-based theatrical fog fluids to 343 °C, i.e., the maximum temperature to which these agents should be exposed under normal use conditions, could not be classified as causing pyrolysis since very little breakdown of these agents could be demonstrated. The presence of typical combustion gases such as CO₂ and CO along with a decline in O₂ concentration would have indicated pyrolysis, but changes in the levels of these gases were not observed in our experiments, except from one 'home-brew' sample which generated carbon monoxide. In addition, little or no polymerization, i.e., PAHs, could be clearly identified as being generated because of heating.

It was demonstrated, however, that certain unwanted agents were released into the air and could be measured using standard techniques. These agents include formaldehyde from all 15 glycol-based fluids, and propionaldehyde and hexaldehyde from most (13/15 and 8/15, respectively). Naphthalene was released by 1 of 15 and acenaphthylene from 2 of 15.

References, Chapter 4

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5 Evaluation of Direct-reading Aerosol Monitors

5.1 Methods

One of the objectives of this project was to evaluate techniques for the measurement of theatrical fogs that could be used by industry personnel to rapidly assess levels of exposure. Accordingly, three real-time direct-reading monitors were evaluated for ease of use, feasibility for use to assess theatrical fogs and smokes, and cost:

1. an integrating nephelometer (M903, Radiance Research, Seattle, WA, USA);
2. a personal aerosol monitor (DataRAM 1000, MIE Inc., Bedford, MA, USA); and
3. a laser single-particle counter (APC-100, Biotest Diagnostics Corporation, Denville, NJ, USA).

To compare them, area air concentrations were measured for approximately 4 hours in 32 production sites at locations near to fogging machines, where personnel would reasonably be expected to spend time (details of area measurements are provided in Chapter 7). All three direct-reading monitors were placed beside two standard filter-based monitoring devices used to assess air concentrations in units of mass per volume of air, i.e., gravimetric monitors (7-hole sampler and Marple cascade impactor), and were turned on and off at the same time as the gravimetric monitors.

The principle of operation is similar for the nephelometer and the DataRAM, as both instruments estimate the mass concentration of particles as a function of the amount of scattered light of a specific wavelength. The nephelometer records light scattering coefficients which can then be converted externally to particle mass concentrations based on calibration with gravimetric monitors measuring the same specific particle mixtures. Here, all nephelometer measurements reported in the results are calculated particle mass concentrations based upon regression of nephelometer light-scattering measurements against the 7-hole sampler mass concentrations. The coefficients for these regressions are presented in Table 5.1. The DataRAM records calculated particle mass concentrations directly; these are based upon a factory calibration with a standard test aerosol. Modifications to the DataRAM calibration and calibration of the APC particle counter can also be done, specific to the particle mixtures being measured; regressions against the 7-hole sampler for these instruments are also presented in Table 5.1.

Table 5.1 Regression slopes for calibration of direct-reading monitors against filter-based (7-hole sampler) concentrations, for all samples combined and stratified by type of fog fluid (results for all fluids in bold)

	<i>All fog fluids</i>		<i>Glycol</i>		<i>Mineral oil</i>	
	<i>Slope</i>	<i>R²</i>	<i>Slope</i>	<i>R²</i>	<i>Slope</i>	<i>R²</i>
Nephelometer	609	0.83	759	0.79	564	0.89
DataRAM-1000	0.399	0.78	0.438	0.67	0.384	0.88
APC-100 Particle Counter	4.65E-06	0.63	5.81E-06	0.63	4.24E-06	0.64

* when calibrating the nephelometer and DataRAM for sites which used both glycol and mineral oil or dry ice, the 'all fog fluids' equation was used

While the laser single-particle counter is also a light-scattering instrument, it measures individual particles in the sample air stream and classifies them into 4 particle diameter size ranges: 0.3-0.5 μm , 0.5-1.0 μm , 1.0-5.0 μm and $>5.0 \mu\text{m}$. The instrument records the total number of measured particles in each of these size ranges during a specified sampling period, enabling the calculation of particle *number* concentrations (rather than particle *mass* concentrations, as for the other monitors). Unless the specific size and density of the individual particles are known, it is not possible to convert these particle number concentrations into particle mass concentrations. The particle counter was factory calibrated at annual intervals prior to and during the September 2000 to December 2001 study period (March 2000, 2001, 2002).

Regular clean-air calibration of the all three instruments was conducted prior to each sampling session by blowing particle-free air (passed through two HEPA filters [Bacterial Air Vent Filters, Gelman Sciences] in series) into the sensing chamber and adjusting the instrument response to 0 mg/m^3 , 0 particle count, or $0 \pm 0.05 \times 10^{-5} \text{ m}^{-1}$, for the DataRAM, APC, and nephelometer, respectively.

Descriptive statistics were used to summarize characteristics of the direct-reading monitors. To compare the instruments' performances when monitoring identical atmospheres, correlations (Pearson r) and simple linear regression models were calculated to determine how well *area* air measurements by the direct-reading monitors predicted *area* measurements by the gravimetric filter-based devices.

To determine whether the direct-reading instruments could reasonably predict the *personal* breathing zone concentrations of production personnel, linear regression models were also developed for each of the area monitors with personal aerosol exposures as the dependent variable. Since the direct-reading instruments' measurements may be affected by the particle size and chemical composition of the theatrical smoke, the type of fog fluid being used was also offered in these models.

Costs for each direct-reading instrument were assessed by contacting local sales representatives, and use characteristics were recorded by study personnel during the field sampling.

5.2 Results

5.2.1 Comparisons of area measurements using direct-reading monitors to area measurements using standard methods

Table 5.2 presents summary statistics for the area aerosol concentrations measured by the standard filter-based 7-hole sampler and the three direct-reading monitors, the nephelometer, DataRAM, and APC-100 particle counter. The measurements using the nephelometer, show a narrower range and a lower arithmetic mean than the 7-hole sampler. For the DataRAM the opposite is the case, i.e., the data show a wider range and higher means than the 7-hole sampler. The APC-100 has the lowest geometric standard deviation of all instruments; other summary statistics are difficult to compare because of the differing scales of measurement.

Table 5.2 Area aerosol concentrations measured using the standard 7-hole sampler, and the direct-reading instruments: Nephelometer, DataRAM-1000, and APC-100 Particle Counter (results for 7-hole sampler in bold)

	<i>7-hole sampler</i>	<i>Nephelometer</i>	<i>DataRAM-1000</i>	<i>APC-100</i>
	<i>[mg/m³]</i>	<i>[mg/m³]</i>	<i>[mg/m³]</i>	<i>[partides per minute]</i>
n	32	28	32	29
Minimum	0.05	0.02	0.01	21,915
Maximum	17.1	2.41	29.3	288,191
Arithmetic mean	1.36	0.78	2.64	169,431
Arithmetic standard deviation	3.16	0.66	4.59	75,896
Geometric mean	0.41	0.45	0.77	142,921
Geometric standard deviation	4.21	3.67	7.31	1.98

Figures 5.1 to 5.4 are scatter plots and regression lines showing the relationships between the air concentrations measured by the three direct-reading monitors, the cascade impactor and the 7-hole sampler, considered here as the reference or ‘gold’ standard. Figure 5.1 is a plot of the two filter-based measurement methods illustrating the ideal of both a high correlation (Table 5.3) and no bias (slope near 1.0), as would be expected given the similarities between these two methods. As is evident in Figure 5.3, although the DataRAM and 7-hole sampler are highly correlated, there is a clear overestimation of the measured concentration by the DataRAM. This is a result of the instrument’s factory calibration against a ‘standard’ particle material, not the fogging fluids. The instrument software allows an adjustment to be made to correct the measurements to account for differences in particle light scattering due to differences in particle size distribution and composition. The regression equations reported in Table 5.1 can be used for this adjustment. Figures 5.2 and 5.4 show the rather strong correlation between the 7-hole sampler and the nephelometer and the weaker correlation with the APC particle counter.

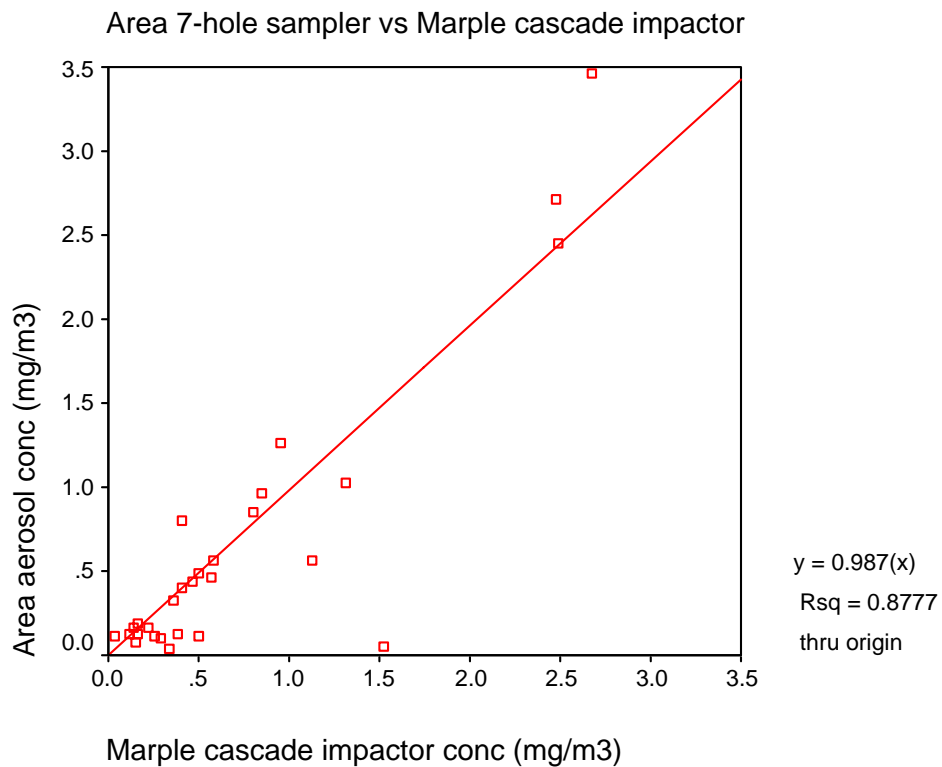


Figure 5.1 Relationship between measurements made using the two filter-based gravimetric methods: the 7-hole sampler and the Marple cascade impactor

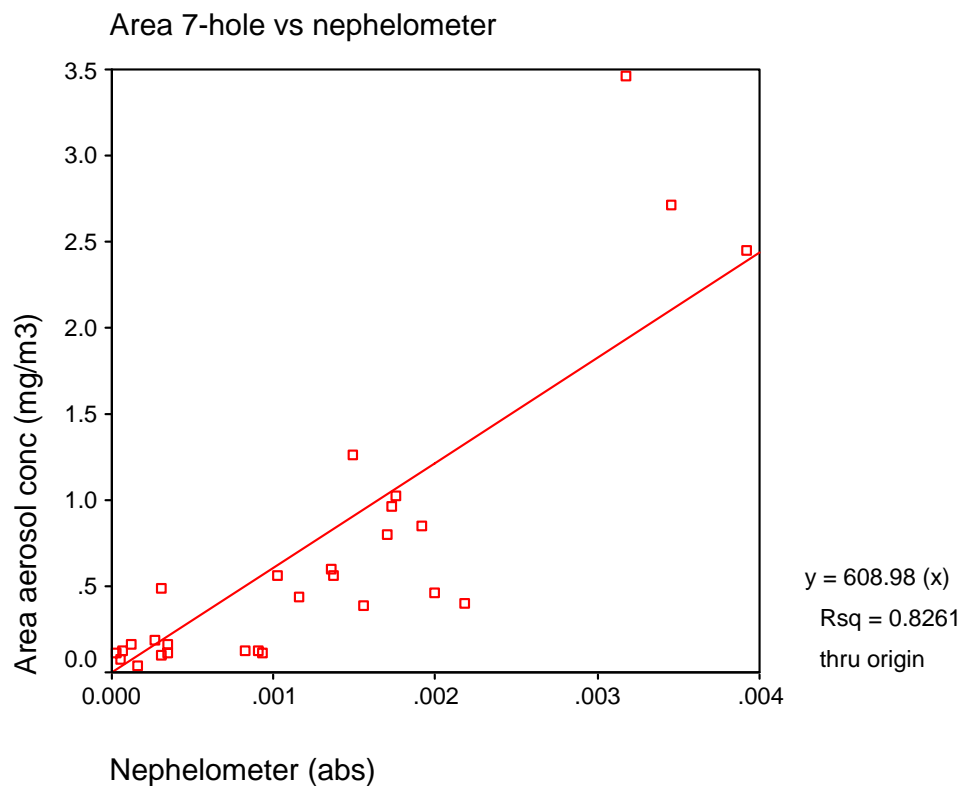


Figure 5.2 Relationship between measurements made using the 7-hole sampler and the nephelometer

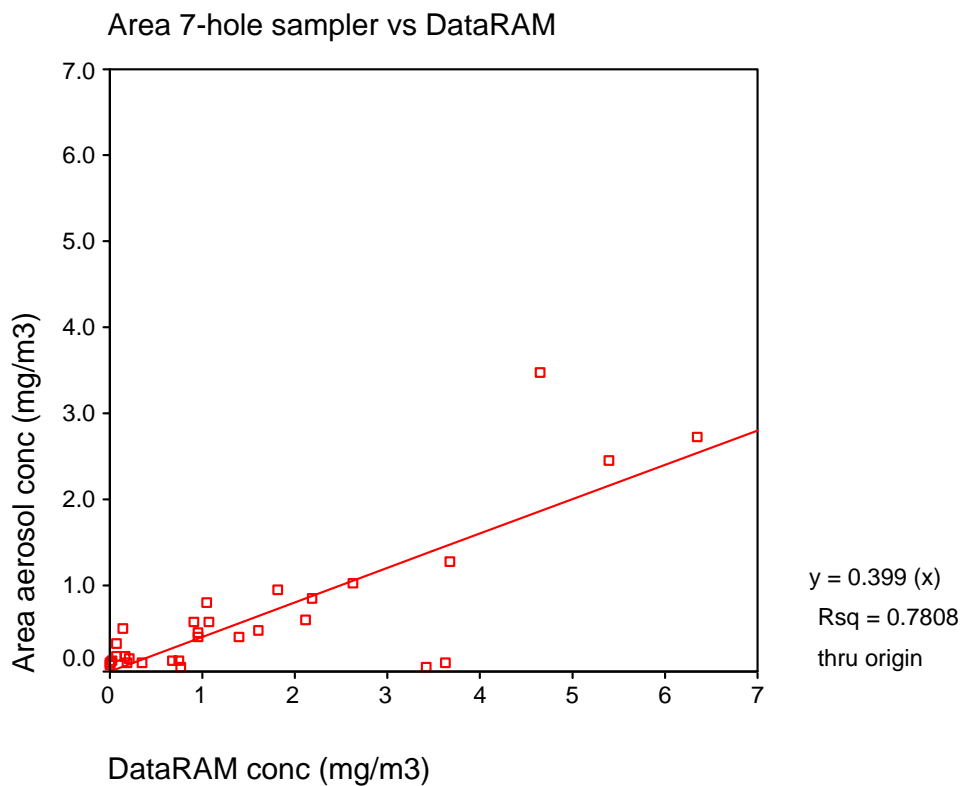


Figure 5.3 Relationship between measurements made using the 7-hole sampler and the DataRAM

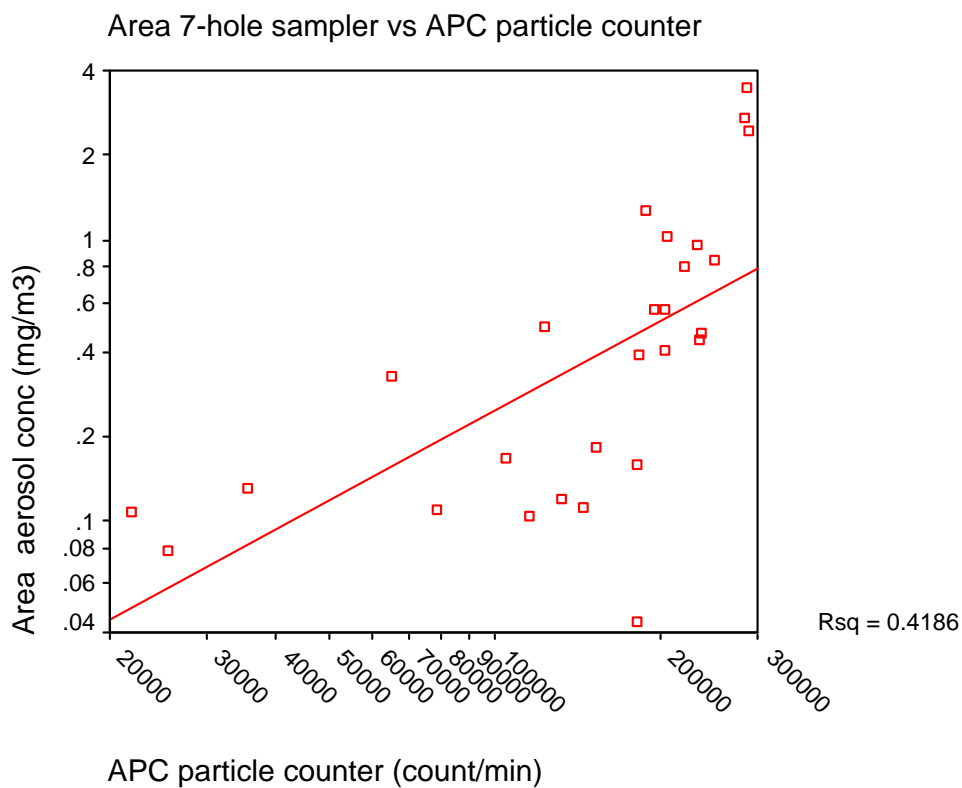


Figure 5.4 Relationship between measurements made using the 7-hole sampler and the APC particle counter

Table 5.3 presents a summary of the correlations between the different direct-reading monitors and the filter-based measurement methods. For both filter-based samplers, correlations were highest for the nephelometer and only slightly lower for the DataRAM. The correlations for these two instruments were similar, as was expected given the similarities in their operating characteristics. Somewhat lower correlations were measured for the laser particle counter. As is evident from the results presented Table 5.1, however, all the direct-reading instruments had lower correlations with the gravimetric methods for measurements of glycol-based fluids relative to those made during sessions in which mineral oil was used. This may result from the higher concentrations present when mineral oil was used, heterogeneity in the particle size of glycol-based fogs resulting in different instrument response, or a combination of these two factors.

Table 5.3 Correlations (Pearson r) between area air concentrations as measured using gravimetric methods vs. direct-reading monitors (all $p < 0.01$)

	<i>Filter-based gravimetric methods</i>	
	<i>7-hole sampler</i>	<i>Cascade impactor</i>
Nephelometer	0.86	0.87
DataRAM 1000	0.81	0.85
APC-100	0.69	0.69

Figures 5.5 to 5.10 provide examples of the types of data recorded by each of the three instruments for two separate sampling sessions, one (Figures 5.5-5.7) in which a glycol-based fluid was used and another (Figures 5.8-5.10) in which a mineral oil fluid was used. In all cases, the instruments responded to increases in airborne particle concentrations although there do appear to be differences in the sensitivity and speed of the response. Figures 5.5 and 5.8 present data from the nephelometer measurements. These figures present mass concentration measurements directly calculated by the nephelometer and calculated using the relationship between the nephelometer and the 7-hole sampler (Table 5.1). Figures 5.6 and 5.9 present DataRAM measurements for both the raw data as recorded by the instrument as well as the 'calibrated' data based on adjusting the instrument response according to the relationship with the 7-hole samples (Table 5.1). This calibration has the effect of decreasing the measured concentration. Figures 5.7 and 5.10 present data from the APC particle counter, in which different size ranges of particles are counted. From these graphs, the predominance of particles larger than $0.5 \mu\text{m}$ is evident, although the particle size distribution appears to be complex, with different size ranges showing increased concentrations at different times. There is general agreement between the calculated results for the nephelometer and the DataRAM.

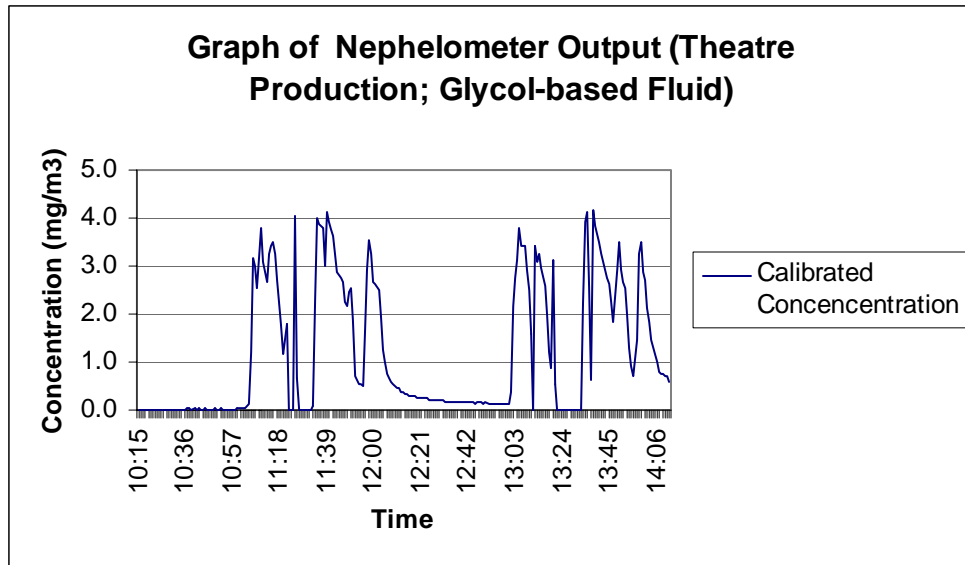


Figure 5.5 Output of nephelometer during a theatre production using glycol-based fluids, data after calibration against 7-hole sampler (relationship shown in Table 5.1)

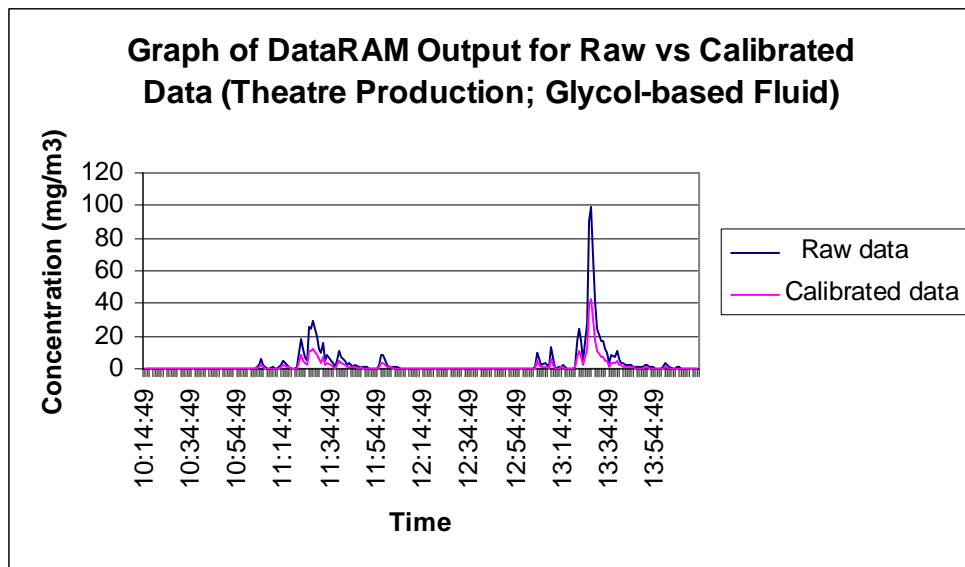


Figure 5.6 Output of DataRAM during a theatre production using glycol-based fluids, raw data and data after calibration against 7-hole sampler (relationship shown in Table 5.1)

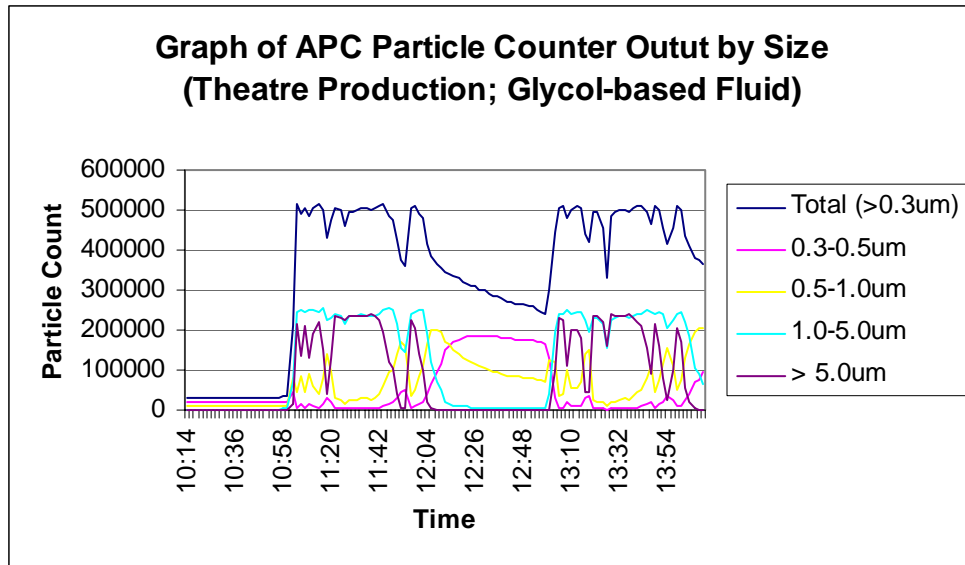


Figure 5.7 Output of APC particle counter during a theatre production using glycol-based fluids, total concentration and concentration stratified by particle size

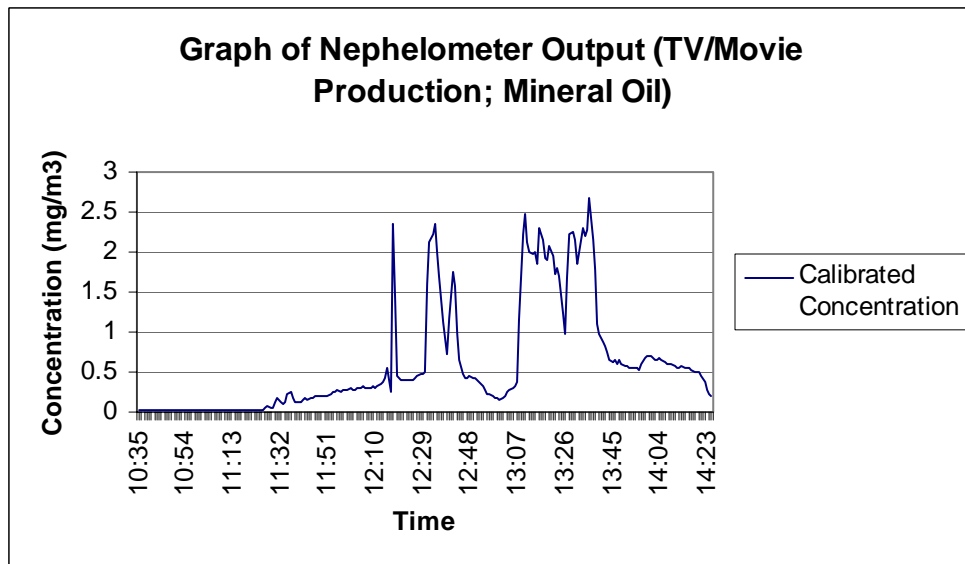


Figure 5.8 Output of nephelometer during a TV/movie production using mineal oil-based fluids, data after calibration against 7-hole sampler (relationship shown in Table 5.1)

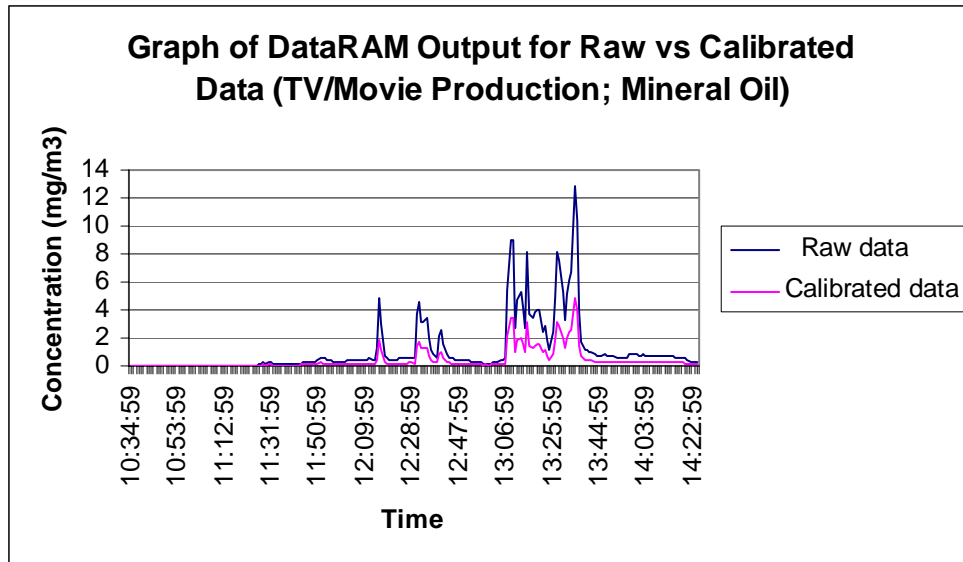


Figure 5.9 Output of DataRAM during a TV/movie production using mineral oil-based fluids, raw data and data after calibration against 7-hole sampler (relationship shown in Table 5.1)

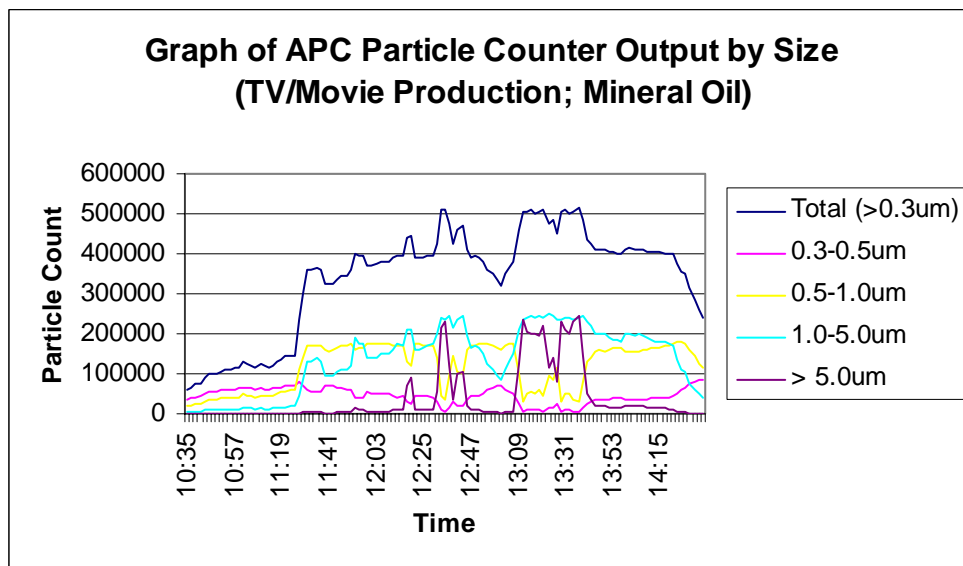


Figure 5.10 Output of APC particle counter during a TV/movie production using mineral oil-based fluids, total concentration and concentration stratified by particle size

5.2.2 Comparisons of area measurements using direct-reading monitors to personal measurements using standard methods

While the previous comparisons were between the various *area* samples, another consideration in assessing the usefulness of the direct-reading monitors is their relationship with measured

personal exposures, taken in the breathing zones of industry personnel. Differences may result from the differences in measured area vs. personal concentrations (Figure 5.11) as well as differences in measurement techniques (direct-reading monitors vs. the 7-hole sampler; Figures 5.12 to 5.14). Table 5.6 presents the results of regression models that also considered the potential impact of different fluid mixtures.

From the scatter plots of the measurement data presented in the figures, it is evident that for equivalent samplers (7-hole samplers, Figure 5.11) only 45% of the variability (R^2) in measured personal exposures can be explained by an area sample. After adjusting for the different types of fluids (Table 5.6) only a slightly higher amount of variability in personal exposures is explained by the area measurements ($R^2=49\%$). The variability predicted by the other area sampler (Marple cascade impactor) is very similar, though slightly higher. Given that all of the direct-reading monitors use different measurement principles, it is unreasonable to expect that their area measurements would explain a greater proportion of the variability in filter-based *personal* exposure measures than either of the two filter-based *area* samplers. While this is clearly the case, the DataRAM and nephelometer perform only moderately worse in predicting the personal sample concentrations (see model R^2 in Table 5.6).

Table 5.6 Linear regressions of concentrations measured using the *area* monitors as predictors of *personal* concentrations measured using gravimetric methods, adjusting for type of fog fluid used

<i>Area Sampler</i>		<i>Fog fluid adjusted for in model</i>		<i>n</i>	<i>Intercept</i>	<i>Model R^2</i>	<i>Model p-value</i>
<i>Type</i>	<i>coefficient</i>	<i>Type of fluid</i>	<i>coefficient</i>				
7-hole sampler	0.72	Mineral oil	0.34	104	0.08	0.49	<0.001
Marple cascade	0.91	-	-	101	0.07	0.50	<0.001
Nephelometer	560	Glycol and mineral oil	0.63	98	0.08	0.40	<0.001
DataRAM-1000	0.31	Mineral oil	0.77	104	697	0.43	<0.001
APC-100	5.9E-06	Glycol and mineral oil	0.71	97	0.21	0.25	<0.001

- = no fluid adjusted for in Marple cascade impactor model

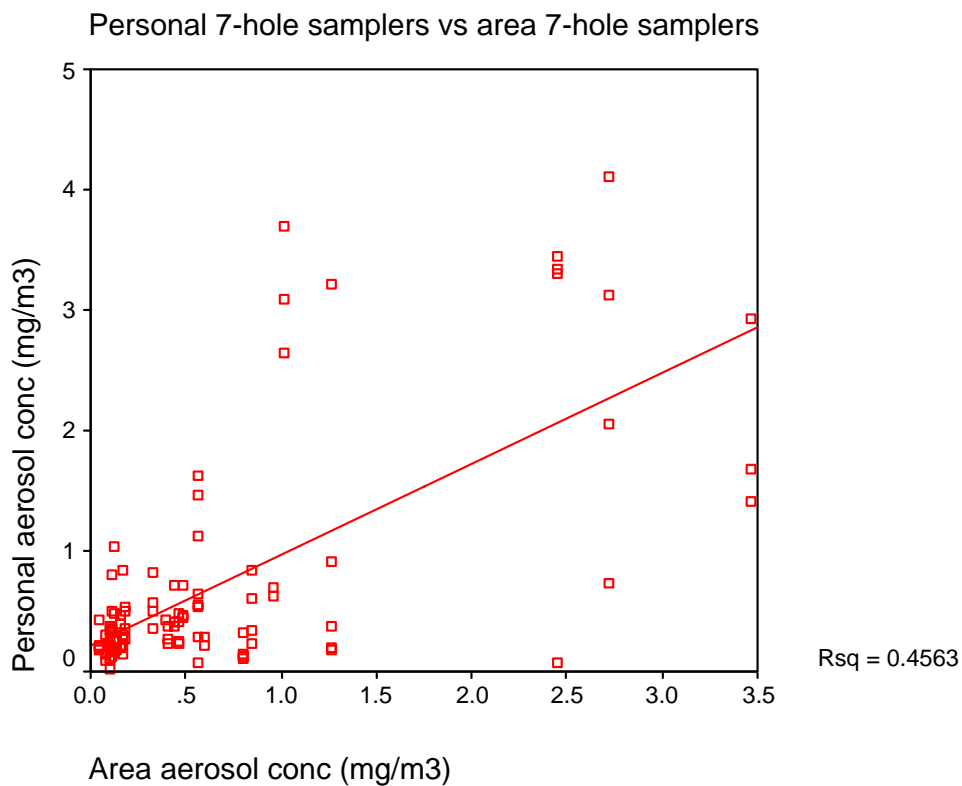


Figure 5.11 Comparison of area and personal measurements using the 7-hole sampler

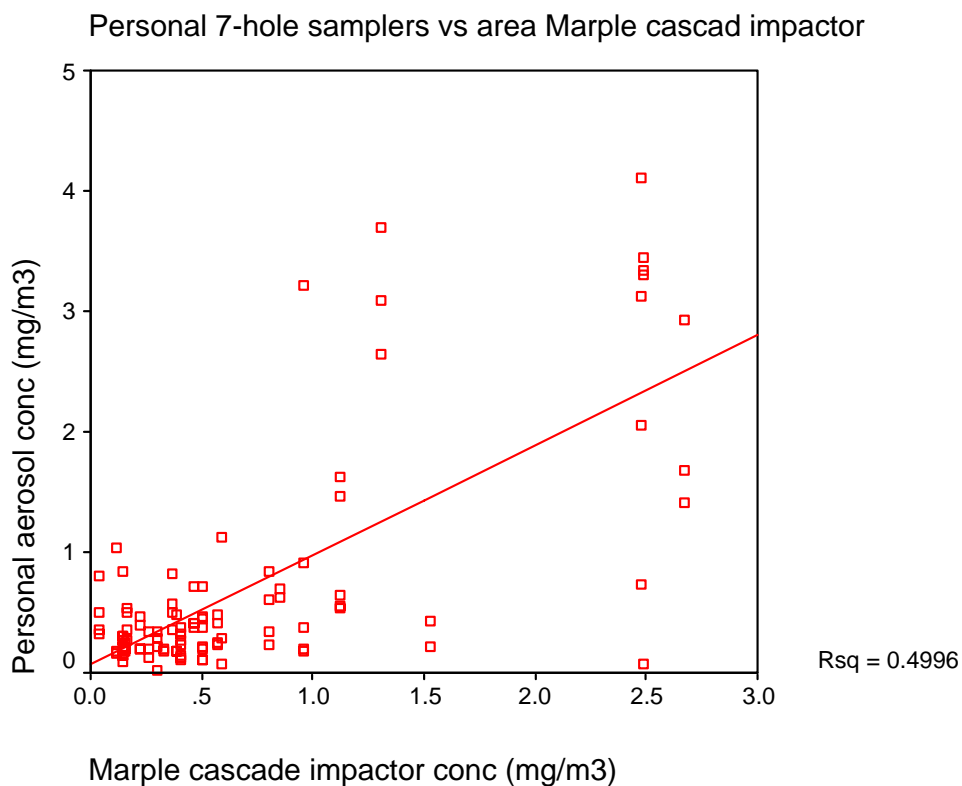


Figure 5.12 Comparison of area (Marple cascade impactor) to personal measurements (7-hole sampler)

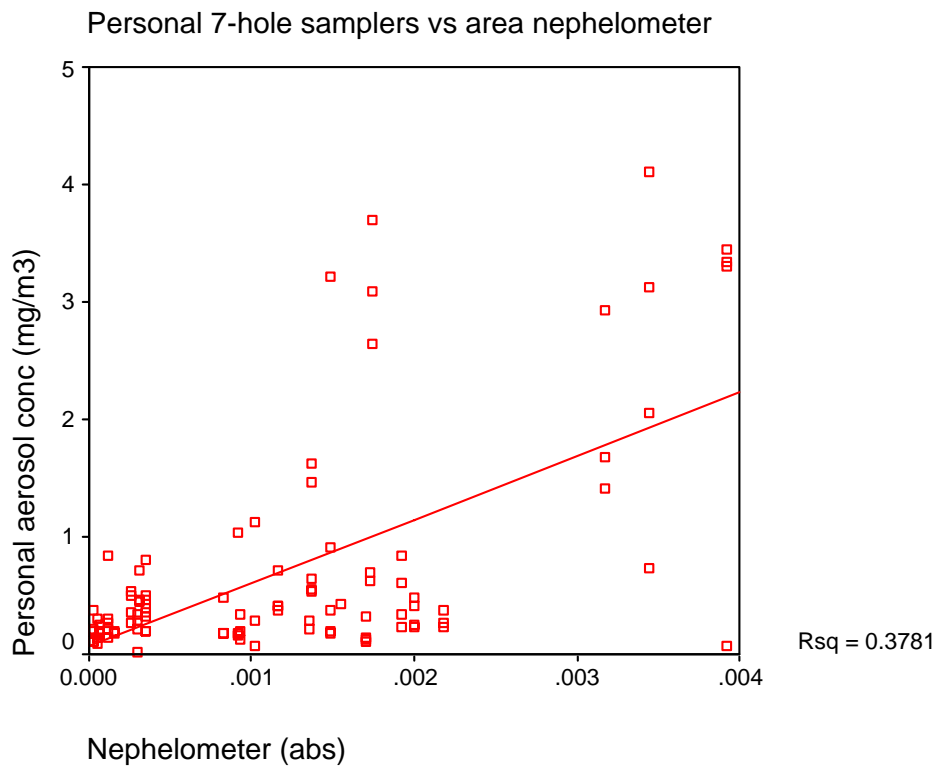


Figure 5.13 Comparison of area (nephelometer) to personal measurements (7-hole sampler)

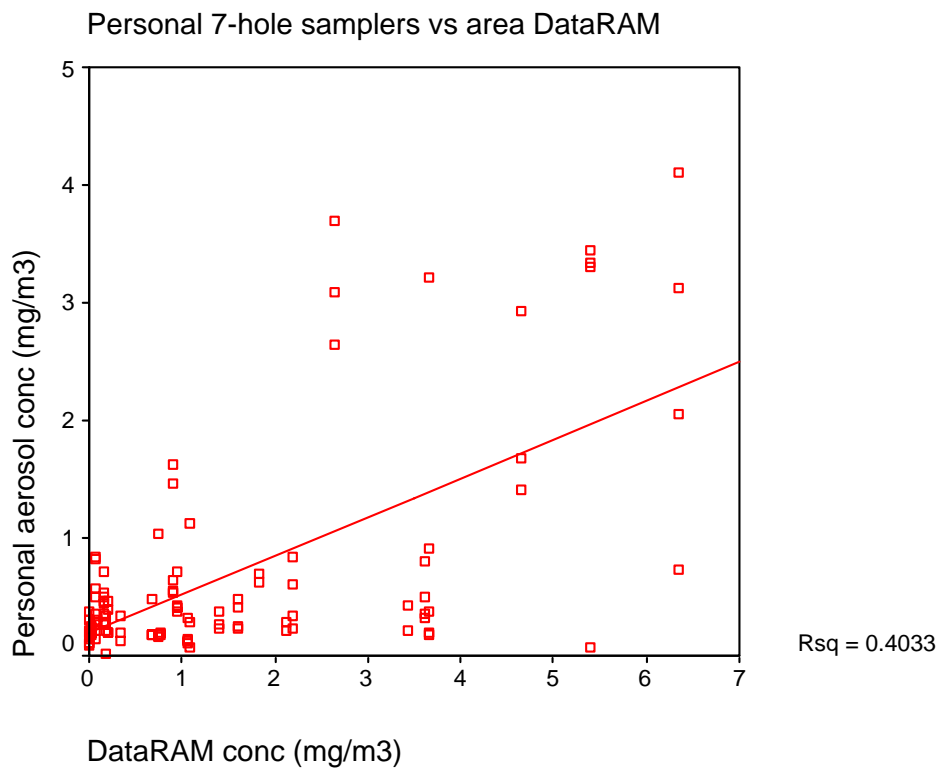


Figure 5.14 Comparison of area (DataRAM) to personal measurements (7-hole sampler)

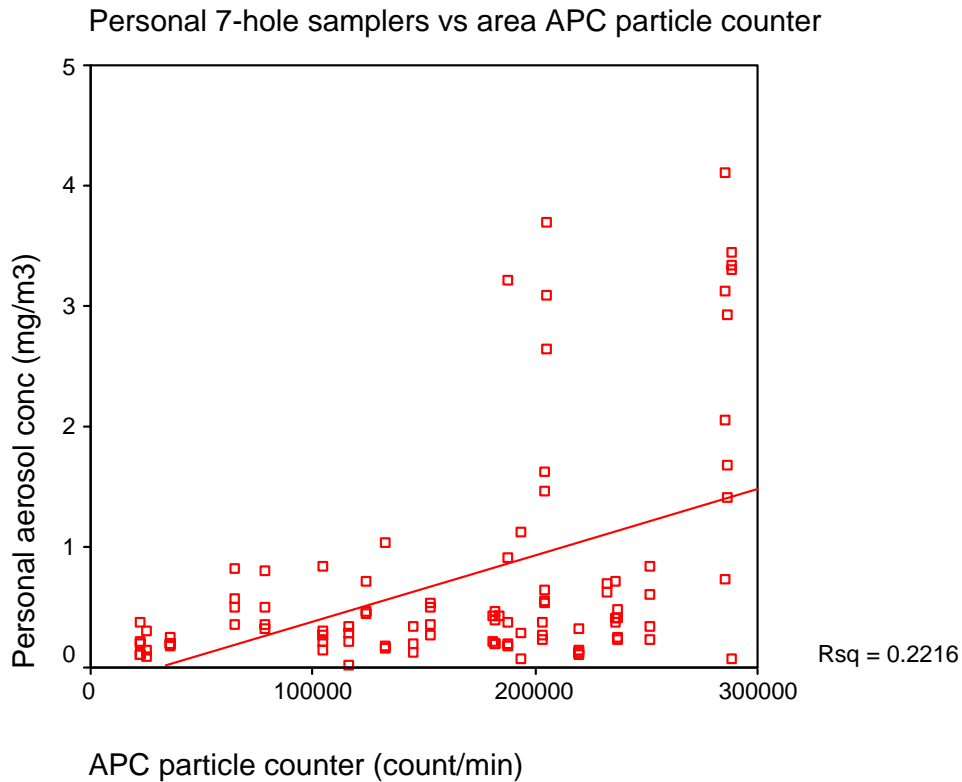


Figure 5.15 Comparison of area (APC particle counter) to personal measurements (7-hole sampler)

5.2.3 Cost and ease of use of the direct-reading monitors

Comparisons between the instruments also were based upon purchase cost and ease of use as assessed by the study technicians.

1. Nephelometer: \$6,200 CAD
 - Bulky
 - Silent
 - Requires external measurements for concentration measurement calibration
2. DataRAM: \$8,000 CAD
 - Most user-friendly (easiest to interpret)
 - Both area and personal samples possible
 - Lightest when using a 9V battery
 - Silent
3. APC: \$6,500 CAD
 - Provides some particle size distribution information
 - Both area and personal samples possible
 - Does not provide particle mass concentration data
 - Memory is limited to only 200 data points so must collect data with longer averaging times or download data frequently

- Not too bulky or loud

In the comparisons between the filter-based samplers and the three direct-reading monitors, the nephelometer and the DataRAM performed equally well. In all cases, the APC showed less agreement with the filter-based samplers. The nephelometer was somewhat superior to the DataRAM in comparisons to the filter-based *area* samples, but both instruments performed similarly in predicting *personal* exposure measurements, the ultimate goal of measurement. Although the DataRAM is somewhat more expensive, its superior ease of use, size and noise characteristics make it the preferred instrument of those tested for the assessment of theatrical smokes and fogs by production personnel. It should be noted that several instruments using similar measurement technology are available and might also be good choices, although they were not specifically tested in this project.

6 Observed vs. Self-reported Time Spent in Visible Fog

6.1 Methods

Perhaps the simplest way for personnel working in special effects atmospheres to gauge their exposures is to estimate the time they spend in visible fog atmospheres. Such 'self-reports' of exposure duration can be used as an exposure estimate in epidemiological studies of health effects. It was one method of estimating exposure in our health effects study (Chapter 8).

To determine how well exposure durations can be self-reported, all study subjects who participated in the cross-sectional study (reported in detail in Chapters 7 and 8) were asked at the end of their exposure measurement period (approximately 4 hours), "How many hours or minutes have you spent in an environment in which visible smoke was present?" Research personnel conducting the air monitoring observed and recorded, every 10 minutes, the location of each study subject and whether visible atmospheric effects were present at the time.

Both observed and self-reported times were measured in minutes and also converted to the percent of the total monitoring period spent in visible fog. The monitoring period differed between the self-reported and observed time records: the *self-reported* period was based on when the subjects were interviewed pre- and post-shift, whereas the *observed* period was based on times when the air sampling pumps were turned on and off. To examine the agreement between the observed and self-reported times, paired sample t-tests and correlations (Pearson r) were conducted. Scatter plots were used to visualize the relationship between the observed and self-reported times and percent times.

The abilities of the observed and self-reported times in the fog environment as predictors of personal exposure concentrations (as measured using the 7-hole sampler) of each subject on that day were tested using simple linear regression.

6.2 Results

Table 6.1 summarizes the times spent in a visible fog atmosphere, as observed by research personnel throughout the measurement period, and as reported by study participants at the end of the period. Self-reported and observed times were positively correlated with each other; the correlations would be considered moderate. Self-reported times and % times were significantly higher on average than the observed times, by about 50% and 30% respectively. Over-reporting of exposure times is a common phenomenon, observed in other studies¹; examination of Figure 6.1 indicates one reason why this occurs. The vertical lines of data points indicate that study subjects, because they are reporting at the end of their measurement period, have the reasonable tendency to round their times to the hour or half-hour. Figure 6.2 shows slightly better agreement when % of the measurement period is used as the basis for comparison.

Table 6.1 Comparison of observed (by research personnel during exposure measurement) and self-reported (by health study subjects at the end of the exposure measurement period) times spent in visible fog

	<i>n</i>	<i>Minimum</i>	<i>Maximum</i>	<i>Arithmetic mean</i>	<i>Arithmetic SD</i>	<i>Paired t-test</i>	<i>Pearson correlation</i>
Observed time (min)	101	0	250	85.9	73.0	p<0.001	0.66 (p<0.001)
Self-reported time (min)	101	0	390	132.6	100.8		
Observed time (% of measurement period)	101	0	100	38.5	31.2	p<0.001	0.68 (p<0.001)
Self-reported time (% of measurement period)	101	0	121	50.4	36.7		

SD = standard deviation

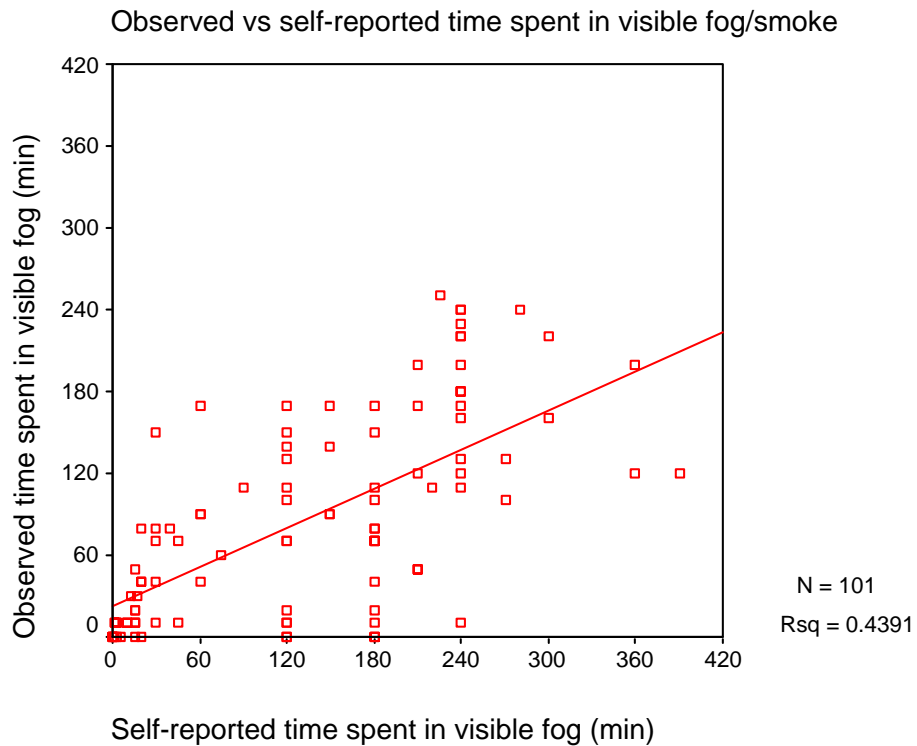


Figure 6.1 Scatterplot of observed and self-reported times spent by study subjects in visible fog

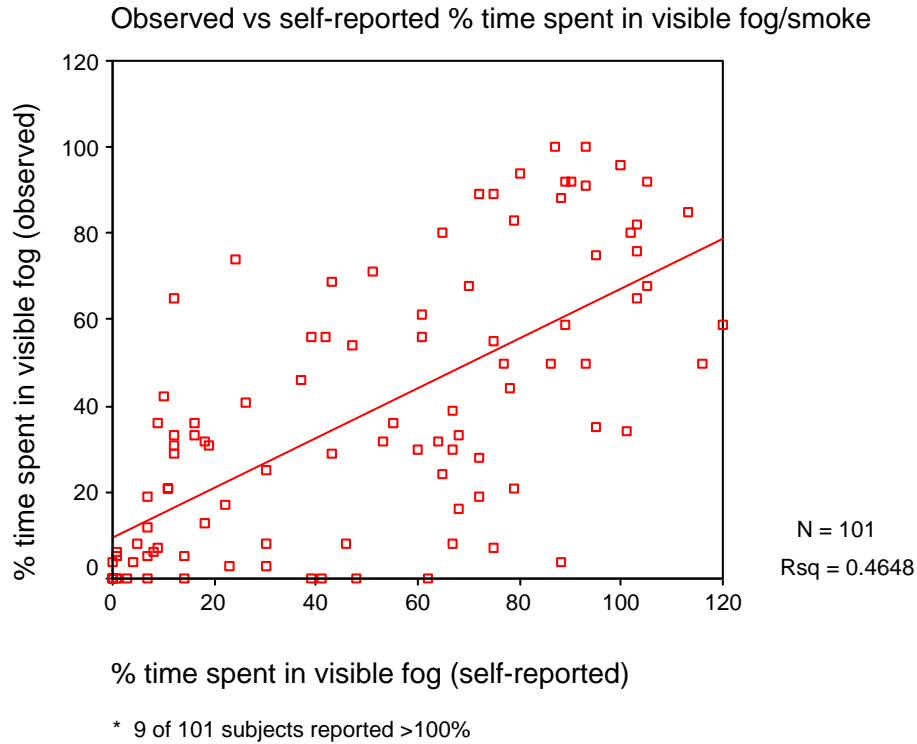


Figure 6.2 Scatterplot of percent of measurement period observed by research personnel and self-reported by study subjects, as spent in visible fog

Table 6.2 summarizes the results of simple linear regressions testing how well the observed and self-reported measures of time spent in visible fog serve as predictors of subjects' personal breathing zone exposure to smokes and fogs. All four models indicated that there were statistically significant positive relationships between the time variable and personal aerosol concentration. The observed time models predicted more of the variability in personal exposures than the self-reported, and the percent of measurement period models were better predictors than the absolute time models. The best model (% observed time) predicted about 25% (R^2) of the personal exposure variability.

Table 6.2 Simple linear regressions testing observed and self-reported time spent in visible fog as predictors of personal 7-hole aerosol concentrations (log-transformed, base e)

	<i>n</i>	<i>Intercept</i>	<i>Coefficient</i>	<i>Model R²</i>	<i>Model p-value</i>
Observed time (minutes)	111	-1.43	0.00589	0.176	<0.001
Self-reported time (minutes)	101	-1.22	0.00245	0.056	0.017
% observed time	111	-1.56	0.01655	0.247	<0.001
% self-reported time	101	-1.37	0.00925	0.105	0.001

References, Chapter 6

1. Teschke K, Kennedy SM, Olshan AF. Effect of different questionnaire formats on reporting of occupational exposures. *American Journal of Industrial Medicine*. 1994;26:327-337