Client Report :

Extending CabinAir measurements to include older aircraft types utilised in high volume short haul operation

Client report number 212034

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Executive Summary

This report describes a study undertaken by BRE for the UK cross-Departmental Aviation Health Working Group (AHWG) to monitor cabin air quality aboard older aircraft types utilised in high volume short haul operations. The purpose of this work is to address two key recommendations made in the House of Lords report on Air Travel and Health with regard to in-flight measurements of air quality parameters.

The AHWG acknowledged that the current European CabinAir project would satisfy most of the elements with regard to these recommendations. CabinAir has monitored key air quality parameters on board 50 flights representing the four generic commercial passenger aircraft types. However, the choice of aircraft types and operators in that project excluded older, classic types and operators other than ‘flag carriers’. One of the overall objectives of this project was therefore to determine whether the cabin air quality of these older aircraft was in any way an issue, and whether they differed significantly from newer types of aircraft.

Therefore, for this project, the AHWG selected two aircraft types, the BAe 146 (ventilation mode selected to provide 100% outside air to the cabin) and Boeing 737-300 (supply into the cabin is a mixture of outside and recirculated air). The intention of this current study was not to compare the two aircraft types with one another, nor to carry out detailed statistical analysis of the monitored data, nor to monitor the air quality during any ‘unusual circumstances’. The emphasis was on obtaining data from scheduled flights, reporting the results, and comparing with any health-based guidance levels that exist.

In total, we monitored fourteen flights (8 x BAe146, 6 x B737). These comprised both UK domestic flights and flights between the UK and other European countries. The flight times ranged between approximately 1 and 3 hours. Air quality parameters were monitored not only during passenger boarding and disembarkation, but also during all phases of flight – from take off, through cruise, and then to descent. We carried out the measurements not only at specific stationary locations within the cabin, but also through traverses across seat rows and along the aisles.

During each flight, we monitored the following air quality parameters within the cabin and the following is a general summary of the results:

- Cabin pressure – the average cabin altitude in cruise never exceeded the regulatory ceiling of 8000 ft. For periods during climb and descent, the rates of altitude increase and decrease did exceed the recommended values;
- Air and globe temperature – mean values usually below 26°C;

- Relative humidity – during cruise, mean RH within the BAe146 was 12.7%, and 20.0% for the B737;
- Air speed – at head height were typically below 0.2 $m.s^{-1}$
- Carbon monoxide – all values were of a similar level or less than those found in studies of air quality in homes in England. Mean levels somewhat higher on the ground than during cruise.
- Carbon dioxide – mean levels were typically between 700 and 2000 ppm during cruise, and did not exceed regulatory requirements;
- Nitrogen dioxide – all levels were below the WHO recommendations, as well as below those values found within a sample of kitchens in gas cooking homes in England. Levels of nitrogen dioxide were higher whilst on the ground than during cruise.
- Volatile organic compounds – all measured values are well within the available guidance on air quality for internal environments. Typically, the highest concentrations were found while the aircraft were on the ground.
- Carbonyls (e.g. formaldehyde, acetaldehyde, acetone, and acrolein) – low levels of all compounds, and well below World Health Organisation (WHO) limits, and HSE guidelines;
- Semi volatile organic compounds - For the BAe 146, analysis focused on testing for Exxon 2380 (used for engine and APU oil) and Skydrol (used for hydraulic oil). For the Boeing 737 flights, analysis focused on Aeroshell Turbine oil 560 (used for engine oil) and Skydrol. Very low (if any) indication of these oils present in the cabin environment of those monitored flights.
- Bacteria and fungi – higher levels whilst the aircraft is on the ground than during cruise;
- Surface dust, dust mite allergens and cat allergens – very low levels found on board;
- Ultrafine particles – elevated levels were always found during the ground phases – levels in cruise are several orders of magnitude lower.

Overall, levels of measured air pollutants on board the scheduled 14 flights were always below any recommended health limits. Although it is not possible at this stage to make detailed comparisons with the newer types of aircraft monitored within the CabinAir project, the results from this study indicate that the levels of parameters measured in this project are broadly in line with the CabinAir measurements. Therefore, we currently see no obvious difference in the cabin environment between these older types of aircraft and the newer types.

Contents

1 Introduction

This report describes the BRE study carried out for the UK cross-Departmental Aviation Health Working Group (AHWG) to monitor cabin air quality on board older aircraft types utilised in high volume short haul operations. The overall objective was to address key recommendations made in the House of Lords report on Air Travel and Health [1] with regard to in-flight measurements of air quality parameters.

Two aircraft types were selected for this work:

- BAe 146
- Boeing 737-300

Both aircraft types were first produced in the 1980s and are commonly used in high volume, short haul operations.

In consultation with the AHWG, a total of fourteen scheduled commercial passenger flights was monitored – eight on BAe146 and six on the B737. These comprised both UK domestic flights and flights between the UK and other European countries. The flight times ranged between approximately one to three hours.

This report describes the background to this project, air quality parameters monitored within the aircraft cabins, a detailed description of the sample methodology, and the monitored results. The report then concludes with the findings on these aircraft and general conclusions that we can draw from this study.

2 Background

The House of Lords Select Committee on Science and Technology published a report [1] on 15 November 2000 entitled ‘Air Travel and Health’. As part of the Government’s response to that report the Department for Transport, Department of Health, Health and Safety Executive, and Civil Aviation Authority jointly commissioned a study into ‘The Possible Effects on Health of Aircraft Cabin Environments’. This study was designed to reveal the main areas of concern, and to identify where there are significant gaps in the existing knowledge base, with a view to promoting or facilitating further, well-targeted research.

A report [2] on the first phase of this study was carried out by the Institute for Environmental Health and published in January 2001. It identified the key areas of concern for aircraft passenger and crew health. BRE carried out the second phase to this study and investigated the current state of knowledge on each of the five issues identified in stage 1. A report [3] on the findings was published at the end of July 2001.

The main aim of this current project was to address two key recommendations made in the House of Lords report on Air Travel and Health [1] with regard to in-flight measurements of air quality parameters. In particular, AHWG identified (in bold italics) the essential elements of these recommendations as follows.

1.25 “We recommend that **airlines collect, record** and use at least some of the **basic cabin environment** data being continuously monitored, not only to give authoritative substance to their refutation of the common allegations, but also to provide a better basis for public confidence in these matters. Indeed we are surprised that they do not already do so.”

1.26 “We recommend airlines to **carry out** simple and inexpensive **cabin atmosphere sampling** programmes from time to time, and to make provision for spot sample **collection in the case of unusual circumstances**. This would be helpful to passengers and staff, and also benefit airlines themselves.”

With the exception of data collection from ‘*unusual circumstances’* (i.e. deterioration or failure cases), the European CabinAir project (http://projects.bre.co.uk/EnvDiv/cabinair) satisfies most of these essential elements. In particular, the various parameters gathered from the 50 flights in the ‘Measurements in the Sky’ work item within CabinAir address all areas that could be reasonably expected in an operator’s sampling programme[1]. However, the choice of aircraft types and operators was made on a basis that excluded older, classic types, and operators other than ‘flag carriers’.

[1] Although all the monitoring work is now complete and the resulting data processed, this information is currently not available in the public domain.

3 Extending CabinAir measurements to include older aircraft – for the UK AHWG

To give a more complete benchmark of cabin air quality in today's fleets, AHWG proposed that the 'Measurements in the Skies' programme in CabinAir be expanded to allow a broader range of commercial passenger transport operations to be evaluated. In particular, the proposal was for the addition of measurements onboard two older generation aircraft types utilised in high volume, short haul operations. AHWG proposed that they should be the BAe 146 and the Boeing 737 Classic (–300 to –500 series) aircraft. The specification was that monitoring should comprise all parameters as monitored in the European CabinAir project.

3 Aircraft Types

3.1 BAe 146 aircraft

The British Aerospace 146 aircraft first flew commercially in 1983. It went out of production in 1993 (replaced by the AVRO Regional Jetliner series). It is a four-engined aircraft and was designed specifically to meet the demanding requirements of the regional air transport market where heavy utilisation over short sector lengths coupled with high reliability are paramount requirements.

Three different length versions of the BAe 146 were built:

- the 100 Series with 70-84 seats;
- the 200 Series with 85-100 seats;
- the 300 Series with 100-112 seats.

These are all single-aisle aircraft. Within this study, we have monitored all three series of aircraft.

The ventilation system can operate in two modes:

- 100% outside air supplied into the cabin;
- a mixture of outside air and recirculated air supplied to the cabin.

It is the airline's decision as to which option to select. The airline has elected to use the former option (there are other airlines that use the latter option) and this was the set-up for all of the flights monitored. This is different and an interesting contrast to most current commercial aircraft (such as the Boeing 737) which provide a mixture of outside and recirculated air to the cabin.

3.2 Boeing 737 aircraft

Within this project, the work has focused on the 300 Series aircraft. The Boeing 737-300 aircraft first flew commercially in 1984. It went out of production in 1999 (replaced by later series models). It is a twin-engined aircraft and was designed as a short to medium range airliner. It has a maximum capacity of 149 passengers. The aircraft has a single aisle.

4 Sampling Methodology

4.1 Introduction

This section describes the sampling methodology. It provides details of the following:

- number of flights;
- monitoring team;
- cabin environment parameters monitored;
- frequency and location of measurements;
- equipment used.

Monitoring of these short-haul operations with relatively intensive utilisation introduced limitations on access and time available for measurements. We therefore had to make significant adjustments and modifications to the CabinAir protocols to allow for this.

4.2 Airline and Flight selection

Two airlines kindly offered to participate in this study. The first airline used BAe146 aircraft whilst the second airline used B737-300 aircraft.

The requirement was that we monitored a total of 12 flight sectors – six on each of the two aircraft types. It was agreed that within each aircraft type, this sum total should not include any single aircraft that would be monitored more than once – a criterion that we achieved in practice.

On two occasions, we had to make return flights on the same aircraft for scheduling reasons. Rather than foregoing the opportunity for additional measurements of some key parameters, we carried out monitoring on both extra flight sectors to end with 14 flights in total.

4.3 Monitoring team

Two BRE employees were on each flight. In addition, an airline representative often accompanied each flight. In the case of the BAe 146 aircraft, an employee of BAE SYSTEMS also assisted on each flight.

4.4 Cabin environment parameters

Table 4.1 shows the cabin environment parameters monitored as part of this project. They are divided into three types of measurements:

- Stationary measurements;
- Mobile measurements;
- Additional measurements.

The following sections describe each of these three types of measurements in more detail.

Table 4.1: Cabin environment parameters monitored in this project

	Parameters
Stationary Measurements	Cabin pressure
	Air temperature
	Globe temperature
	Air speed
	Relative humidity
	Carbon dioxide
	Carbon monoxide
Mobile Measurements	Air temperature
	Air speed
	Carbon dioxide
Additional Measurements	Bacteria
	Fungi
	Endotoxins
	Volatile organic compounds (VOCs), and very volatile organic compounds (VVOCs)
	Carbonyl compounds (aldehydes and ketones)
	Semi-volatile organic compounds (SVOCs)
	Ultrafine particles
	Infra-red thermography
	Nitrogen dioxide
	Surface dust
	Dust mite and cat allergens

4.4.1 Stationary measurements

Stationary measurements were taken at two seat locations on each flight. The parameters were the following.

- Cabin pressure – The aircraft environmental control system maintains the cabin pressure, and therefore the partial pressure of oxygen, at an acceptable level. It is commonly expressed as 'cabin altitude' which is the equivalent pressure at the stated height above sea level.
- Air temperature – This was measured at both seated head height and ankle height.
- Globe temperature – This is a measure of the temperature felt by the occupant, and takes into account both the air and radiant temperature components. It was measured at seated head height.
- Air speed – Air speed is a measure of air movement within the cabin. It was measured at seated head height.
- Relative humidity – This is a measure of the moisture content of the air within the cabin. The relative humidity is naturally low in the cabin of an aircraft flying at high altitude as the outside air drawn in has very low moisture content. It was measured at seated head height.
- Carbon dioxide – Within the cabin, this is usually a product of occupant respiration and metabolism. Dry ice, if carried within the aircraft can contribute to this. However, we were not aware of the presence of the latter during the flights we monitored. At very high concentrations, carbon dioxide can have adverse health effects on occupants. However, at the levels typically found in the passenger aircraft, it is used principally as a proxy for the level of body odour and ventilation in the cabin. It was measured at seated head height.
- Carbon monoxide - This is a product of incomplete combustion. It was monitored due to the public concern over bleed air contaminants in aircraft. It was measured at seated head height.

Air temperature, radiant temperature, air speed and relative humidity are the principal environmental determinants of thermal comfort. They also influence both odour perception and the sensation of dryness (of eyes, nose, throat and skin).

Instruments to monitor and record each of these seven parameters were installed into a flight case (see Figure 4.1). Two of these flight cases were installed on different passenger seats on each flight, thus allowing simultaneous measurements in different parts of the aircraft cabin. The seats selected differed between flights to investigate different rows and seats within rows (i.e. window, middle and aisle seats).

As part of the monitoring protocol, the monitoring team endeavoured to gain access to the aircraft as early as possible prior to flight. In practice, for the BAe146 flights, the monitoring team boarded the aircraft prior to passengers boarding. For the B737 flights, the monitoring team boarded the aircraft either just prior to or towards the start of passengers boarding. Once the flight cases were safely secured to their respective seats and the instruments deployed, the monitoring began. Measurements were recorded at one minute intervals. The monitoring was stopped towards the end of passenger disembarkation (at which time the monitoring team was required to disembark).

Figure 4.1: Flight case instrumentation

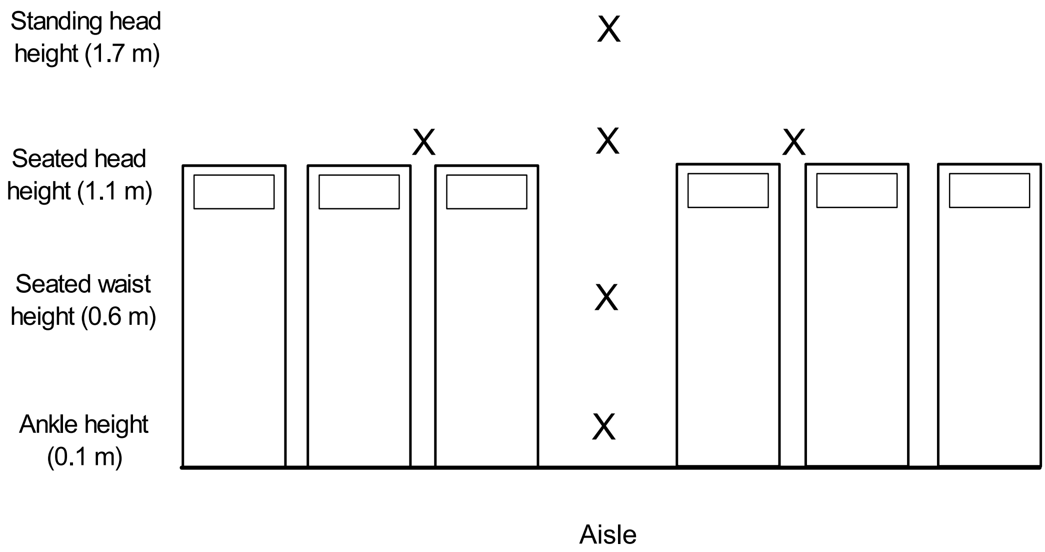
4.4.2 Mobile measurements

The stationary measurements provided good detail of the cabin environment at specific seats. The mobile measurements were carried out to determine better the variation of these parameters within rows of the aircraft. The parameters investigated were air temperature, air speed and carbon dioxide.

Both the air temperature and air speed were recorded as one minute averages (this was a pragmatic averaging period since it was difficult for the observer to capture the continuous air speed fluctuations observed at shorter intervals). The carbon dioxide reading was taken during this period and the reading recorded typically after one minute at any sampling location (unless it appeared that the reading had not stabilised, in which case, the observer waited until it did so).

On each flight, two rows were monitored once during the course of the flight. Typically one row was located within the front half of the aircraft and the other located in the rear. Six locations were monitored in each row, as shown in Figure 4.2.

Figure 4.2: Locations for transverse mobile measurements in each row



4.4.3 Additional measurements

In addition to the stationary and mobile measurements, a wide range of other cabin environment parameters were monitored. These were monitored at a single location (coincident with the stationary measurements) on each flight.

4.4.3.1 Microbiological air contaminants

This project monitored bacteria, fungi and endotoxins (components derived from the cell walls of gram negative bacteria). They are all present in the outdoor air and usually enter the cabin during boarding and disembarkation. They are also present in the outdoor air during flight, but at much lower levels, and can be entrained into the cabin air through the ventilation system. However, these are likely to be inactivated by the high temperature and pressure of the engine bleed air system.

There are also a number of other sources in the cabin environment itself. In particular, the cabin occupants are a significant source of both bacteria and endotoxins. The low levels of humidity means that the levels of fungi and mould in the cabin at altitude should be less than in most internal environments.

The sampling protocol was to take samples of bacteria and fungi during the following four phases (each sample taking one minute):

- before boarding;
- during passenger boarding;
- during cruise;
- during passenger disembarkation.

This protocol was followed for the BAe146 flights. In the case of the B737 flights, the monitoring team did not have access to monitor the aircraft prior to the passengers boarding and hence the first phase was not monitored. Whilst the pre-boarding readings provide useful 'background' levels, we consider that the absence of these readings is not too important because measurements on the BAe 146 indicate that levels are higher during other phases.

Endotoxin levels were determined in samples collected during the following two phases:

- during passenger boarding and disembarkation;
- during cruise.

Fewer measurements were made of endotoxin levels since it was necessary to sample for longer to obtain sufficient sample volume and thus obtain an accurate reading. A minimum of 30 minutes sampling time was identified and used.

4.4.3.2 Organic Compounds

A wide range of organic compounds are released from many substances used in the cabin environment including materials used in the fuselage and its fabrics and furnishings. Organic compounds are also released by the occupants themselves and their clothing and luggage. At the airport, the engine emissions from both the ground vehicles and the aircraft themselves contain organic compounds, which can be entrained into the air stream. Finally, as discussed in Section 3.1, there is some concern that bleed air contaminants can get into the cabin environment. Organic compounds can be perceived as odours and a number of them are irritants.

The organic compounds monitored in this project are classified according to their different boiling point ranges as follows.

a) Volatile organic compounds (VOCs) and very volatile organic compounds (VVOCs) – These are organic compounds, which were collected on a solid adsorbent and analysed by thermal desorption followed by gas chromatography. VOCs have boiling points usually between 75 to 250 °C. Tenax is used to collect compounds with a boiling point between approximately 75°C and 280°C and Chromosorb 106 extends the range of compounds analysed to those boiling as low as 50°C (VVOCs).

   The presence of compounds that were monitored during the European CabinAir project was investigated, as well as any other major compounds that were observed in the resulting chromatograms.

   The presence of some of the individual compounds that can be found in the cabin environment can be tentatively assigned to specific sources. For example:

   - ethanol is likely to be released into the atmosphere from the serving and consumption of alcoholic beverages;
   - toluene is a common solvent used, for example, in adhesives;
   - limonene is a scenting product added to air fresheners;
   - tetrachloroethene is a solvent used, for example, in dry-cleaning processes so its detection could be due to the presence of recently dry-cleaned clothes;
   - undecane is a major component of kerosene fuel.

b) Carbonyl compounds - This is a class of organic compound with a particular chemical functional group, the boiling points of which encompass the VOC/VVOC boiling point ranges. The more volatile members of the group are determined using derivatisation followed by solvent desorption and liquid chromatography.

   The simplest carbonyl compound is formaldehyde which is released into the atmosphere from various types of sources. Major sources of formaldehyde in the indoor environment are resins including phenol-formaldehyde and urea formaldehyde (UF) which occur for example in wood based products such as particleboard in furniture and in UF-based lacquers. Formaldehyde, as well as acetaldehyde, acetone and acrolein, are also constituents of combustion gases.

c) Semi volatile organic compounds (SVOCs) – These are collected on polyurethane foam and solvent extracted followed by gas chromatography. This technique permits analysis of compounds with a boiling point between approximately 270°C and 400°C. In this project the technique is particularly aimed at monitoring for the presence of engine oils and hydraulic fluids in the atmosphere.

The original protocol was to undertake duplicate measurements of all of these organic compounds during the following flight phases:

- on the ground;
- during climb;

- during cruise;
- during descent.

This protocol was followed for Flights 1 and 2. However, in practice, it was found that the time taken to change the many sample tubes for each phase of flight (plus those of the microbiological measurements), significantly reduced the sampling time for any one measurement. The protocol was therefore revised such that only single measurements were taken in each phase. In addition, a further measurement was taken from before take-off until the end of descent. Hence, if any particularly high reading was recorded for any phase, the additional whole flight measurement would be able to provide a verification of this reading.

4.4.3.3 Ultrafine particles and nitrogen dioxide

Both ultrafine particles (defined here as less than 1000 nm aerodynamic diameter) and nitrogen dioxide are formed as a by-product of combustion. They were both monitored continuously throughout the flight and readings taken each minute. The instruments were usually placed on a passenger seat.

4.4.3.4 Infrared thermography

Infrared thermography uses an electronic infrared camera to display the surface temperature of objects in its view. In particular, it can highlight hot and cold spots. Thermographic surveys were carried out once in each type of aircraft.

4.4.3.5 Surface dust, dust mite allergens and cat allergens

For the BAe146 aircraft, measurements were made on one aircraft on the ground. Dust was collected from the aisle carpet at three locations along the aisle. The area sampled was 50 cm x the width of the carpet and the area was vacuumed twice. It was not possible to gain access to a B737 aircraft for this work.

4.5 Sampling and analytical methods

4.5.1 Introduction

The equipment selected had to meet the following constraints for use during commercial flights.

- Suitable for use aboard commercial aircraft (i.e. would not affect the operation of the aircraft or the safety of those on board, e.g. from interfering transmitted signals, or from rupture of components at low pressure resulting in toxic chemical leaks).

- Battery operated (mains power was potentially available but at non-typical output voltage and frequency and would have required trailing cables, which would affect safety and portability).
- Small.
- Portable.
- Quick to set up.

All of the equipment used in this study was tested for radio frequency radiated emissions according to EUROCAE ED-14D/RTCA DO-160D Section 21. This testing was undertaken at BRE and approved by the airlines.

The equipment used in this study was calibrated at normal atmospheric pressure. In addition, to determine any pressure impact on the sensor response, calibration was also performed at reduced pressure. These latter measurements were performed within a hypobaric chamber at RAF Henlow. Calibrations were performed to determine the response to pressures equivalent to cabin altitudes between 0 and 8000ft (the range of pressures encountered within commercial aircraft cabin environments under normal operation). Calibration factors for reduced pressure were necessary and determined for both the carbon monoxide and carbon dioxide detectors using standard Tedlar air sampling bags filled with either zero or span gases. It was more difficult to determine these calibration factors for the nitrogen dioxide detector as nitrogen dioxide is a reactive gas and interacts with the surfaces of the Tedlar bags. A pragmatic approach was decided upon, in which this detector would only be calibrated, at a later date, if elevated levels were observed in the study whilst at altitude (which did not occur in practice). The air velocity measurements were simply calibrated by using the standard formula allowing for the change in air density.

4.5.2 Stationary measurements

The parameters were monitored as follows.

Cabin pressure – Cabin pressure was monitored with a Wika pressure transmitter type S-10. It has a range of 0 to 1 bar and an accuracy of ±2.5 mbar.

Temperature – Air temperature was measured with a T-type thermocouple. Globe temperature was measured with a T-type thermocouple contained within a hollow black ball (38 mm diameter).

Air Speed – Air speed was measured using a TSI air velocity transducer, series number 8470. This has an omni-directional probe and has a minimum detection of 0.05 ms^{-1}. It was set with a range of 0 to 2.5 ms^{-1}. It has an accuracy of ±3.0% of reading and ±1.0% of full scale.

Relative humidity – Relative humidity was measured using a Vaisala humidity and temperature probe HMP44. It has a range from 0.8 to 100% RH with an accuracy of typically ±2.0% RH.

Carbon dioxide - Carbon dioxide was measured using an Anagas Multigas infra-red analyser CD98. It has a range of 0 to 10,000 ppm with an accuracy of ±100 ppm. It has an internal data logger.

Carbon monoxide – Carbon monoxide was measured using a City Technology electrochemical sensor (A3CO EnviroCel). It has a range of 0 to 500 ppm with an minimum detection limit of 0.1 ppm.

Pump - A KNF Air Pump NMP 08L was used to supply air to the carbon dioxide and carbon monoxide sensors.

Data logger – All measurements, with the exception of the carbon dioxide unit, were recorded using a INTAB PC-Logger 2001. It includes eight analogue inputs and 220 kB memory. It includes a cold junction for the thermocouples.

4.5.3 Mobile measurements

Temperature and air speed – These were measured with a Dantec 54N50 low velocity analyser. Temperature measurements were made with a thermistor type sensor with a range of 0°C to 45°C and an accuracy of ±0.5°C. Air speed was measured with an omnidirectional low velocity transducer (54R10) with an effective measurement range of 0.1 to 5.0 ms^{-1} with an accuracy of ±5% of reading ±0.01 ms^{-1}.

Carbon dioxide – Same as for stationary measurements.

4.5.4 Additional measurements

Bacteria and fungi - These measurements were made with MB2 Microbiological Aerosol Samplers. The agar plates contained 2% (w/v) malt extract (Oxoid), 1.2% Agar No. 3 (Oxoid), 20 units benzyl penicillin ml-1 and 50 mg streptomycin sulphate ml^{-1} for fungi, for bacteria the medium was tryptone soya agar (Oxoid) containing 50 µg ml^{-1} cycloheximide. Following exposure, the plates were incubated at 25°C for 4 to 7 days after which the resulting colonies were counted. The total counts were corrected for multiple impaction by the positive hole method, following the manufacture's instructions. Fungi were identified by colony morphology or microscopic examination of the sporing structure. Pure colonies of bacteria were subcultured onto mannitol salt agar (MSA) and incubated at 37°C for 2 days, after incubation the total number of colonies which grew on MSA were considered as presumptive micrococci.

Endotoxins – Air samples within the cabin environment were drawn through 0.4µm polycarbonate filters housed in a 3-part plastic cassettes by the use of a battery operated portable air pump (Genie VSS5, Buck Inc, USA) operating at 4000cc min^{-1}. After exposure the collected endotoxins are released from the filters into pryogen free liquid and analysed using the pyrochrome Limulus Amebocyte Lysate assay (Associates of Cape Cod Inc, USA).

VOCs/VVOCs – Air is drawn through a Perkin Elmer type stainless steel tube using an air sampling pump. The tube contains a solid adsorbent, either Tenax TA (for VOCs) or Chromosorb 106 (for VVOCs). Analysis is by thermal desorption followed by gas chromatography (GC) using a Perkin Elmer Turbomass mass spectrometer (MS) for identification and flame ionisation detection (FID) for quantification. Calibration curves of the routinely determined volatile organic compounds are prepared by spiking tubes with solutions of the pure compounds. VVOCs are determined by passing clean air loaded with known amounts of the pure compounds through standard tubes. Other major compounds observed, for which calibration has not been undertaken, are quantified using the response factor for toluene.

Carbonyl compounds – Air is drawn through a Waters 'Xposure' DNPH cartridge using an air sampling pump. The cartridge is solvent desorbed using acetonitrile and the eluant analysed by high performance liquid chromatography (HPLC) using a gradient elution technique with UV detection. Identification is by retention time and quantification by external standards.

SVOCs – Air is sampled onto a polyurethane (PU) foam plug using an air sampling pump and the PU foam is solvent extracted. Analysis is by GC/MS/FID using splitless/split injection. Identification is by comparison to mass spectral libraries and reference samples of potential sources (e.g. oils) supplied by the airlines. Quantification is accomplished by comparison to the reference samples and n-C_{16} (hexadecane).

Nitrogen dioxide – Nitrogen dioxide was measured using a City Technology electrochemical sensor (A3OZ EnviroCel) and measurements recorded by an EasyLog data logger (EL-1). It has a range of 0 to 4 ppm with a minimum detection limit of 20 ppb.

Ultrafine particles – These were measured using a P-TRAK Ultrafine Particle Counter Model 8525. This instrument is based on a condensation particle counter and monitors the number of particles per unit volume in the size range 20-1000 nm. It contains an integral datalogger.

Infrared thermography – This was carried out using a FLIR systems ThermaCAM SC2000 infrared camera. It is of the 'uncooled microbolometer' detector type with a resolution of 320 x 240 pixels. It has a measurement accuracy of ±2%, a thermal sensitivity of < 0.1°C and a spectral range of 7.5 to 13 μm.

Surface radiation received by the infrared camera does not only depend on the temperature of the object in the field of view. It is also a function of surface emissivity and a number of other parameters. In order to measure temperature accurately, it is necessary to measure and compensate for the effects of these parameters.

Surface dust, dust mite allergens and cat allergens - Dust was collected using a 9.6 V battery operated portable vacuum cleaner into pre-weighed nylon bag filters. The weight of the dust collected was measured (after conditioning for 24 hr) using a five point mass balance. Cat and house dust mite antigen (Fel d1 & Der p1) was extracted from the collected dust by agitating samples in phosphate buffered saline at 4°C overnight. The levels of the antigens were measured using specific monoclonals (Indoor Biotechnologies Ltd, USA).

5 Findings

5.1 General information

Table 5.1 summaries the general flight information. All monitoring was undertaken during Winter 2002/03. Most flights were between the UK and Europe to maximise the time for data acquisition. All outbound flights had a morning departure time and all return flights had an afternoon departure time. The flight times are from take-off until landing. As discussed in Section 4.2, Flights 5 and 6 were both aboard the same aircraft (146-5) and Flights 7 and 8 were both aboard the same aircraft (146-6). Apart from this, all the aircraft monitored were different. Thus we monitored six different BAe 146 aircraft and six different B737-300 aircraft as per the work specifications.

Table 5.1: General flight information

Flight Number	Route	Aircraft Type	Aircraft ID	Passenger Loading (%)	Date	Flight Time (hrs:mins)
1	UK domestic	146-300	146-1	52	28/11/2002	1:00
2	UK domestic	146-300	146-2	65	28/11/2002	0:58
3	UK to Europe	146-200	146-3	67	10/01/2003	1:23
4	Europe to UK	146-200	146-4	65	10/01/2003	1:36
5	UK to Europe	146-100	146-5	27	17/01/2003	1:32
6	Europe to UK	146-100	146-5	27	17/01/2003	1:22
7	UK to Europe	146-200	146-6	56	24/01/2003	1:24
8	Europe to UK	146-200	146-6	30	24/01/2003	1:53
9	UK to Europe	737-300	737-1	68	04/02/2003	1:25
10	Europe to UK	737-300	737-2	70	04/02/2003	1:22
11	UK to Europe	737-300	737-3	91	07/02/2003	2:25
12	Europe to UK	737-300	737-4	87	07/02/2003	2:38
13	UK to Europe	737-300	737-5	97	12/02/2003	2:39
14	Europe to UK	737-300	737-6	83	12/02/2003	2:44

5.2 Stationary environmental measurements

5.2.1 Introduction

A summary of the results of the environmental monitoring is given here. More detailed results are given in Appendix A.

The results have not been divided between passenger classes. Whilst there were different classes on board some of the aircraft, it was not apparent that it would have a significant impact on the cabin air quality results as the seating density was the same and the only difference was likely to be the level of service received.

The results have been divided into three flight phases

- The initial ground phase – from the start of monitoring, either prior to or during passenger boarding (see Section 4.4.1), until take-off.
- The cruise phase – this is the period from the end of climb and until the start of descent.
- Whole flight – this is from the start of monitoring until the end of monitoring. It includes the initial ground phase and the cruise phase as well as climb, descent and the first five minutes on the ground time after the flight.

5.2.2 Cabin pressure

Figures 5.1 and 5.2 are examples of the variation in cabin pressure (here presented as cabin altitude in feet[2]) for the BAe146 and B737 aircraft respectively. The reasons for the non-zero cabin altitudes on the ground are due to both the height of the airports relative to sea level and the fluctuation of the atmospheric pressure from standard conditions (101.32 kPa).

Table 5.2 summarises the cabin altitude values for all flights on each aircraft type. The values were calculated as follows for each aircraft type.

- Average values were determined by calculating the mean values for each flight and then taking the average over all of the flights. The range of mean values is also shown.
- The maximum values were determined by calculating the maximum values for each flight and then taking the average over all of the flights. The range of maximum values is also shown.

According to FAR/JAR 25.841, the cabin altitude must not exceed 8000 ft under normal operating conditions. As can be seen, this limit was never exceeded. Note that whilst there are a range of values recorded, they are not random. The environmental control system is set to provide a safe cabin altitude and is dependant on several factors

[2] Following the usual convention followed in aviation.

including the aircraft's altitude. The range of maximum cabin altitudes mainly reflects the different cruise altitudes flown during the study.

SAE (ARP) 1270 recommends that in normal operation, the cabin altitude should increase at a rate no greater than 500 feet per minute and decrease at a rate no greater than 300 feet per minute. These values are sea level equivalent and hence the rates recorded need to be multiplied by the relative density at the relevant cabin altitude. This is only a recommendation and not a regulation. As can be seen, the limits were exceeded for both aircraft types.

Further analysis of the data showed that for the BAe146 aircraft, four (of seven) flights exceeded the 500 feet per minute recommendation for two or three minutes at the start of climb. Similarly, three (of six) B737 flights exceeded the recommended level again for two or three minutes at the start of climb.

The data also showed that for the BAe146 aircraft, six (of seven) flights exceeded the maximum recommended descent rate of 300 feet per minute for between 1 and 11 minutes (depending on the flight) and towards the end of descent. In a similar vein, all of the B737 flights exceeded the recommended level for between 1 and 9 minutes (depending on the flight) and towards the end of descent.

Table 5.2: Summary of cabin altitude – mean (range)

Aircraft Type	N	Average cabin altitude in cruise (ft)	Maximum rate of cabin altitude increase during climb (ft/min)	Maximum rate of cabin altitude decrease during descent (ft/min)
146	7	6729 (5916 – 7460)	506 (416 – 654)	402 (236 – 571)
737	6	6574 (6337 – 6822)	486 (418 – 554)	368 (321 – 449)

Figure 5.1: Example of cabin pressure for BAe146 aircraft

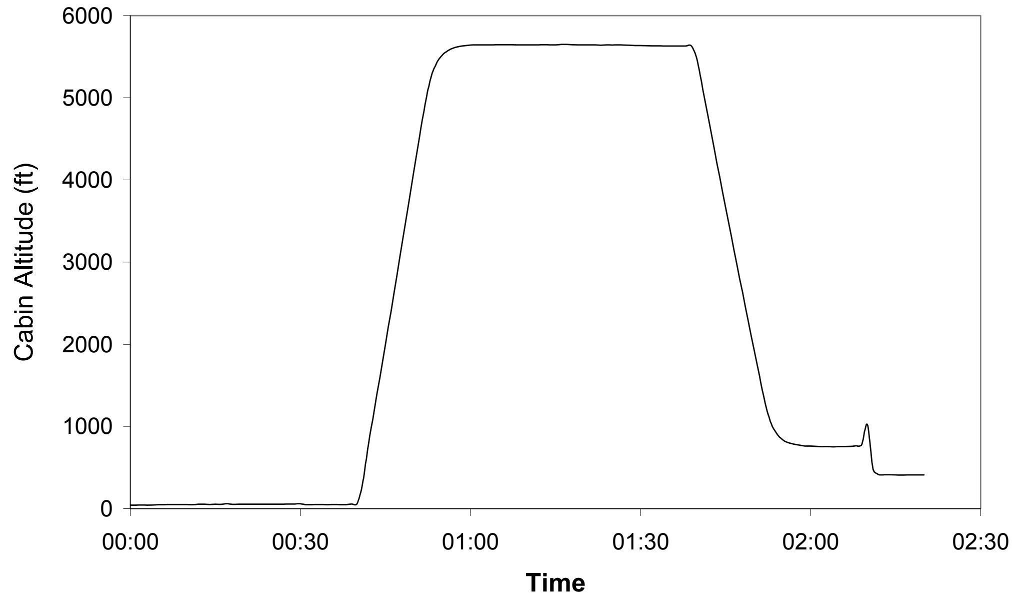
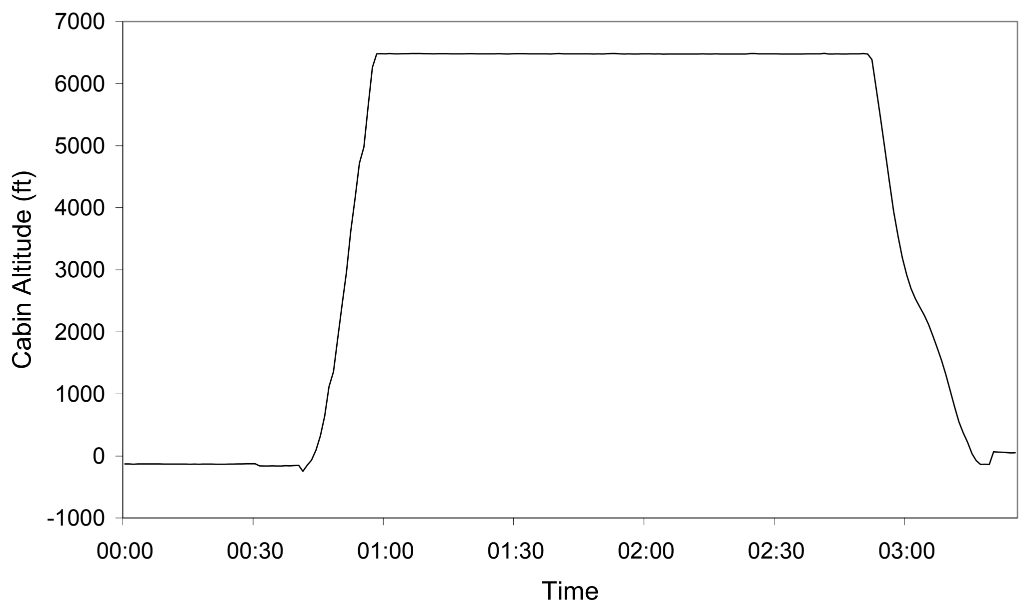


Figure 5.2: Example of cabin pressure for B737 aircraft



5.2.3 Temperature

Figures 5.3 and 5.4 provide examples of the temperature data for the BAe146 and B737 aircraft respectively. In both figures (as with the proceeding figures in this report), cabin altitude is also shown to indicate the occurrence of different phases of flight (i.e. climb, cruise, descent etc). In the BAe146 example shown in Figure 5.3, the air and globe temperature at 1.1 m are similar but the ankle height air temperature is several degrees lower. In the B737 example shown in Figure 5.4, all three temperature measurements are similar.

Table 5.3 provides a summary of the temperature results for both aircraft types. Note that for the summary tables for the stationary measurements, each set of measurements comprises N readings, one for each flight with available data. The result for each flight was determined as the average of the two sets of stationary equipment employed on the flight. Appendix A provides more detailed data-set, including the results for each set of stationary equipment on each flight. It should be noted that for both aircraft, the crew is able to select the temperature and hence it is not automatically set by the environmental control system and can be varied according to the needs of the crew and passengers.

The highest mean temperature at seated head height during cruise at any stationary instrument set was 29.8°C during Flight 6 on a BAe146 aircraft (see Table A3, Appendix A). The temperature profile for this flight is shown in Figure 5.5. In this case the seat was located adjacent to a window and the sun was directly incident onto that area. The highest recorded instantaneous air temperature was 37.8°C. In practice, a passenger would probably have pulled down the window shade and avoided experiencing these high temperatures. Apart from this flight, all other mean cruise temperatures at seated head height were below 26.0°C.

Temperature measurements have been undertaken in a number of other cabin air quality studies and these are given in Table 5.4. Where the research reports specify the period of the measurements [4,5,6,7], all parameters in Table 5.4 were measured when the aircraft were in the air, either during cruise or from seat belt signs off (or smoking sign on) at the start of flight until seat belt signs on (or smoking sign off) at the end of flight. It should also be noted that the minimum and maximum values quoted for four of the studies [4,5,6,8] are based on short-term readings (1 to 10 minute averages) whereas the minima and maxima quoted for the remaining study [7] are based on flight means (as is the data for this study given Table 5.3, although more detailed data for each flight is given in Appendix A).

Figure 5.3: Example of temperature data from BAe146 aircraft

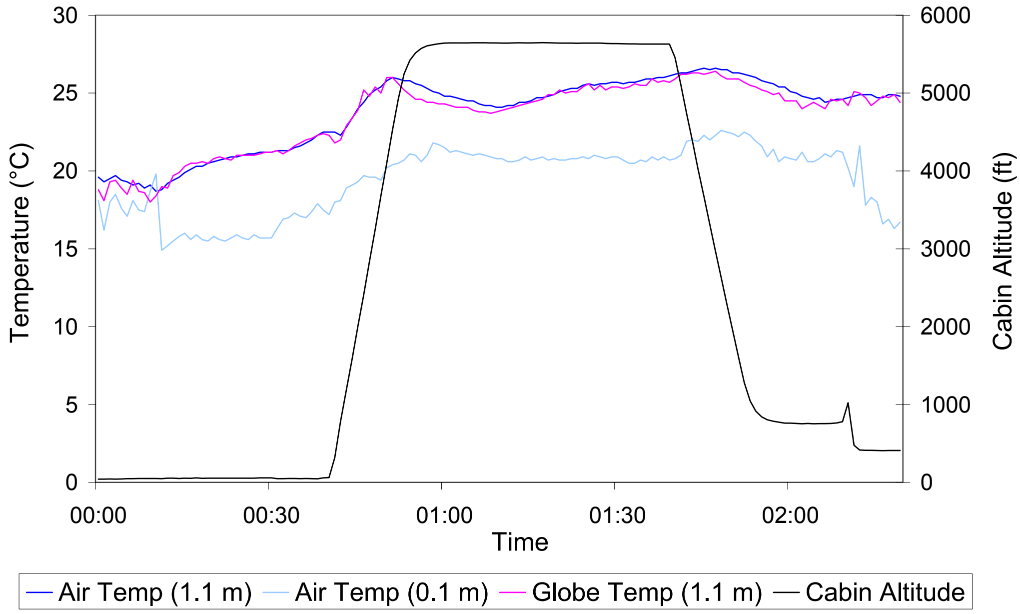


Figure 5.4: Example of temperature data from B737 aircraft

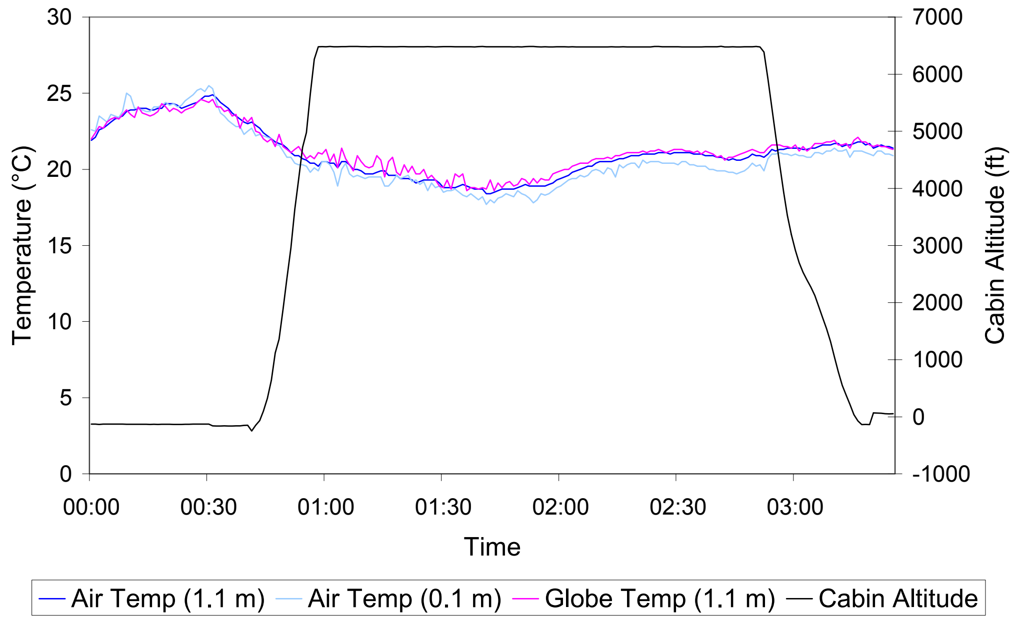


Figure 5.5: Temperature data from Flight 6

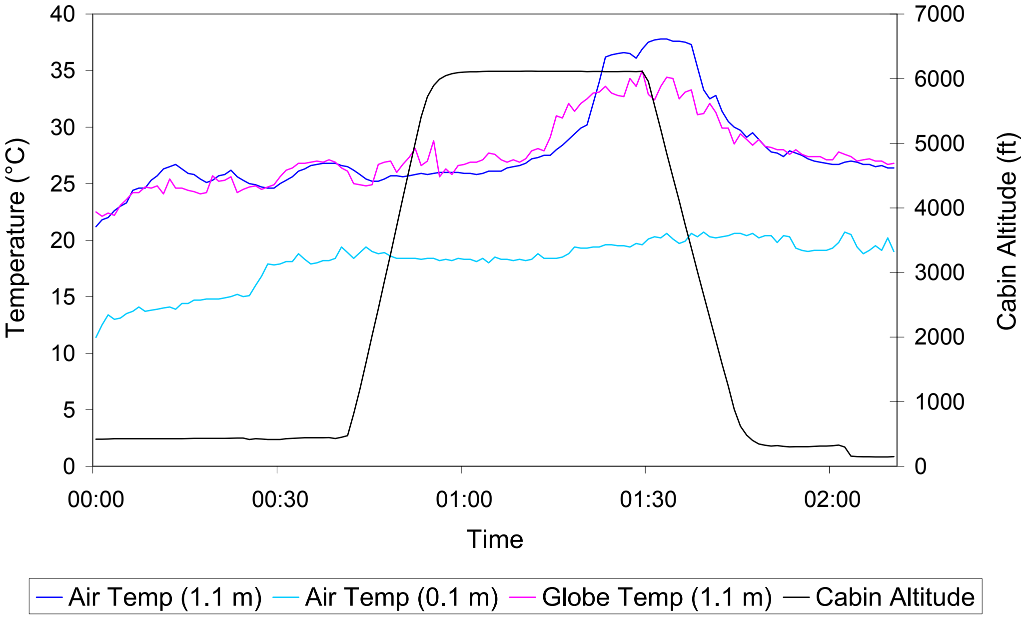


Table 5.3: Summary of the temperature data

Aircraft Type	Flight Phase	Air Temperature, 1.1m (°C)		Air Temperature, 0.1m (°C)		Globe Temperature, 1.1m (°C)	
		N	mean (range)	N	mean (range)	N	mean (range)
146	Whole Flight	7	23.7 (21.7-26.6)	6	20.3 (18.3-22.2)	7	23.5 (21.6-27.7)
	Cruise	7	24.5 (22.2-27.6)	6	20.8 (18.5-22.4)	7	24.3 (22.5-27.4)
	Ground	7	21.9 (20.0-24.9)	6	19.0 (16.7-20.8)	7	21.5 (18.3-24.5)
737	Whole Flight	6	23.0 (21.9-23.9)	6	20.3 (18.8-21.7)	6	23.0 (22.2-23.8)
	Cruise	6	22.9 (21.4-24.2)	6	20.2 (18.4-21.1)	6	23.0 (21.9-24.2)
	Ground	6	23.0 (21.6-24.1)	6	20.1 (16.9-23.5)	6	22.6 (21.4-23.9)

Table 5.4: Measurements from other studies

Study	Temperature (°C)			Relative Humidity (% RH)			Carbon Monoxide (ppm)			Carbon dioxide (ppm)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Nagda et al. - non-smoking sub-sample [4]	24.2	21.0	27.3	17.0	4.7	38.1	0.6	<1.0	1.3	1756	765	3157
CSS [5]	24.4			16.8						1162		
Pierce et al. [6]	23.0	17.8	26.1	14.7	8.8	27.8		<0.1	7	1509	942	1959
Spengler et al. – 1994 study [7]	24.0	23.0	26.0	15.0	10.0	24.0	0.1	0.0	1.0	1200	750	1500
Spengler et al. – 1996 study [7]	25.0	22.0	26.0	18.0	13.0	23.0	0.7	0.0	1.0	1400	1200	1800
O'Donnell et al. [8]	23.4	13.2	35.1	18.5	4.6	48.5	1.6	1	4.0	719	330	2170

As can be seen, comparing the values in Tables 5.3 and 5.4, the mean air temperatures (1.1 m) measured for both the BAe146 and B737 aircraft types were very similar to those from other studies.

As suggested in Table 5.3, and confirmed by the individual flight data in Appendix A, the difference between the mean air and globe temperatures at 1.1 m height was typically less than 1.0°C. This highlights the small difference between the air and radiant temperature components. The air at ankle height is on average several degrees cooler than at seated head height. Ideally the vertical temperature gradient across the body should be as small as possible, with any gradient slightly negative (i.e. the feet should be slightly warmer than the head). However, the effect on comfort is likely to be small; for example, based on ISO 7730 and ASHRAE 55, it is estimated that more than 80% of the occupants of a conditioned space will find the vertical air temperature gradient acceptable if it is less than 3°C.

The largest difference (11°C) occurred on Flight 6, and is also shown in Figure 5.5. However, as discussed earlier in this section, this temperature difference would be unlikely to have occurred in practice as the passenger would probably have pulled down the window shade. Excluding this flight, the vertical temperature difference was greater than 3°C in two out of nine BAe146 flights and two out of six B737 flights. The mean difference was 3.0°C for BAe146 flights and 2.2°C for B737 flights. Perhaps more worrying, the difference rose to 3.0°C for B737 flights on which the globe temperature was within the derived optimum range of 23-24°C (see below). Hence, while the temperature gradient is not a major issue for either aircraft type, it could be improved.

Further work was undertaken to determine the likely effect of the findings on the comfort of passengers and cabin crew. This is provided in detail in Appendix B. The analysis suggests that it will be difficult to satisfy both passengers and crew in the same thermal environment. Only at about 24°C can both groups achieve the ideal temperature. However, this is to take a mechanistic view of comfort. Thermal comfort does not depend purely on an environment being imposed on people. It also depends on the response of people to adapt to the environment. Seen in this way, the question changes from “what temperature is comfortable” to “what is the range of temperatures to which people can easily adapt to achieve comfort”. For example, as discussed further in Appendix B, the level of clothing the occupants wear can have a large impact on their thermal comfort. It would be helpful to ensure that the crew have a light clothing ensemble. The crew uniform is relatively easily controlled and modified if the analysis presented here is accepted. Passenger clothing cannot be dictated but, if a certain level of crew clothing became standard across the industry, temperatures could become more similar between flights and, in our view, recommendations on dress could more easily be made to passengers.

5.2.4 Relative humidity

Relative humidity was measured at seated head height (1.1 m) in the cabin. Figures 5.6 and 5.7 show examples of the measurements recorded on the BAe146 and B737 aircraft respectively. The relative humidity falls during flight as the outside moisture content is very low.

Table 5.5 provides a summary of the data. During cruise, the average levels in the BAe146 aircraft are lower than those in the B737 aircraft. There are two reasons for this:

- The ventilation mode selected for the BAe146 aircraft is 100% outside air. If recirculation mode had been selected, the RH level would have been higher. The recirculated air stream includes moisture from the cabin (principally that generated by the occupants themselves), which has a higher moisture content than that of the outside air.
- As shown in Table 5.1, the passenger loading on the BAe146 flights are lower than those on the B737 flights. Thus the BAe146 flights had lower internal emissions of moisture into the cabin air. This is further demonstrated by the detailed RH data in Appendix A for each flight, which shows that passenger loading can have a significant impact on RH levels.

Relative humidity measurements from other cabin air quality studies are shown in Table 5.4. Comparing the 'cruise' data from Table 5.5, the mean relative humidity levels measured for the BAe146 tended to be below the other studies and the levels measured for the B737 tended to be higher. The reason for the lower readings on the BAe146 is likely due to the supply of 100% outside air and lower passenger density (do not have comparative data for all of the other studies) as discussed above. The reason for the higher readings on the B737 are most likely the high passenger loading and the short flight sectors (and hence limited time for the relative humidity to fall in the cabin during flight, for example in Figure 5.7 the humidity level is still falling at the end of cruise).

In buildings under normal circumstances, humidity in the range 40-70% is deemed acceptable and often lower levels are acceptable for short periods [9]. The low humidity on aircraft is often a cause for public concern and complaint but it is not clear that, in reality, it is a major problem [3]. Given the relative short duration of flights on the aircraft types studied here, it is unlikely that any harm would come to the passengers or crew, although some might well experience sensations of dryness.

Table 5.5: Summary of the relative humidity data

Aircraft Type	Flight Phase	Relative Humidity (%RH)	
		N	Mean (range)
146	Whole Flight	7	20.9 (13.2-32.2)
	Cruise	7	12.7 (7.4-19.1)
	Ground	7	33.7 (23.7-44.7)
737	Whole Flight	6	25.7 (22.4-29.4)
	Cruise	6	20.2 (17.5-24.7)
	Ground	6	44.1 (33.1-54.2)

Figure 5.6: Example of relative humidity data from BAe146 aircraft

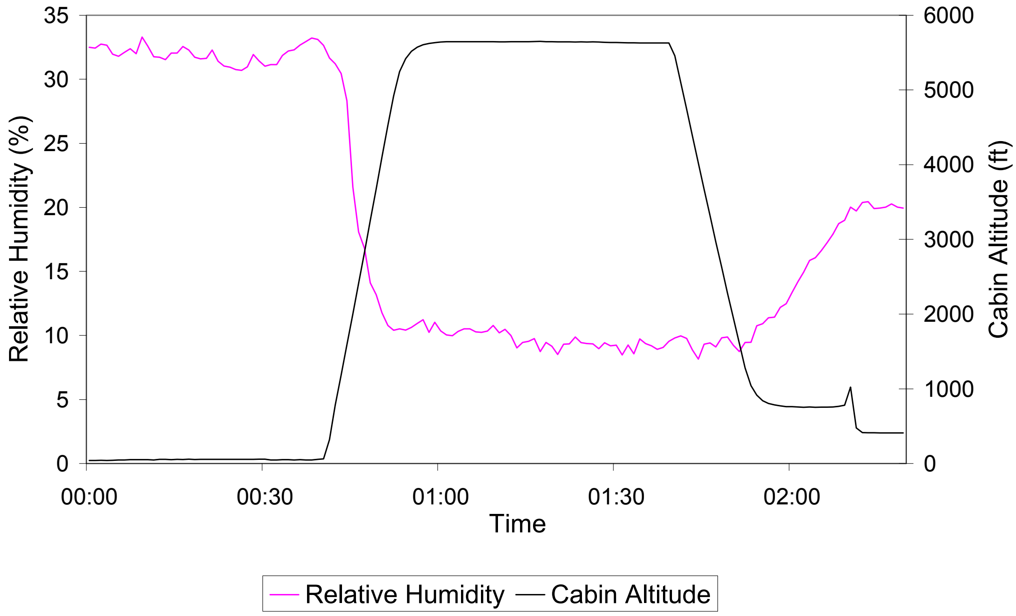
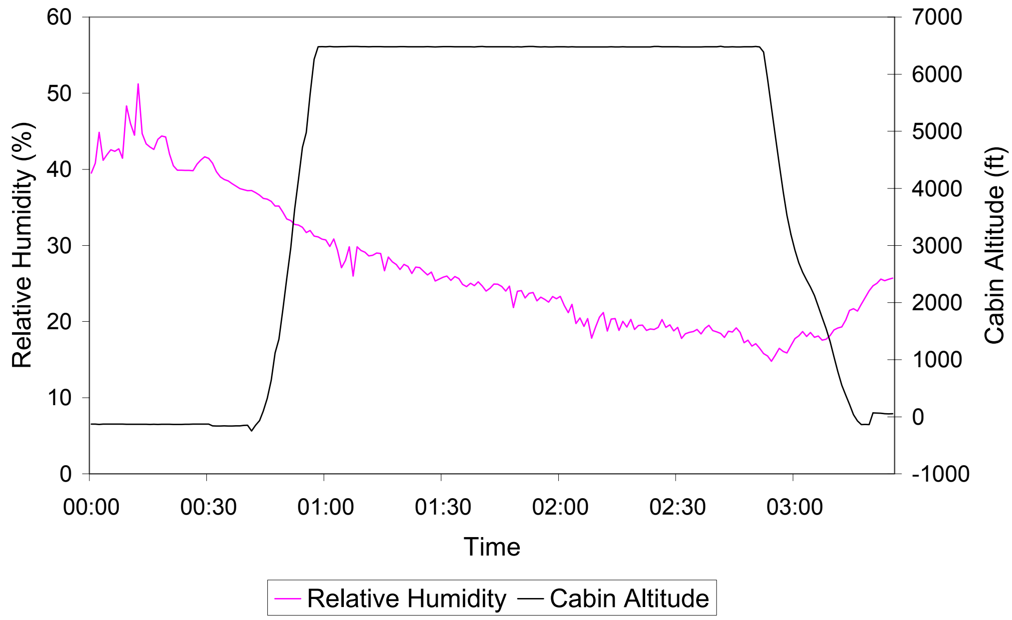


Figure 5.7: Example of relative humidity data from B737 aircraft



5.2.5 Internal air speed

Air speed was measured at seated head height (1.1 m) in the cabin. Figures 5.8 and 5.9 show examples of the measurements recorded on the BAe146 and B737 aircraft respectively. Table 5.6 shows average air speeds on both aircraft. Levels were typically below 0.20 ms^{-1}. The maximum on any flight was 0.36 ms^{-1}.

Table 5.6: Summary of the air speed data

Aircraft Type	Flight Phase	Air speed (ms^{-1})	
		N	Mean (range)
146	Whole Flight	7	0.08 (<0.05-0.20)
	Cruise	7	0.06 (<0.05-0.12)
	Ground	7	0.16 (<0.05-0.67)
737	Whole Flight	6	0.08 (0.06-0.12)
	Cruise	6	0.08 (0.05-0.12)
	Ground	6	0.09 (0.05-0.11)

Figure 5.8: Example of air speed data from BAe146 aircraft

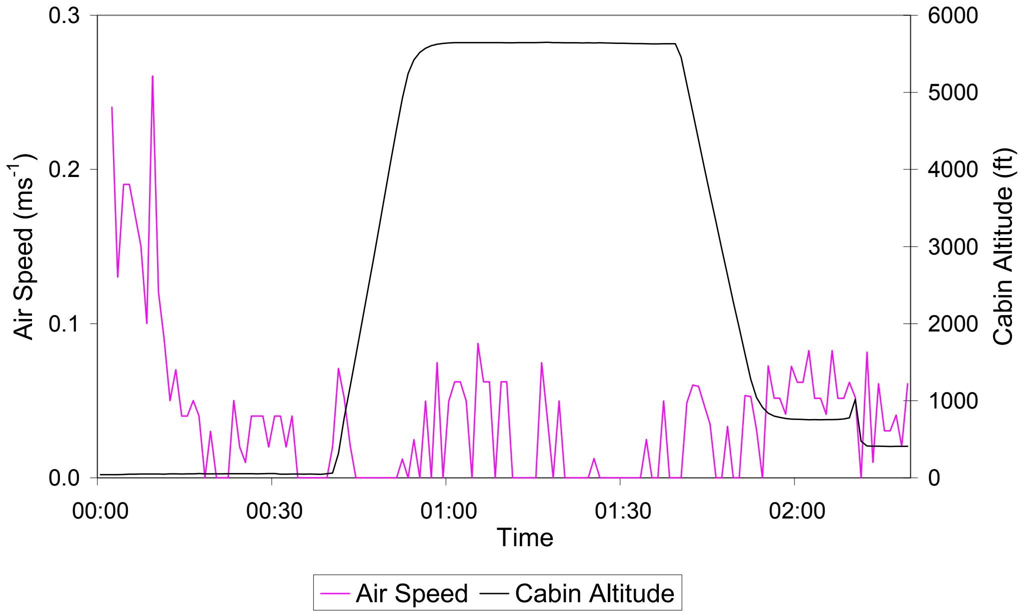
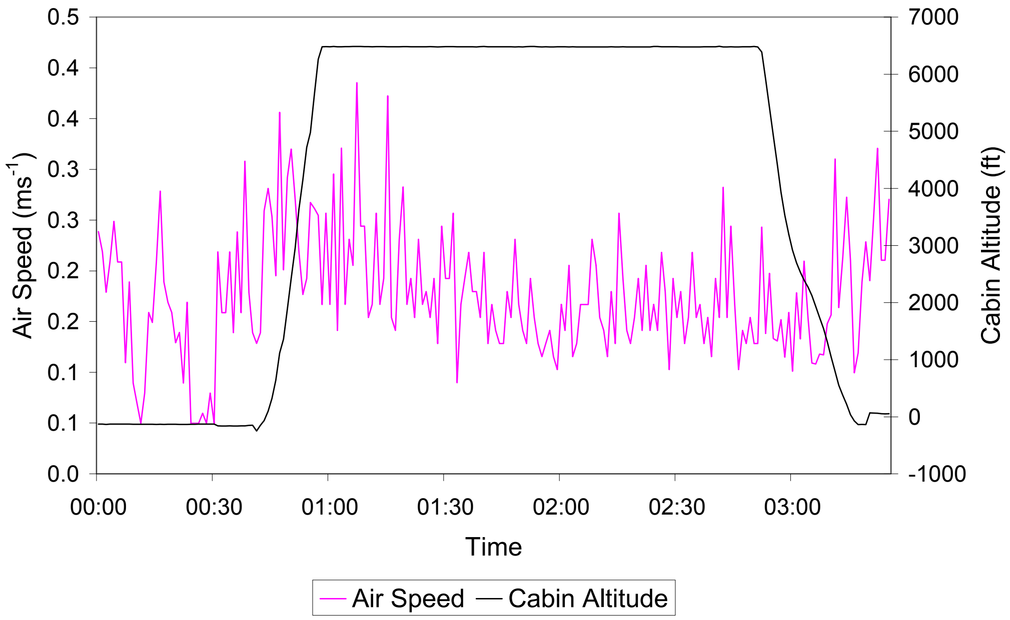


Figure 5.9: Example of air speed data from B737 aircraft



5.2.6 Carbon monoxide (CO)

CO was measured at seated head height (1.1 m) in the cabin. Figures 5.10 and 5.11 show examples of the measurements recorded on the BAe146 and B737 aircraft respectively. Higher levels of CO were always measured on the ground, most likely due to the elevated levels of CO in the outside air from aircraft and ground transport exhaust emissions. Table 5.7 shows average CO levels on both aircraft types. Ground levels were typically below 2 ppm, with a maximum instantaneous level of 5.8 ppm (see Appendix A – Table A2). The maximum level during cruise was 0.3 ppm.

Both FAR 25.831 and JAR 25.831 state that CO concentrations should be below 50 ppm. The monitored levels were an order of magnitude below this requirement. The levels are also consistent with those monitored in other cabin air quality studies (as shown in Table 5.4) in which mean levels from these studies were all below 2 ppm and a maximum recorded value of 7 ppm was measured as a 10 minute average in a galley during food preparation [6].

By comparison with other internal environments, in a study of indoor air in 876 homes in England, the two-weekly mean concentrations were 0.4 ppm [10]. The levels recorded in this study during cruise were thus much lower than found to be in these homes. In a further study in which CO was measured continuously in the kitchens of 68 gas cooking homes in England [11], the sample mean of the maximum level averaged over one hour for each home was 10 ppm. This is greater than all of the values observed in this study.

Table 5.7: Summary of the carbon monoxide data

Aircraft Type	Flight Phase	Carbon Monoxide (ppm)	
		N	Mean (range)
146	Whole Flight	7	0.2 (0.1-0.4)
	Cruise	7	0.0 (<0.1-0.2)
	Ground	7	0.6 (0.3-0.9)
737	Whole Flight	6	0.2 (0.1-0.4)
	Cruise	6	<0.1 (<0.1-0.1)
	Ground	6	0.7 (0.5-1.3)

Figure 5.10: Example of carbon monoxide data from BAe146 aircraft

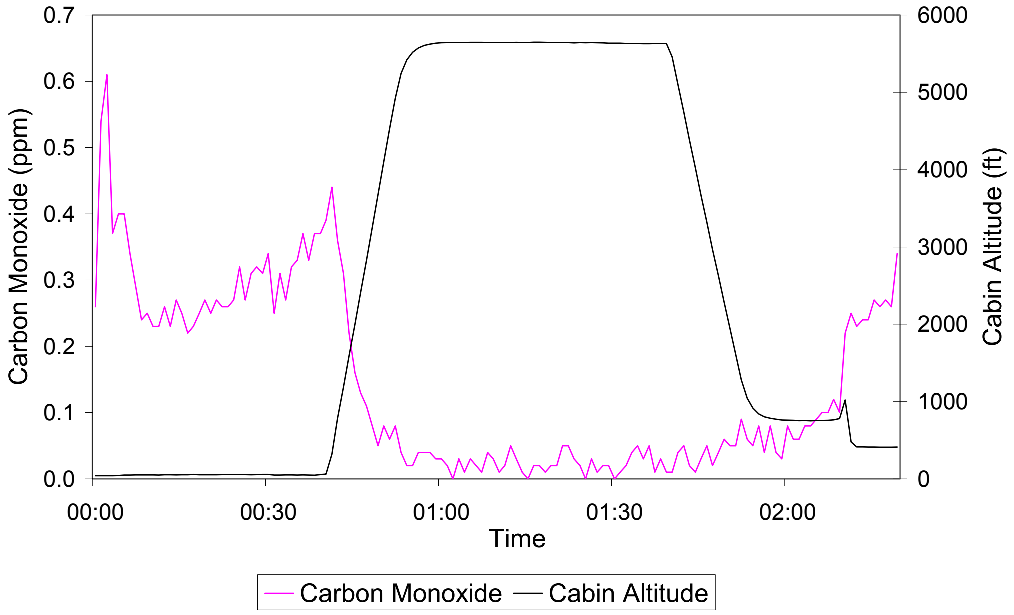
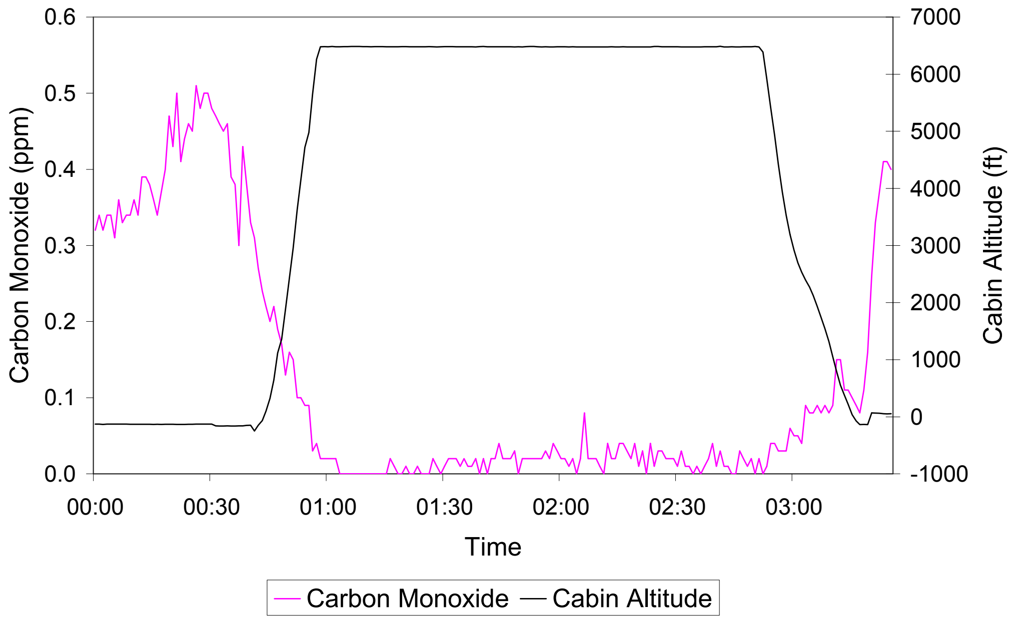


Figure 5.11: Example of carbon monoxide data from B737 aircraft



5.2.7 Carbon dioxide (CO_2)

CO_2 was measured at seated head height (1.1 m) in the cabin. Figures 5.12 and 5.13 show examples of the measurements recorded on the BAe146 and B737 aircraft respectively. As can be seen, there is often an increase in levels prior to take-off, as the ventilation system is yet to operate at levels set for flight. Table 5.8 shows average CO_2 concentration on both aircraft types. The maximum instantaneous level recorded was 3500 ppm which was taken prior to take off on a B737 aircraft. Levels were typically between 700 and 2000 ppm during cruise. The levels tend to increase with passenger loading for a given aircraft type. The levels are lower for the BAe146 aircraft which is due to its selection of the ventilation mode with 100% outside air (i.e. no recirculation, as discussed in Section 3.1) and that the BAe146 flights had a lower passenger loading than the B737 flights (see Table 5.1).

Both FAR 25.831 and JAR 25.831 state that CO_2 concentrations during flight must not exceed 5000 ppm (sea level equivalent). This value is equivalent (as a mass concentration) to approximately 6700 ppm during cruise. All the values recorded were significantly below this requirement. Furthermore, the values reported here are similar to those from other studies (see Table 5.4).

Within the UK, a carbon dioxide level of 800 to 1000 ppm is often used as an indicator that the air quality in a building is adequate [12] and a similar value is used in many other countries. This value is to control the level of body odour in a space such that no more than 20% of visitors to that space are dissatisfied. As shown in Tables 5.4 and 5.8, this value is often exceeded in the cabin environment. However, care should be taken in interpreting this data. Firstly, the cabin occupants spend a pro-longed period within the aircraft and will show adaption to the body odour present. Secondly, as referred to by many (e.g. Nagda et al. [13]) carbon dioxide should not be viewed as a comprehensive indicator of air quality as there are many other contaminants potentially present in the air. In an environment with a high density of people such as an aircraft cabin, carbon dioxide would be expected to be higher without many of the health concerns associated with other environments.

It should be noted that there are other sources of carbon dioxide, not associated with body odour. On the ground, elevated levels can be observed throughout the aircraft cabin due to the possible ingress of air pollution from outside from other transport vehicles. In addition, dry ice is sometimes used for refrigeration of food that is served during flights and principally results in elevated levels in the galleys both on the ground and during flight (the level decays away during flight as the dry ice becomes exhausted).

Table 5.8: Summary of the carbon dioxide data

Aircraft Type	Flight Phase	Carbon Dioxide (ppm)	
		N	Mean (range)
146	Whole Flight	8	1073 (780-1324)
	Cruise	8	1002 (746-1221)
	Ground	8	1180 (921-1421)
737	Whole Flight	6	1639 (1474-1806)
	Cruise	6	1637 (1330-1761)
	Ground	6	1941 (1443-2219)

Figure 5.12: Example of carbon dioxide data from BAe146 aircraft

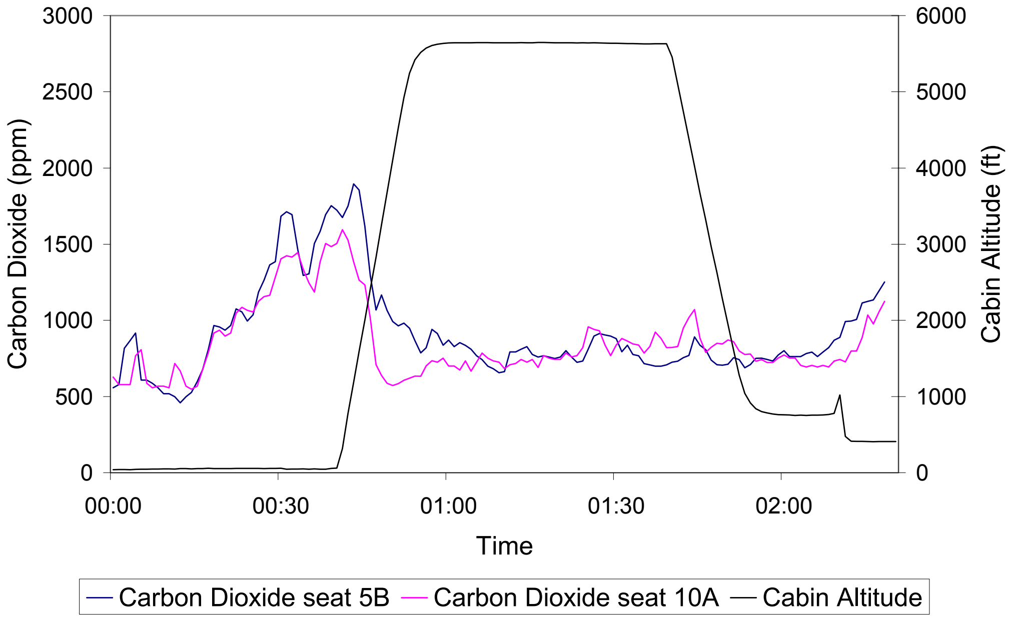
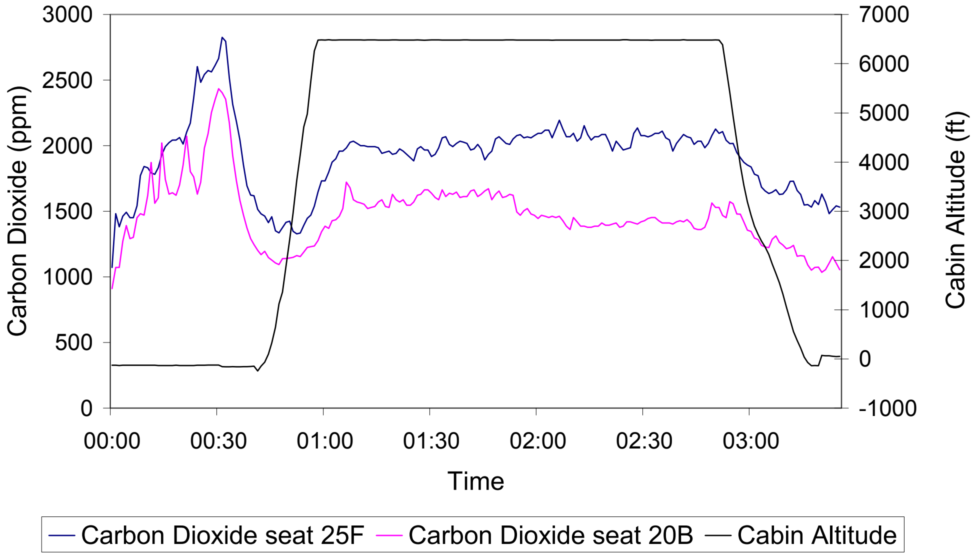


Figure 5.13: Example of carbon dioxide data from B737 aircraft



5.3 Mobile environmental measurements

These measurements focussed on the variation of the parameters across rows (rather than the actual values themselves). For each set of measurements within a row, we took the aisle reading at standing head height (1.7 m) as the baseline measurement and the deviation from this measurement determined for all other locations in the row.

In this section, the data are displayed as a series of graphs for each parameter and aircraft type. Two sets of graphs have been presented, as follows.

i. The first set compares the levels at head height for both passengers and crew. It includes three locations in each row:

   - passenger seated head height for seats on left hand side
   - aisle standing head height
   - passenger seated head height for seats on right hand side

ii. The second set shows the distribution between the four locations within the aisle.

For each aircraft type, all the data for the different rows and flights have been collected together. The results (which are deviations from the baseline measurements at head height in the aisle) are shown as quartile distributions, i.e. 0 - 25%, 25 - 50%, 50 - 75% and 75 - 100%.

Figures 5.14 to 5.17 show the temperature distribution for the two aircraft types. The results suggest that, across the sample as a whole, there is little, if any, temperature variation across the row on the BAe146. In comparison, on the B737, the cabin crew in the aisle on average experience lower temperatures at head height than the seated passengers (which is in most cases likely to be a beneficial difference since crew are more active than passengers). The results also suggest that for both aircraft types, there is little, if any, vertical variation in temperature within the aisle, with the possible exception of cooler temperatures at ankle height for the BAe146 aircraft.

Figures 5.18 to 5.21 show the air speed distribution for the two aircraft types. The results suggest that, as for temperature, there is little, if any, variation in air speed across the row on the BAe146. The singularly high reading on the right seats corresponded to a passenger getting up from his seat. In comparison, on the B737, the cabin crew in the aisle on average experience higher speeds at head height than the seated passengers (as for temperature, in most cases this is likely to be a beneficial difference). The results also suggest that for both aircraft types, the air speed reduces below standing head height in the aisle.

Figures 5.22 to 5.25 show the carbon dioxide distribution for the two aircraft types. The results suggest that for both aircraft types, levels are higher at passenger seated height than in the aisles. This is expected as the measurements were often taken close to passengers (dependant on passenger location within measurement rows) and people exhale high levels of carbon dioxide. There appears to be variation in the levels of carbon dioxide within the aisles for both aircraft types. In both aircraft types, the results suggest higher levels at both 0.6 m and 1.1 m heights. Taken together with the elevated levels at passenger seated head height, this suggests that exhaled carbon dioxide from the passengers’ breathing is being transported to the aisles (which would be unsurprising). We are aware that this was the design aim of the BAe146.

Figure 5.14: Variation in temperature across row on BAe146 aircraft

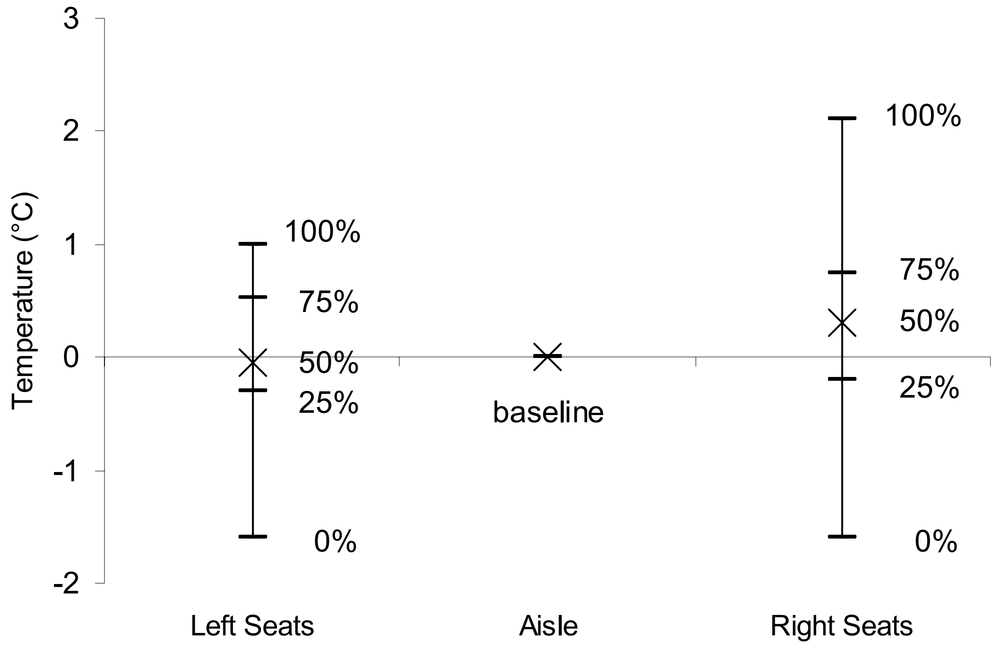


Figure 5.15: Variation in temperature across row on B737 aircraft

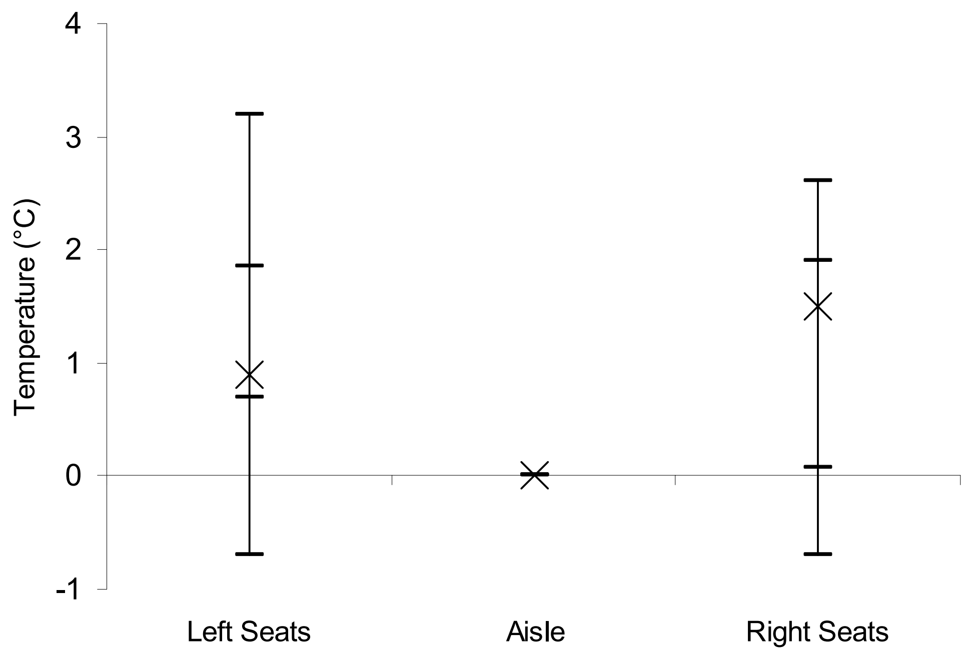


Figure 5.16: Variation in temperature within aisle on BAe146 aircraft

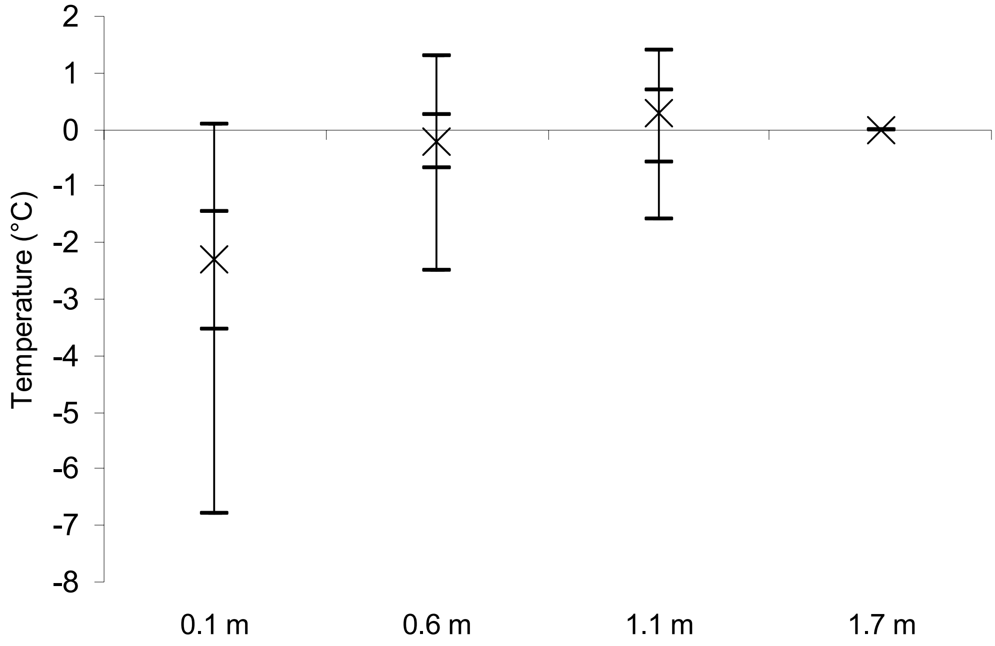


Figure 5.17: Variation in temperature within aisle on B737 aircraft

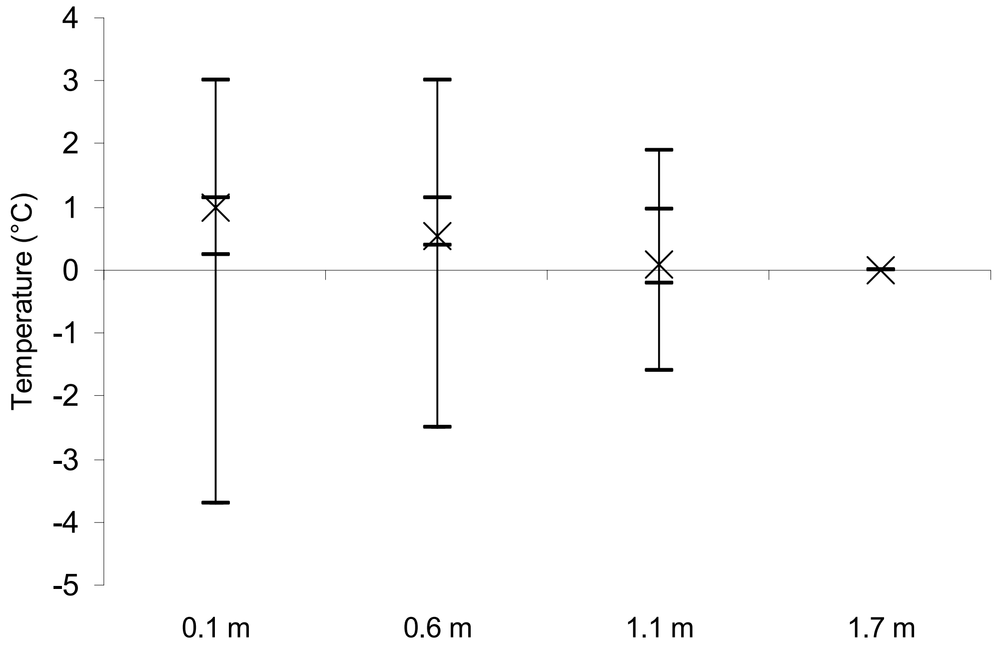


Figure 5.18: Variation in air speed across row on BAe146 aircraft

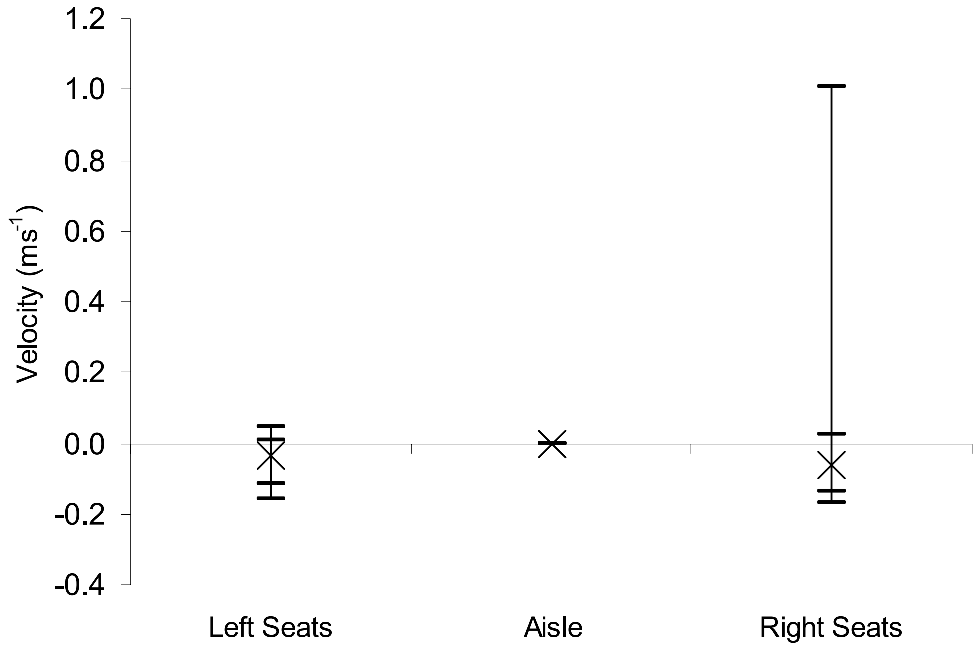


Figure 5.19: Variation in air speed across row on B737 aircraft

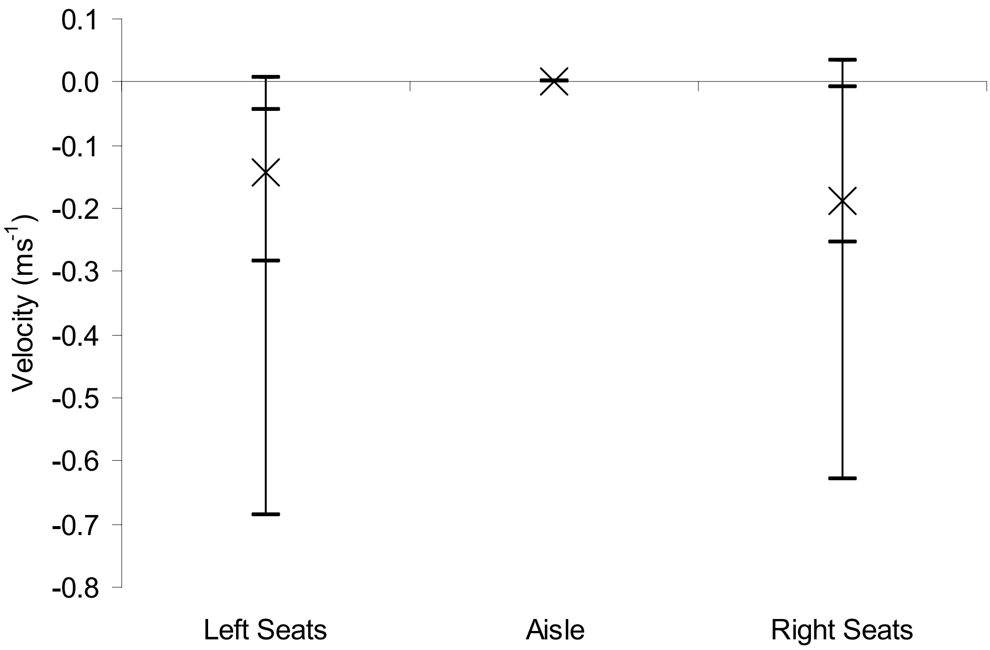


Figure 5.20: Variation in air speed within aisle on BAe146 aircraft

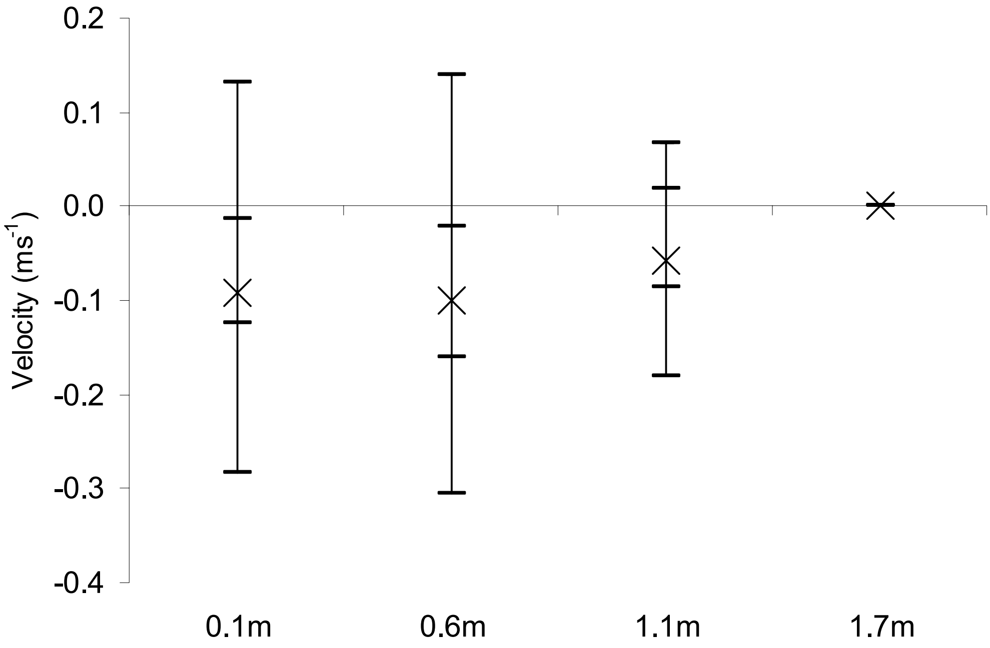


Figure 5.21: Variation in air speed within aisle on B737 aircraft

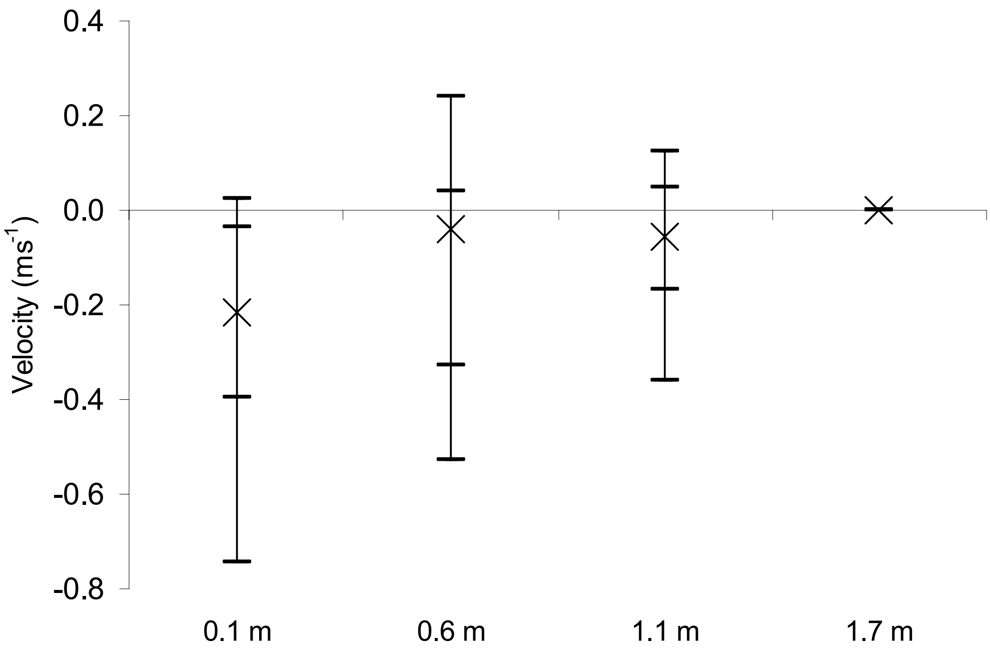


Figure 5.22: Variation in carbon dioxide across row on BAe146 aircraft

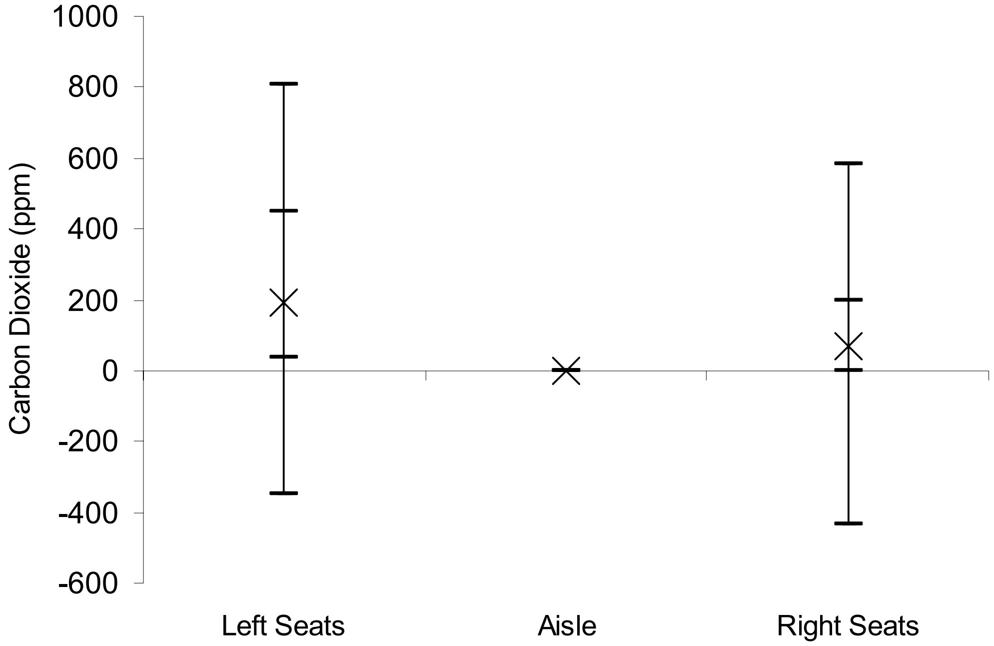


Figure 5.23: Variation in carbon dioxide across row on B737 aircraft

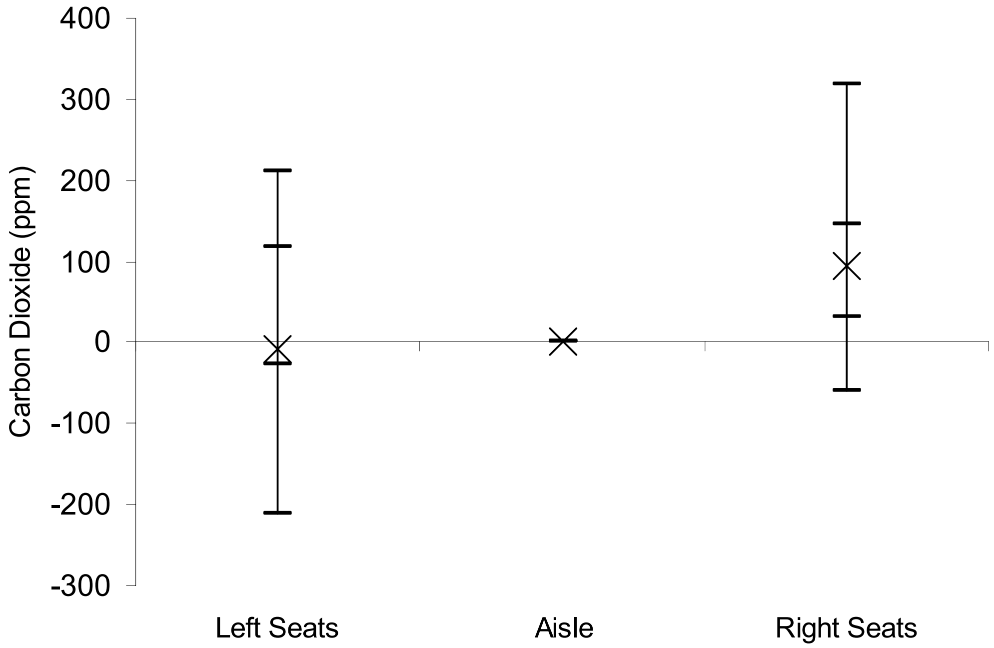


Figure 5.24: Variation in carbon dioxide within aisle on BAe146 aircraft

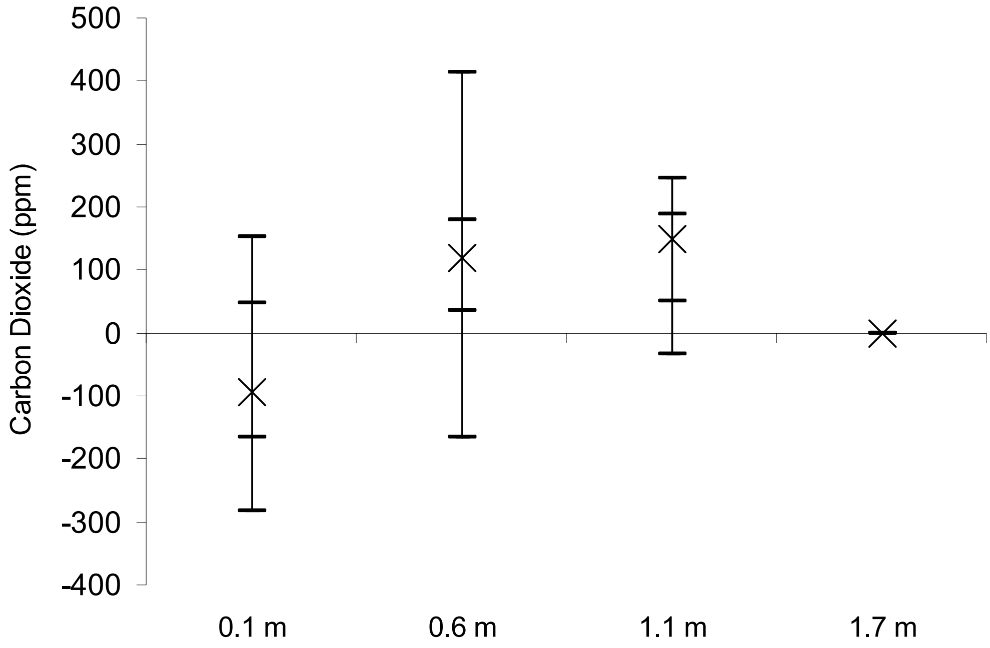
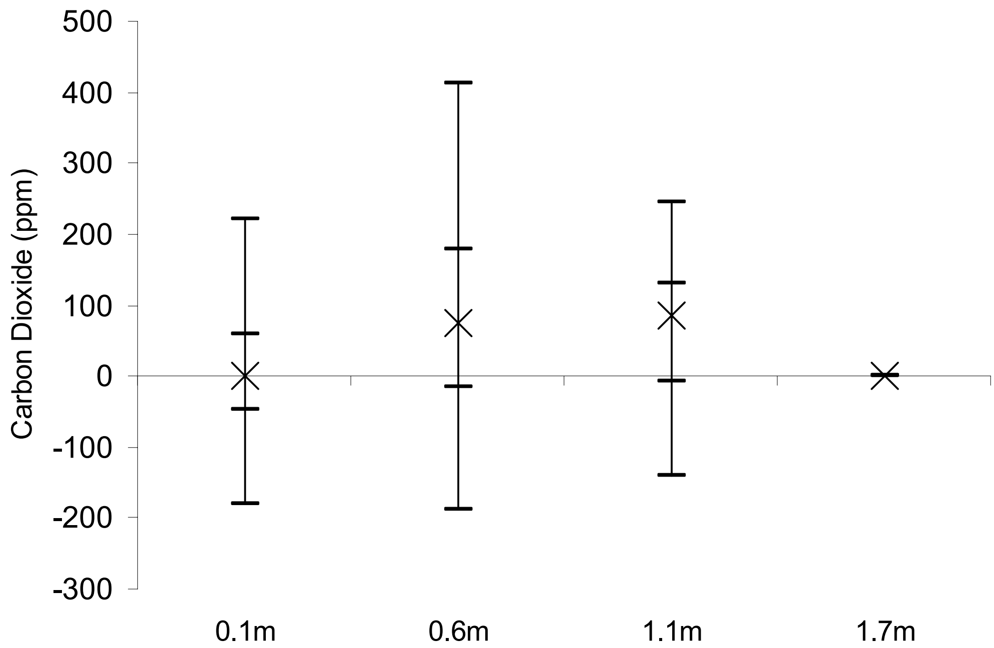


Figure 5.25: Variation in carbon dioxide within aisle on B737 aircraft



5.3.1 Microbiological data

5.3.1.1 Bacteria and fungi

Table 5.9 shows a summary of the bacteria and fungi levels for the flights. A full set of results is given in Appendix C.

The results show that higher levels of bacteria and fungi occur whilst the aircraft is on the ground than whilst at cruise. For the BAe146 aircraft it was possible to make measurements before passenger boarding. This suggests that for the bacteria measurements, the levels are higher during boarding than before boarding, and thus it is the presence of moving passengers that causes these elevated levels. For fungi, the levels are similar both before boarding and during boarding, suggesting that the outdoor air is the main source of the fungi.

Although several attempts have been made to set permissible maximum levels of fungi and bacteria in the indoor environment, there is no widely accepted guideline or standard value(s). Wanner et al [14] proposed a series of guideline categories for aerial concentration of fungi and bacteria, developed under the European Collaborative Action programme, and these are given in Table 5.10. Bacteria levels range from intermediate to high categories during boarding and disembarkation and low to intermediate categories during cruise. Fungi levels range from very low to high categories during boarding and disembarkation and very low to intermediate during cruise.

The results from other studies are given in Table 5.11. The incubation temperatures were only provided by Wick and Irvine (30-35ºC) and Spengler et al. (30ºC). From the literature, there appears to be quite a wide variation in the total microbial count. The results from this study suggest that this will be partly influenced by the phase of flight. Furthermore, as shown in Dechow et al. [17], a release of bacteria into the air very quickly decays (approximately 5 minutes in the study) due both to the high air change rate and the presence of a high efficiency filter in the recirculation system. The values recorded in the present study are similar to those given in the literature.

Appendix C provides details of the composition of the viable fungi in the air samples. During pre-boarding and boarding, the cabin atmosphere is being influenced by the outside air. This is shown by the range of fungal genera isolated during these two sampling periods. Many of the rarely isolated genera are considered outdoor fungi. They drop away during cruise and reappear again on de-boarding when again the outside air enters the cabin. The level of *Penicillium* species reflects activity in the cabin: these spores are small and easily resuspended into the air. They are not completely removed from the air during cruise, possible as even light movement (a few passengers moving, the cabin crew serving meals, etc) will resuspend these spores.

Bacteria colonies were subcultured for micrococci, the gram positive bacteria found on our skin. At pre-boarding, 66.6% of the colonies were deemed presumptive micrococci, increasing at boarding to 71.5% and again during cruise to 80.2%. During passenger disembarkation the highest percentage of presumptive micrococci was obtained (82.6%).

Table 5.9: Summary of the bacteria and fungi results for each aircraft type – geometric mean (range)

Aircraft Type	N	Flight Phase	Bacteria (cfu m^{-3})	Fungi (cfu m^{-3})
146	7	Before Boarding	194 (60-638)	40 (8-123)
	7	During Boarding	538 (225-945)	33 (10-175)
	7	Cruise	158 (40-445)	2 (0-10)
	7	Disembarking	592 (365-1905)	26 (10-60)
737	6	Before Boarding	No Sample	No Sample
	6	During Boarding	302 (65-735)	115 (13-1360)
	6	Cruise	130 (30-400)	7 (0-110)
	6	Disembarking	484 (70-1960)	75 (10-1230)

Table 5.10: Environmental categories for mixed populations of fungi and bacteria in non-industrial indoor environments [14]

Category	Bacteria (cfu m^{-3})	Fungi (cfu m^{-3})
Very Low	<50	<25
Low	<100	<100
Intermediate	<500	<500
High	<2,000	<2,000
Very High	>2,000	>2,000

Table 5.11: Measurements of bacteria and fungi in other studies

Study	Bacteria (cfu m^{-3})			Fungi (cfu m^{-3})		
	Mean	Min	Max	Mean	Min	Max
Nagda et al. - non-smoking sub-sample [4]	131		642	9		61
Pierce et al. [6]		39	244		<1	37
Spengler et al. – 1996 study [7]	201	0	659			
Wick and Irvine [15]		56	1763		0	450
Lee et al. [16]		44	93		17	107
Dechow et al. [17]		20	1700			

The microbiological culture technique was specifically aimed at environmental microorganisms, such as micrococci and fungi. These are naturally occurring organisms that humans are exposed to, on a daily basis, whilst undertaking normal activities. The culture findings from this study are consistent with bacterial counts and known airflow patterns in, for example, surgical operating theatres. When groups of individuals are confined within a limited environmental space (operating theatre / aircraft cabin), and are moving around, the mechanics of clothing brushing against skin or removal of jackets, will dislodge skin scales and dust particles that will contain many millions of bacterial and fungal organisms. This is a natural process, and outside of a healthcare facility, poses no risk of infection to others.

It is not possible from this study to determine the risk of infection of cabin occupants via the cabin air, as the organisms cultured for are regarded as non-pathogenic in persons with normal immune systems. Infection risk would vary depending on a number of factors including pathogenicity of a particular organism, method and ease of transmission of the organism, duration of exposure and the susceptibility of the other passengers.

The potential risk of infection was considered as part of the Stage 2 study, based on a review of the published literature [3]. It concluded that:

> "For most diseases, and TB in particular, the perceived risk is most probably far greater than the real risk. This perceived risk has been fuelled by the introduction of recirculated air within the aircraft, giving the impression that airborne infections are distributed throughout the cabin by the ventilation system. The actual arrangement of the ventilation in aircraft cabins is designed with the intention that this will not happen and filtration is put in place to extract any likely pathogen. Consequently, the reality is that the engineering of the ventilation system suggests that there is a reduced risk of transmission by comparison with other means of transport given similar long-term and dense occupancy patterns."

5.3.1.2 Endotoxins

No endotoxins, components of the gram negative bacteria cell wall, were found on either aircraft during the monitoring period. This is consistent with the low number of this type of bacteria obtained during the air sampling of the cabin environment.

In work conducted in the US [18], low airborne levels of endotoxins were detected (average of 1.5 EU m^{-3}) and this is similar to previous BRE studies in which levels of endotoxins were associated with the boarding phase of the flight. The reason for the lack of detection of endotoxins during this study is likely due to the short sampling time possible within the limited duration of flights in this study and hence the quantity of endotoxins collected on the filter was below the limit of detection of the procedure.

5.3.1.3 Surface dust, dust mite allergens and cat allergens

It was possible to access only a BAe146 aircraft for these measurements. Table 5.12 summarises the results for the three samples of dust taken.

Table 5.12: Summary of surface dust, dust mite allergens and cat allergens

Sample	Dust level	Mite antigen (Der p1)		Cat antigen (Fel d1)	
	$g.m^{-2}$	$\mu g.g^{-1}$ dust	$\mu g.m^{-2}$	$\mu g.g^{-1}$ dust	$\mu g.m^{-2}$
1	0.52	0.39	0.20	0.00	0.00
2	0.45	0.22	0.10	0.12	0.06
3	0.34	0.59	0.20	0.18	0.06

Very low levels of dust, dust mite antigen and cat antigen were found on board the BAe146 aircraft. Table 5.13 shows proposed preliminary guideline levels of 2 µg Der p1 per gram of dust that should be taken as the risk level for the development of asthma. All samples were well below this, ranging from 0.22 to 0.59 µg. g^{-1} Der p1 and 0.00 to 0.18 µg. g^{-1} Fel d1.

Table 5.13: Threshold levels of house dust mite allergen (Der p1) in the internal environment [19]

Risk Level	Allergen level (µg g^{-1} dust)
Low	<2
Moderate	<10
High	>10

5.3.2 Organic compounds

Organic compounds were measured as volatile organic compounds (VOCs), very volatile organic compounds (VVOCs), semi-volatile organic compounds (SVOCs) and carbonyls (aldehydes and ketones) using the definitions presented in Section 4.4.3.2. It is normal for there to be a wide range of organic compounds in the air of indoor environments produced by a wide range of indoor sources as well as outdoor sources such as traffic [10, 20, 21]. Spengler et al [7] reported a wide range of sources of VOCs in transport vehicles such as aircraft, trains and buses including; fuel exhaust (toluene, xylenes, benzene, decane, undecane, hexane pentadiene), distilled spirits and human bioeffluents (propan-2-ol, ethanol, acetone), air fresheners and cosmetics (limonene, toluene), dry cleaning agent (tetrachloroethene), refrigerants (dichlorodifluoromethane), solvents (butan-2-one, toluene, 1,1,1-trichloroethane, xylenes) and plastic resin (vinyl acetate).

5.3.2.1 VOCs

Total VOC concentrations are summarised in Table 5.14 and provided in more detail in Table D1, Appendix D. The TVOC concentration has been derived by summing the detector response given by the many individual VOCs (C_6 to C_{16}) collected by the sampler and calculating a concentration value based on the detector response to toluene. It is therefore an indicator of the total VOC concentration of the air. There is no internationally agreed method of measurement of TVOC, although this study has applied a method used in other BRE studies of VOCs in indoor environments in the UK and it is consistent with proposals in a draft international standard for measurement of VOCs in indoor air (ISO 16000-6).

The TVOC concentrations ranged from 11 to 1140 μg m^{-3}. The highest concentrations were observed on the ground; during this phase of the flights concentrations exceeded 600 μg m^{-3} on Flights 3, 4 and 10. The highest concentration when the aircraft was airborne was 444 μg m^{-3} during climb in Flight 3. The concentrations are similar to those measured in a study of 876 randomly selected homes across England [10]. This study of normally occupied homes found a monthly geometric mean concentration of 210 μg m^{-3} (95^{th} percentile of 1010 μg m^{-3}) and this is higher than the geometric mean concentration of all measurements on both aircraft types (153 μg m^{-3}).

There are no UK standards or guidelines and there is no World Health Organisation (WHO) guideline for acceptable TVOC concentrations in indoor air. Table 5.15 shows some suggested guidelines that have been applied by some groups in other countries. With reference to the guidelines proposed by the Finnish Society of Indoor Air Quality and Climate, most flights meet the minimum requirement of <600 μg m^{-3}, this value being exceeded only on the ground.

Considerable caution is required when comparing TVOC results from different studies because the sampling and analytical techniques applied can be different and therefore the range of compounds included in the TVOC calculation can be different. For example three studies of air quality on aircraft reviewed by Nagda et al [13] used different methods of sampling and analysis of VOCs and these three methods differed significantly from the method used by BRE. The TVOC values summarised by Nagda et al. [13] included ethanol which was the dominant individual compound, but ethanol is not within the TVOC range used by BRE.

The TVOC concentration represents the sum of a wide range of individual compounds. For this study a target list of compounds was developed based on those compounds monitored in the European CabinAir project with additional compounds routinely measured by BRE in indoor environments. If other significant peaks were observed in the GC chromatograms these were also noted. The results are summarised in Table 5.16 and the full data are provided in Table D2, Appendix D.

There are no UK air quality standards for individual VOCs for non-occupational indoor environments. Table 5.16 does list the UK maximum exposure limits (MEL) and occupational exposure standards (OES) for an 8 hour exposure period set by the UK Health and Safety Executive for occupational environments [26]. These are appropriate for the protection of the health of a working adult exposed in a workplace and are not applicable to other groups such as children and other environments that are not workplaces. However it is of note that for those VOCs detected in the aircraft, the concentrations were several orders of magnitude lower than the exposure limits and standards.

The World Health Organisation (WHO) publish guidelines [27] for air quality that include recommended limits for some VOCs in air and these limits are to protect the general population from adverse health effects. For carcinogens such as benzene, the WHO do not provide a guideline but give a risk estimate for the incidence of cancer due to long term exposure to a unit concentration of the compound. Table 5.16 summarises the available WHO guidelines for VOCs based on non-carcinogenic end points. None of the measurements on the aircraft exceeded the available WHO guidelines.

A total of 21 VOCs were found above their detection limit in the present study and 11 of these compounds were determined in the indoor air quality study of homes in England mentioned previously [10]. Concentrations of these compounds may be compared with those found in the homes study which are also given in Table 5.16. The majority of readings for these compounds obtained in the present study are within the range found in the homes study. The concentration of tetradecane recorded during climb on flight 10, was higher than the 95th percentile value for the homes study, but was similar to the maximum value recorded in one of the homes.

Five compounds for which no standards or guideline values are available and which were not determined as part of the homes study were found in very low concentrations in the air of one or more flights. Odour threshold values [28] are available for two of these compounds, pentanal (21.9 µg m^{-3}) and 2-ethylhexan-1-ol (500 µg m^{-3}), both of which are significantly higher than the concentrations recorded during this study. Another of the five compounds, p-tolualdehyde, is used in perfumes and as a flavouring agent e.g. for chewing gum. The final two compounds were not identified. Mass spectral searches suggested that these were a hydrocarbon and a siloxane, but further work would be required to determine which particular compounds were present.

Table 5.14: Summary of TVOC levels – geomean (range)

Aircraft Type	N	Flight Phase	Mean TVOC Concentrations (µg m^{-3})
146	7	Ground	241 (49-619)
	5	Climb	158 (96-444)
	7	Cruise	100 (48-204)
	5	Descent	87 (11-250)
737	5	Ground	402 (166-1140)
	5	Climb	188 (83-373)
	6	Cruise	139 (86-175)
	4	Descent	75 (25-150)

Table 5.15: Proposed guidelines for acceptable TVOC concentrations in indoor air

Author	Concentration (µg m^{-3})	Comment
National Health & Medical Research Council (Australia) [22]	500	No single compound should contribute >50%
Mølhave, L [23]	<200	Comfort range
	200-3,000	Multifactorial exposure
	3000-25,000	Discomfort
	>25,000	Toxic
Seifert, B [23]	300	Target guideline value. No individual compound should exceed 10% of target value
Finnish Society of Indoor Air Quality and Climate [24]		Target values:
	<200	best air quality; 90% of occupants satisfied
	<300	Intermediate air quality-room; may have slight odour
	<600	Minimum requirement
Japanese Ministry of Health, Welfare and Labour [25]	<400	Advisable TVOC value for indoor air quality for residential air

Table 5.16: Summary of individual VOC measurements for all flights

Compound	Concentration Range (μg m^{-3})	UK MEL/OES (μg m^{-3})	WHO Guideline (μg m^{-3})	English Homes (μg m^{-3})	
				Mean	95th Percentile
Tetrachloroethane	ND (<~20)	13000	-	-	-
Benzene	<0.1 - 4.5	3190^{A}	-	3	15
1,2-dichloropropane	ND (<~0.1)	-	-	-	-
Pentanal	<0.5 - 5.9	-	-	-	-
Bromodichloromethane	ND (<~20)	-	-	-	-
Cis-1,3 dichloropropene	ND (<~5)	-	-	-	-
Toluene	<0.2 - 64	191000	260^{C} (1000^{B})	15	75
Tetrachloroethene	<1.2 - 94.6	345000	250^{D} (8000^{B})	-	-
Trans-1,3-dichloropropene	ND (<~5)	-	-	-	-
1,1,2-trichloroethane	ND (<~5)	-	-	-	-
2-hexanone	ND (<~10)	21000	-	-	-
Hexanal	<0.3 - 10	-	-	1	16
Dibromochloromethane	ND (<~25)	-	-	-	-
1,2-dibromoethane	ND (<~10)	3900	-	-	-
Chlorobenzene	ND (<~3)	-	-	-	-
Ethylbenzene	<0.1 – 2.8	441000	-	1	8
M+p-xylenes	<0.1 – 3.9	220000	-	4	30
Styrene	<0.1 – 3.2	430000	260^{C} (70^{B})	-	-
Tribromomethane	ND (<~5)	-	-	-	-
1,1,2,2-tetrachloroethane	ND (<~5)	-	-	-	-
Limonene	<0.2 – 32.2	-	-	6	51
Benzaldehyde	<0.1 – 1.3	-	-	1	13
1,3-dichlorobenzene	ND (<~1)	-	-	-	-
1,4-dichlorobenzene	<0.2 – 3.5	153000	-	-	-
1,2-dichlorobenzene	ND (<~1)	153000	-	-	-
P-tolualdehyde	<0.8 – 1.2	-	-	-	-
4-methylpentan-2-one	ND (<~3)	208000	-	-	-
Undecane	<0.2 – 18.8	-	-	3	34
2-ethylhexan-1-ol	<0.1 – 3.4	-	-	-	-
2-butoxyethanol	ND – 56.8	123000	-	-	-
Decamethylcyclopentasiloxane	(ND – 18.2)^{E}	-	-	6	74
1,2-propanediol	ND - 1137	474000	-	-	-
Hydrocarbon ^{F} (RT 53.8 min)	(ND – 8.2) ^{E}	-	-	-	-
Nonanal	ND – 12.9	-	-	3	11
Tetradecane	ND - 14	-	-	1	3
Siloxane (RT 36.1 min)	(ND – 13.9) ^{E}	-	-	-	-

^{A} from June 2003; ^{B} guideline based on sensory effects or annoyance reaction, using an averaging time of 30 minutes; ^{C} one week averaging period; ^{D} annual averaging period; ^{E} quantified using detector response to toluene; ^{F} compound identity not known; ND = none detected (detection limit will depend upon compound type and volume of air sampled; where value shown this is a typical detection limit for the majority of the sampling events undertaken).

5.3.2.2 VVOCs

The method was used to determine those VVOCs determined by the European CabinAir project and significant additional compounds. Table 5.17 summarises the results of measurements. Since our sampling technique was developed to measure overall VVOCs, it was not fully optimised for measurement of ethanol and acetonitrile. Therefore the readings obtained of these two compounds are expected to be an underestimate.

Table 5.17: Summary of individual VVOC measurements for all flights

Compound	Concentration range ($\mu g\ m^{-3}$)	UK MEL/OES ($\mu g\ m^{-3}$)	WHO guideline ($\mu g\ m^{-3}$)
Hexane	<0.6 – 5.1	72000	-
1,1,1-trichloroethane	ND (<~5)	555000	-
Trichloromethane	ND (<~30)	9900	-
1,2-dichloroethane	ND (<~5)	21000	700
Trichloroethene	<1.2 – 4.3	550000	-
Trans-1,2-dichloroethene	ND (<~5)	806000	-
Propan-2-ol	6 - >3070	999000	-
Vinyl acetate	ND (<~5)	36000	-
Cis-1,2-dichloroethene	ND (<~5)	806000	-
Butan-2-one	<1.7 - 25	600000	-
Ethanol	(>8 - >3822)[B]	1920000	-
Acetonitrile[A]	(>9 - >1115)[B]	68000	-

[A] interference in the analysis from propan-2-ol prevented measurement of acetonitrile in some samples

[B] method not optimum for measurement of ethanol and acetonitrile and expect calculated concentrations to be underestimates.

Hexane was found on flights 1, 2 and 3, generally during the ground phase and at low concentrations. Trichloroethene was only found during the ground phase of flight 1, again at low concentrations. Propan-2-ol was found on all flights, however concentrations varied through the different phases of flight. Propan-2-ol is used in the operation of the P-TRAK ultrafine particle counter and it is likely that some of the propan-2-ol measured derives from this process. Butan-2-one (MEK) was detected on most flights during the ground, climb and cruise periods on the BAe146 aircraft and during all phases on the B737 aircraft, but concentrations were low. It is used as a general solvent in the aviation industry.

Concentrations of VVOCs determined were well below occupational exposure limits and standards and the concentration of 1,2-dichloroethane was well below the WHO guideline value. The samples indicated the presence of ethanol in all samples as a major peak in the GC chromatograms. Whilst it was only semi-quantified, it is three orders of magnitude below the HSE exposure limit and is not thought to be at a level of concern.

Acetonitrile was also significant in some samples, although its possible presence in the GC chromatogram was sometimes masked by the propan-2-ol peak. A maximum level of 1115 µg m^{-3} was recorded on the ground in Flight 13 which quickly reduced to 14 µg m^{-3} during climb. The highest level during flight was 280 µg m^{-3} during descent on Flight 5. Given that these values are an underestimate and that they are only one to two orders of magnitude below the HSE occupational exposure limit, further investigation may be warranted. It is not clear at present what the source of acetonitrile is, although it is used as a solvent. A different sampling and analytical technique would need to be applied to determine ethanol and acetonitrile quantitatively in the air of aircraft cabins.

The results are presented in more detail in Table D3, Appendix D.

5.3.2.3 Carbonyls

Table 5.18 provides a summary of the carbonyl compounds measured in the flights. Of the carbonyl compounds determined, only formaldehyde, acetaldehyde and acetone were found on all flights. Higher levels were found on the ground, but were well below WHO guideline levels of 100 µg m^{-3} for formaldehyde [27]. The acetone concentration was slightly higher during descent on flight 2, but all levels were four orders of magnitude less than the HSE MEL/OES 8 hour TWA guideline level of 1200 mg m^{-3} [26].

Acrolein was only found on the first flight while the aircraft was still on the ground at 4 µgm^{-3}, and propionaldehyde was detected on only one flight on the ground, at a low concentration. Concentrations of crotonaldehyde, butyraldehyde and methacrolein were below the detection limit of the method.

The detailed results of carbonyl sampling are found in Table D4, Appendix D.

Table 5.18: Summary of individual carbonyl compound measurements for all flights

Compound	Concentration range (µg m^{-3})	UK MEL/OES (µg m^{-3})	WHO guideline (µg m^{-3})
Formaldehyde	<1 – 15	2500	100[A]
Acetaldehyde	<1 – 31	37000	-
Acrolein	<0.2 – 4	230	-
Propionaldehyde	<0.5 – 32	-	-
Acetone	<1 – 198	1210000	-
Crotonaldehyde	ND (<~5)	-	-
Butyraldehyde	ND (<~5)	-	-
Methacrolein	ND (<~3)	36000	-

[A] 30 minute averaging period

5.3.2.4 SVOCs

The SVOC levels are given in Tables D5a and D5b of Appendix D. For the BAe146 aircraft, the analysis focussed on quantifying the level of Exxon 2380 (used for engine and APU oil) and Skydrol (used for hydraulic oil) in the cabin air. For the Boeing 737 aircraft, the analysis focussed on quantifying the level of Aeroshell Turbine oil 560 (used for engine oil) and Skydrol 500 B-4 (used for hydraulic oil and of a different formulation than the Skydrol used for the BAe146 aircraft). Note that the aircraft manufacturer will approve of a number of brands of oil for use in their aircraft and the airline then selects which brands to use.

There are a number of different chemical compounds in each of the oils, and several compounds were used for the quantification of each oil type. The reason we chose more than one compound to quantify each oil type is because we considered that different compounds within any oil may be removed (say by condensing out or through chemical reactions) in differing amounts from release at source through to possible ingress into the cabin air. Therefore, by focussing on more than one compound in each oil type, we consider that we can provide a more accurate quantification of the amount of each oil type in the cabin air.

The analysis can detect levels of oil vapours well below those known to be hazardous to health. The detection limit of the method for oil vapours depended upon the amount of air sampled and also the presence of some interfering compounds in blank samples. Typically detection limits were; for Exxon 2380 ~80 µg m^{-3} , Skydrols ~10 µg m^{-3} and Aeroshell 560 ~20 µg m^{-3}.The HSE occupational exposure standard (OES) for tributylphosphate (a major component of Skydrols) is 5000µg m^{-3} (15 min and 8 hour TWA). For tritolyphosphate, a minor component (typically <5%) of engine oils, the 15 minute TWA is 300 µg m^{-3} and the 8 hour TWA is 100 µg m^{-3}.

The concentrations of oils in air measured were below the detection limit of the method. There is some evidence for tributylphosphate in Flights 4, 5 and 6 and Aeroshell 560 in flight 9 but the levels are too low to make a positive identification. In the analysis, the presence of other chemical compounds was also investigated but none were detected. It should be noted that tributlyphosphate is also used in other applications such as a plasticiser and a defoaming agent in various types of paints, inks, adhesives and plastics.

5.3.3 Nitrogen dioxide

The levels of nitrogen dioxide were higher whilst on the ground than during cruise. The mean levels on the ground ranged from 20 to 70 ppb, whilst during cruise the mean levels were < 20 ppb (minimum detection limit of the detector).

There are no JAR/FAR requirements for nitrogen dioxide. The World Health Organisation recommends a maximum level of 105 ppb averaged over a one hour period [27]. Furthermore, in a study in which nitrogen dioxide was measured continuously in the kitchens of 68 gas cooking homes in England [11], the sample mean of the maximum level averaged over one hour for each home was 165 ppb. Within this study, the maximum one hour averages were 43 ppb and 70 ppb for the BAe146 and B737 aircraft respectively. These concentrations are both below the WHO guideline value and levels found in gas cooking homes.

5.3.4 Ultrafine particles

Figures 5.26 and 5.27 show examples of the ultrafine particle levels recorded on the BAe146 and B737 aircraft respectively. Elevated levels were always monitored on the ground, most likely due to the elevated levels in the outside air from aircraft and ground transport exhaust emissions. It is interesting that, in Figure 5.26, elevated levels were also recorded during the climb phase. The levels in cruise are several orders of magnitude lower.

Table 5.19 shows average ultrafine particle levels on both aircraft types. Currently there are no guideline levels for ultrafine particles. Table 5.20 shows the maximum particle levels during each flight phase. As highlighted in Figure 5.26, there are elevated levels during climb on flights 3 to 6. The peaks only last several minutes and occur within three minutes of the aircraft changing from APU to engine bleed air. This suggests that this changeover results in a quick burst of particles into the cabin air. The similarly high levels on the ground, seen for both aircraft, are likely due to exhaust emissions from both ground transport and other aircraft polluting the outside air, which is then drawn in to the ventilation system. For flights 1,6 and 8, are slightly elevated during descent above the other flights. For flights 1 and 8, these levels occurred within a few minutes of the start of descent and for flight 6 it occurred in the final minute of the flight (and may include a number of seconds on the ground). More information is given in tables within Appendix E.

As an aside, there are no widely recognised health-based guidelines for levels of ultrafine particles in the air.

5.3.5 Infra-red thermography

This technique can highlight hot and cold spots aboard aircraft. It is particularly useful in trouble-shooting a problem, especially if there is a concern with the thermal environment. Figures 5.28 and 5.29 show examples of images from the BAe146 and B737 aircraft respectively. The figures show a more even spread of inlet air within the B737 aircraft, and a more focused airflows from within the BAe 146. However, none of these appear to indicate any issues of concern.

Table 5.19: Summary of ultrafine particle levels

Aircraft Type	Flight Phase	Ultrafine Particle Counts (particles per cm^3)	
		N	Mean (range)
146	Whole Flight	8	20674 (8990-37524)
	Cruise	8	1121 (45-4985)
	Ground	8	38166 (20986-75369)
737	Whole Flight	6	5381 (1292-9040)
	Cruise	6	57 (28-93)
	Ground	6	28592 (6816-57020)

Table 5.20: Maximum ultrafine particle levels in each flight phase

Aircraft Type	Flight No.	Ultrafine Particle Counts (particles per cm^3)			
		Ground	Climb	Cruise	Descent
146	1	46421	27911	109	48963
	2	51266	21238	558	5700
	3	47185	249633	94848	7295
	4	85483	231233	10296	1783
	5	135733	256183	8986	8104
	6	185616	126333	4442	25810
	7	32845	12675	182	4944
	8	126333	7284	25810	61801*
737	9	112970	37960	39	669
	10	129976	24946	136	997
	11	74351	983	714	9290
	12	34733	4458	204	37*
	13	63378	5159	104	528
	14	382416	18778	652	692

* ultrafine particle counter did not run for the full duration of descent due to power failure

Figure 5.26: Example of ultrafine particle levels from BAe146 aircraft

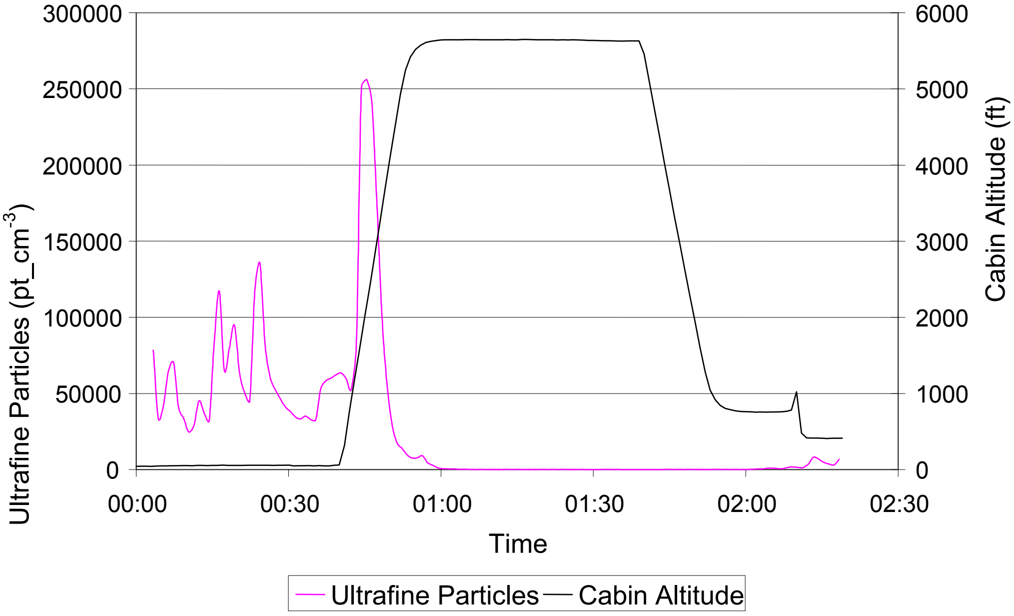


Figure 5.27: Example of ultrafine particle levels from B737 aircraft

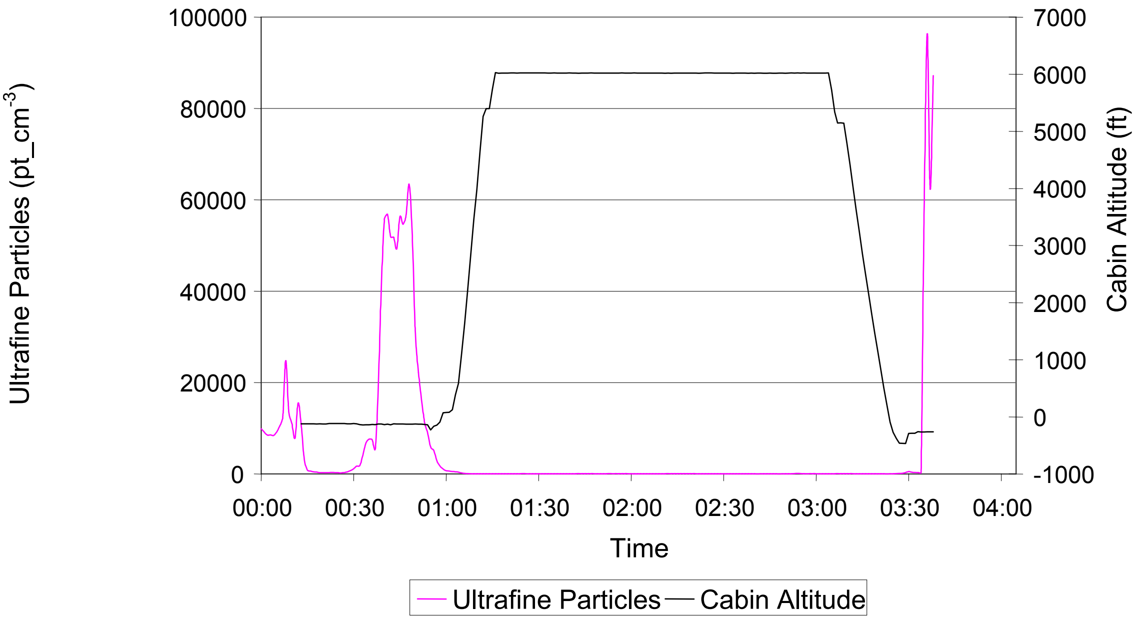


Figure 5.28: Example of Infra-red data of the cabin from BAe146 Aircraft

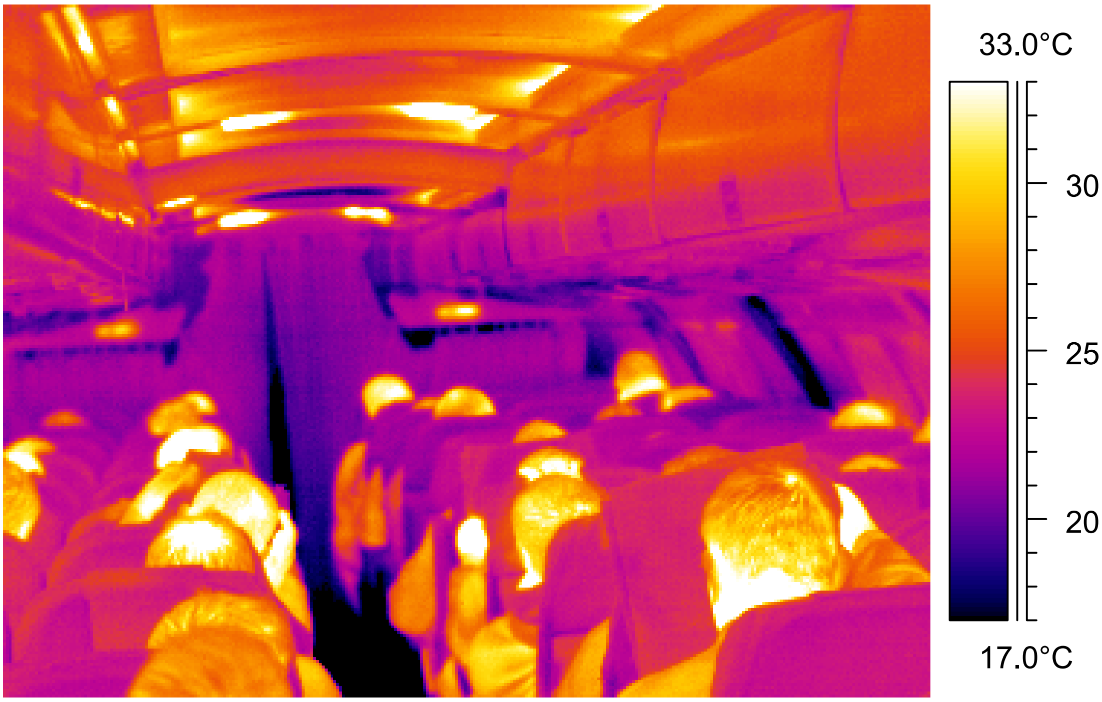
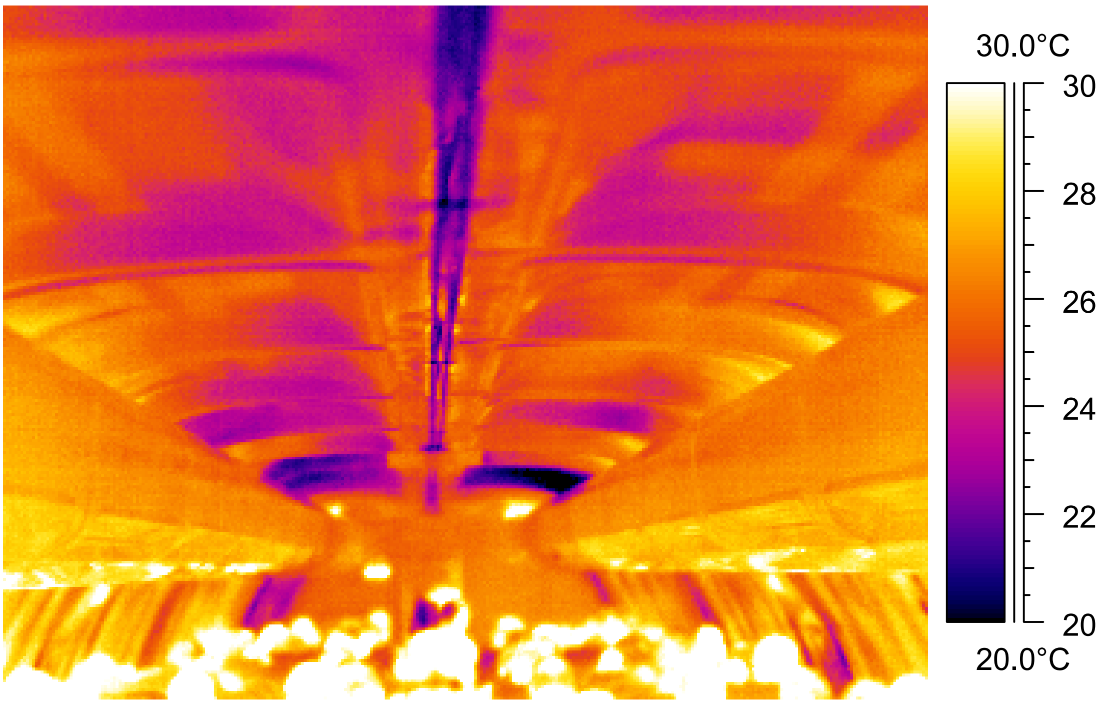


Figure 5.29: Example of Infra-red data of the cabin from B737 Aircraft



6 Conclusions

This in-flight monitoring study focused on the AHWG selected BAe 146 and Boeing 737-300 aircraft types – both commonly used in high volume, short haul operations. The intention was that this study would be complementary to the measurements of key air quality parameters already carried out under CabinAir. The intention of this study was not to compare the two aircraft types with one another, nor to carry out detailed statistical analysis of the monitored data, nor to monitor the air quality during any 'unusual circumstances'. The emphasis was on obtaining this additional complementary data, and comparing with any health-based guidance levels that exist.

In total, we monitored fourteen scheduled commercial flights (8 x BAe146, 6 x B737). These comprised both UK domestic flights and flights between the UK and other European countries. The flight times ranged between approximately 1 and 3 hours.

The study included the following measurements on each flight.

- Continuous fixed site measurements at two seat location of: air temperature, globe temperature, relative humidity, air speed, carbon monoxide and carbon dioxide.
- Mobile measurements in the cabin of: air temperature, air speed and carbon dioxide.
- Measurements at different flight phases of: volatile organic compounds (VOCs), very volatile organic compounds (VVOCs), semi volatile organic compounds (SVOCs) and carbonyl compounds (aldehydes and ketones).
- Measurements at different flight phases of: bacteria, fungi and endotoxins.
- Continuous measurement of nitrogen dioxide and ultrafine particle counts.

In addition, we made measurements of surface dust and dust mite and cat allergens on the BAe146 aircraft. We also carried out infra-red thermography surveys within the cabin of each aircraft type.

The following summarises the results:

- Cabin pressure – the average cabin altitude in cruise never exceeded the regulatory ceiling of 8000 ft. For periods during climb and descent, the rates of altitude increase and decrease did exceed the recommended values;
- Air and globe temperature – mean values usually below 26°C;
- Relative humidity – during cruise, mean RH within the BAe146 was 12.7% in 100% external air mode, and 20.0% for the B737 in recirculation mode;
- Air speed – at head height were typically below 20 $cm.s^{-1}$

- Carbon monoxide – all values were of a similar level or less than those found in studies of air quality in homes in England. Mean levels somewhat higher on the ground than during cruise.
- Carbon dioxide – mean levels were typically between 700 and 2000 ppm during cruise, and did not exceed regulatory requirements;
- Nitrogen dioxide – all levels were below the WHO recommendations, as well as below those values found within a sample of kitchens in gas cooking homes in England. Levels of nitrogen dioxide were higher whilst on the ground than during cruise.
- Volatile organic compounds (VOC) – all measured values are well within the available guidance on air quality for internal environments. Typically, the highest concentrations were found while the aircraft were on the ground.
- Carbonyls (formaldehyde, acetaldehyde, acetone, and acrolein) – low levels of all compounds, and well below World Health Organisation (WHO) limits, and HSE guidelines;
- Semi volatile organic compounds - For the BAe 146, analysis focused on testing for Exxon 2380 (used for engine and APU oil) and Skydrol (used for hydraulic oil). For the Boeing 737 flights, analysis focused on Aeroshell Turbine oil 560 (used for engine oil) and Skydrol. Very low (if any) indication of these oils present in the cabin environment of those monitored flights.
- Bacteria and fungi – higher levels whilst the aircraft is on the ground than during cruise;
- Surface dust, dust mite allergens and cat allergens – very low levels found on board;
- Ultrafine particles – elevated levels were always found during the ground phases – levels in cruise are several orders of magnitude lower.

In all instances, the measured values were similar to other cabin air quality studies and the air pollutant concentrations were below health guideline levels. While it is currently not possible to compare these results in detail with those from the European CabinAir project, our initial view is that the levels of air quality parameters measured in these older type aircraft are comparable with those measured in newer types.

7 Acknowledgements

We gratefully acknowledge the help and support of both airlines that participated in this study. This includes the management boards, engineering teams and the ground, cabin and flight crews.

Similarly, we thank BAE SYSTEMS, in particular Trevor Mickleburgh and John Downey. They helped us identify and recruit a suitable airline with BAE146 aircraft and Trevor accompanied and helped on each of those flights.

Thanks also to Peter Chittenden of the Civil Aviation Authority who helped us to recruit the airline with B737-300 aircraft.

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Appendix A - Stationary environmental measurements

Table A1: Cabin pressure data for each flight

Flight Number	Mean cabin altitude during cruise (ft)	Maximum rate of cabin altitude increase during climb (ft/min)	Maximum rate of cabin altitude decrease during descent (ft/min)
1*			
2	6759	463	236
3	6994	553	361
4	6842	654	478
5	5916	416	320
6	6384	431	360
7	7460	512	487
8	6748	517	571
9	6378	439	329
10	6769	424	449
11	6385	534	419
12	6753	550	345
13	6337	554	344
14	6822	418	321

* Problem with recording of data-set on first flight

Table A2: Environmental data on BAe146 aircraft during the whole flight

Flight No.	Seat	RH (%)			Air Speed ($m.s^{-1}$)			Air Temp 1.1m (°C)			Air Temp 0.1m (°C)			Globe Temp (°C)			CO (ppm)		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1																			
2	10C	33.5	18.3	51.0	0.07	<0.05	0.29	22.8	20.8	24.0	20.3	18.8	21.6	22.7	20.9	23.7	0.2	<0.1	1.8
	21A	30.9	13.4	53.1	0.06	<0.05	0.18	22.1	20.3	23.6	19.8	16.2	22.0	22.0	19.6	23.8	0.3	<0.1	1.8
3	6B	26.2	14.2	41.2	<0.05	<0.05	0.12	22.6	19.1	24.6	18.3	13.7	22.6	22.4	19.0	24.7	0.3	<0.1	1.9
	18A	21.6	9.7	44.1	0.20	0.15	0.30							24.6	20.6	26.9			
4	7A	22.6	14.0	40.0	<0.05	<0.05	0.10	20.5	15.0	23.3				20.3	15.0	22.9	0.3	<0.1	5.8
	8D	19.2	8.0	38.9	0.07	<0.05	0.21	22.9	22.4	24.2				22.8	18.3	24.9			
5	5B	19.4	7.2	35.8	0.05	<0.05	0.28	24.4	19.4	26.8				24.2	19.9	26.3	0.1	<0.1	0.4
	10A	18.4	8.2	33.3	<0.05	<0.05	0.26	23.8	18.7	26.6	19.4	14.9	22.6	23.5	18.0	26.4	0.1	<0.1	0.6
6	6B	17.5	5.1	32.0	0.10	<0.05	0.26	25.2	23.0	26.4	24.4	23.9	24.9	24.7	23.2	25.7	0.4	<0.1	1.1
	10A	13.1	4.8	22.0	0.06	<0.05	0.15	27.9	21.2	37.8	18.1	11.4	20.7	27.7	22.1	35.0	0.3	<0.1	0.9
7	7B	21.6	9.9	39.4				23.5	17.9	25.9	19.4	15.0	23.9	23.4	18.2	25.5	0.2	<0.1	2.0
	10A	21.6	9.6	45.3	0.20	<0.05	1.42	23.9	20.5	25.2	21.4	20.0	24.0	22.9	18.9	24.5	0.1	<0.1	2.6
8	7B	13.7	6.1	27.9				23.9	21.1	26.0	20.8	17.7	23.7	24.0	20.8	25.9	0.2	<0.1	2.1
	10A	12.6	5.7	30.8	0.05	<0.05	0.17	25.4	24.4	26.4	23.5	22.4	24.8	23.9	22.3	25.4	0.3	<0.1	2.2

Table A3: Environmental data on BAe146 aircraft during cruise

Flight No.	Seat	RH (%)			Air Speed (m.s^{-1})			Air Temp 1.1m (°C)			Air Temp 0.1m (°C)			Globe Temp (°C)			CO (ppm)		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1																			
2	10C	20.9	18.3	25.1	<0.05	<0.05	0.10	23.8	23.5	24.0	21.0	20.5	21.6	23.4	23.0	23.7	<0.1	<0.1	<0.1
	21A	17.2	13.4	23.4	<0.05	<0.05	0.06	23.1	21.5	23.6	21.3	20.1	22.0	23.2	22.0	23.8	0.1	<0.1	0.1
3	6B	18.6	14.2	22.5	<0.05	<0.05	0.10	23.8	22.3	24.4	18.5	16.7	20.8	23.5	22.3	24.3	<0.1	<0.1	<0.1
	18A	11.2	9.7	13.3	0.22	0.17	0.26							25.5	23.7	26.4			
4	7A	17.6	14.0	20.5	<0.05	<0.05	0.08	21.7	20.8	23.1				21.4	20.4	22.8	<0.1	<0.1	<0.1
	8D	12.3	8.0	15.8	0.08	<0.05	0.21	22.6	22.4	23.0				23.5	22.4	24.6			
5	5B	10.1	7.3	14.1	<0.05	<0.05	0.11	25.5	24.9	26.4				25.2	24.6	25.9	<0.1	<0.1	0.1
	10A	9.7	8.5	11.2	<0.05	<0.05	0.09	25.4	24.1	26.2	20.9	20.5	21.8	24.8	23.7	25.9	<0.1	<0.1	0.1
6	6B	7.6	5.1	10.1	0.13	0.05	0.24	25.4	24.1	26.2	24.4	24.2	24.5	24.8	23.6	25.6	<0.1	<0.1	0.1
	10A	7.2	5.1	8.9	0.07	<0.05	0.14	29.8	25.8	37.5	18.8	18.0	20.1	29.9	25.8	35.0	0.1	<0.1	0.2
7	7B	15.6	11.8	21.2				24.0	23.3	25.1	19.6	18.9	20.9	23.9	23.1	24.9	<0.1	<0.1	<0.1
	10A	13.4	9.6	18.0	0.05	<0.05	0.15	24.1	23.6	24.7	21.3	20.7	21.9	23.2	22.7	24.3	<0.1	<0.1	<0.1
8	7B	9.8	7.5	12.3				24.3	22.7	25.2	21.4	19.8	22.9	24.4	23.2	25.4	0.1	<0.1	0.1
	10A	7.0	5.8	8.4	<0.05	<0.05	0.05	25.3	24.7	24.8	23.4	22.9	23.2	24.0	23.0	23.3	0.2	0.1	0.2

Table A4: Environmental data on BAe146 aircraft on the ground prior to departure

Flight No.	Seat	RH (%)			Air Speed (m.s^{-1})			Air Temp 1.1m (°C)			Air Temp 0.1m (°C)			Globe Temp (°C)			CO (ppm)		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1																			
2	10C	45.7	38.2	51.0	0.08	<0.05	0.13	21.7	20.8	22.6	19.9	18.8	21.1	21.6	20.9	22.2	0.6	0.3	1.8
	21A	43.6	38.0	53.1	0.09	<0.05	0.18	21.0	20.3	22.1	18.9	16.6	21.4	20.9	20.0	22.7	0.5	0.3	1.8
3	6B	36.0	29.6	41.2	<0.05	<0.05	0.09	21.0	19.1	22.5	18.0	14.1	21.4	20.8	19.0	22.5	0.7	0.4	1.9
	18A	33.7	27.8	44.1	0.19	0.15	0.26							22.9	20.6	25.0			
4	7A	33.1	27.7	40.0	<0.05	<0.05	0.09	16.6	15.0	19.3				16.8	15.0	19.4	0.9	3.0	5.8
	8D	33.9	27.6	38.9	0.07	<0.05	0.13	23.4	22.8	24.2				19.7	18.3	21.7			
5	5B	33.7	32.1	35.8	0.08	<0.05	0.28	21.6	19.4	23.7				21.5	19.9	23.1	0.3	<0.1	0.4
	10A	32.0	30.7	33.3	0.06	<0.05	0.26	20.5	18.7	22.5	16.7	14.9	19.8	20.4	18.0	22.4	0.3	0.2	0.6
6	6B	27.7	23.4	32.0	0.05	<0.05	0.20	24.6	23.0	26.1	24.1	23.9	24.2	24.1	23.2	25.5	0.9	0.8	1.1
	10A	19.6	17.0	22.0	0.04	<0.05	0.07	25.2	21.2	26.8	15.6	11.4	19.4	24.9	22.1	27.1	0.7	0.5	0.9
7	7B	36.9	34.1	39.4				21.4	17.9	22.5	18.4	15.5	23.9	21.4	18.2	22.3	0.5	0.2	2.0
	10A	40.5	37.6	45.3	0.67	0.06	1.42	22.3	20.5	23.2	20.5	20.0	22.1	21.1	18.9	22.1	0.5	0.2	2.6
8	7B	26.5	24.7	27.9				21.6	21.3	22.1	18.5	17.9	19.4	21.9	20.8	22.5	0.5	0.1	2.1
	10A	29.0	27.3	30.8	0.10	0.07	0.17	24.6	24.4	24.9	23.0	22.4	23.2	22.6	22.3	23.1	0.4	<0.1	2.2

Table A5: Environmental data on B737 aircraft during the whole flight

Flight No.	Seat	RH (%)			Air Speed (m.s^{-1})			Air Temp 1.1m (°C)			Air Temp 0.1m (°C)			Globe Temp (°C)			CO (ppm)		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
9	2F	20.9	12.6	42.4	0.07	<0.05	0.26	24.6	21.0	26.0				24.4	20.4	25.9	0.2	<0.1	1.8
	20A	23.8	18.4	35.2				23.0	20.3	23.7	18.8	15.8	21.3	22.9	20.0	23.9	0.2	<0.1	1.8
10	3F	23.6	15.5	39.3	0.06	<0.05	0.16	24.2	22.6	25.3				24.2	22.2	25.2	0.2	<0.1	0.7
	22F	22.8	14.3	38.9				22.2	20.9	23.3	20.9	14.0	22.8	22.2	21.1	23.1	0.2	<0.1	1.0
11	7A	24.1	15.1	51.1	0.06	<0.05	0.25	24.1	23.1	25.6	17.6	14.3	22.9	23.8	22.0	24.8	0.1	<0.1	0.7
	22A	24.5	17.4	48.1	0.09	<0.05	0.27	23.6	21.8	24.6	22.8	20.5	23.9	23.7	21.4	24.3	0.1	<0.1	0.6
12	20B	29.1	16.8	53.2	0.18	<0.05	0.39	21.1	18.4	24.9	20.7	17.7	25.5	21.3	18.6	24.6	0.1	<0.1	0.5
	25F	29.6	18.3	54.2	0.05	<0.05	0.10	23.3	21.6	25.7	22.1	20.1	22.9	23.7	22.3	24.9	0.2	<0.1	0.6
13	4A	24.0	8.4	59.2	0.10	<0.05	0.20	24.0	20.3	27.0				24.5	20.1	26.9	0.4	<0.1	3.0
	24F	32.0	18.6	55.9	<0.05	<0.05	0.10	21.5	20.4	24.5	18.9	13.5	22.6	21.4	19.8	24.1	0.4	<0.1	2.6
14	1F							22.8	21.7	25.4	21.7	20.3	24.5	22.4	21.2	24.8			
	24F	26.8	16.6	65.1	0.11	0.05	0.21	21.0	19.7	24.7				22.9	22.2	24.6	0.2	<0.1	1.6

Table A6: Environmental data on B737 aircraft during cruise

Flight No.	Seat	RH (%)			Air Speed ($m.s^{-1}$)			Air Temp 1.1m (°C)			Air Temp 0.1m (°C)			Globe Temp (°C)			CO (ppm)		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
9	2F	15.0	12.6	18.4	0.07	<0.05	0.13	25.2	24.6	25.7				25.1	24.5	25.5	0.0	<0.1	<0.1
	20A	20.0	18.4	22.2				23.2	22.8	23.6	18.4	18.0	18.8	23.3	22.9	23.9	0.0	<0.1	<0.1
10	3F	18.9	16.7	22.5	0.05	<0.05	0.14	24.4	24.1	24.7				24.3	23.9	24.6	0.1	<0.1	0.3
	22F	17.6	14.5	21.3				22.2	21.7	22.6	21.1	20.6	21.8	22.3	21.9	22.6	<0.1	<0.1	0.1
11	7A	19.9	16.8	27.3	0.05	<0.05	0.25	24.0	23.2	25.1	17.5	14.3	22.9	23.9	23.2	24.8	<0.1	<0.1	0.2
	22A	20.2	17.4	25.8	0.09	<0.05	0.18	23.6	23.0	24.2	23.1	21.6	23.6	23.7	23.3	24.3	<0.1	<0.1	<0.1
12	20B	25.1	18.5	33.2	0.18	0.09	0.39	19.9	18.4	21.1	19.4	17.7	20.6	20.3	18.6	21.4	<0.1	<0.1	0.1
	25F	24.2	18.6	32.6	0.05	<0.05	0.10	22.8	21.6	23.6	22.5	22.1	22.9	23.5	22.9	24.2	0.1	<0.1	0.2
13	4A	12.8	8.4	23.4	0.10	<0.05	0.20	24.7	21.7	27.0				25.3	23.1	26.9	0.1	<0.1	0.2
	24F	24.8	19.0	34.9	0.10	<0.05	0.10	21.2	20.4	22.2	19.2	17.6	21	21.1	19.9	22.2	0.1	<0.1	0.2
14	1F							22.6	21.7	24.6	21.1	20.3	21.7	22.1	21.2	23.4			
	24F	21.8	16.6	31.3	0.10	0.05	0.17	20.5	19.7	21.3				22.6	22.2	23.4	<0.1	<0.1	0.2

Table A7: Environmental data on B737 aircraft on the ground prior to departure

Flight No.	Seat	RH (%)			Air Speed ($m.s^{-1}$)			Air Temp 1.1m (°C)			Air Temp 0.1m (°C)			Globe Temp (°C)			CO (ppm)		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
	2F	33.3	29.7	42.4	0.11	<0.05	0.26	22.4	21.0	23.4				21.6	20.4	22.8	0.7	0.2	1.8
9	20A	32.8	30.5	34.2				21.9	20.3	23.3	18.5	15.8	21.3	21.8	20.0	23.3	0.7	0.2	1.8
	3F	36.7	34.5	39.3	0.05	<0.05	0.09	23.4	22.6	24.2				23.2	22.2	23.9	0.6	0.5	0.7
10	22F	34.5	30.5	38.9				21.9	20.9	22.5	18.4	14.0	20.6	21.8	21.1	22.4	0.8	0.6	1.0
	7A	46.5	38.5	51.1	0.06	<0.05	0.15	24.3	23.1	25.2				23.3	22.0	24.1	0.5	0.4	0.7
11	22A	44.0	38.5	48.1	0.11	<0.05	0.27	22.6	21.8	23.2	20.7	20.5	21.0	22.3	21.4	23.0	0.4	0.2	0.6
	20B	43.5	39.2	53.2	0.15	<0.05	0.31	23.8	21.9	24.9	23.9	22.3	25.5	23.7	22.0	24.6	0.4	0.3	0.5
12	25F	47.3	40.9	54.2	<0.05	<0.05	0.10	24.4	22.9	25.7	20.9	20.1	21.7	24.0	22.3	24.9	0.5	0.3	0.6
	4A	50.9	42.7	59.2	0.10	<0.05	0.10	21.9	20.3	22.7				21.6	20.1	22.2	1.4	0.7	3.0
13	24F	51.0	45.2	55.9	<0.05	<0.05	0.10	21.3	20.6	21.6	16.9	13.5	19.7	21.1	19.8	21.6	1.2	0.5	2.6
	1F	49.3	45.6	55.7	0.06	0.06	0.07	24.0	23.2	24.7	23.5	22.6	24.5	23.7	22.3	24.8			
14	24F	59.0	49.6	65.1	0.10	0.06	0.21	23.7	22.4	24.7				24.1	23.0	24.6	0.8	0.5	1.6

Table A8: Carbon dioxide data from BAe146 aircraft during the whole flight

Flight Number	Seat	Mean (ppm)	Min (ppm)	Max (ppm)
1	6C	900	389	1341
	6F	887	383	1288
2	10C	1420	344	2186
	21A	1228	419	2429
3	6B	1246	402	2244
	18A	1251	612	2564
4	8D	1007	349	1995
	7A	1202	337	2138
5	5B	922	459	1895
	10A	857	548	1595
6	6B	1129	800	2010
	10A	1123	642	2403
7	7B	1156	516	1994
	10A	1272	577	2135
8	7B	746	575	1245
	10A	814	657	1225

Table A9: Carbon dioxide data from BAe146 aircraft during cruise

Flight Number	Seat	Mean (ppm)	Min (ppm)	Max (ppm)
1	6C	814	708	1341
	6F	786	683	875
2	10C	1370	1173	1556
	21A	1071	900	1478
3	6B	1171	919	1612
	18A	1083	902	1277
4	8D	931	728	1214
	7A	1299	1107	1578
5	5B	790	656	940
	10A	773	634	958
6	6B	1113	982	1261
	10A	985	863	1279
7	7B	1109	968	1240
	10A	1278	1176	1465
8	7B	714	586	1015
	10A	777	706	891

Table A10: Carbon dioxide data from BAe146 aircraft on the ground prior to departure

Flight Number	Seat	Mean (ppm)	Min (ppm)	Max (ppm)
1	6C	1011	389	1315
	6F	979	383	1288
2	10C	1432	344	2186
	21A	1411	419	2429
3	6B	1299	402	2244
	18A	1306	612	2564
4	8D	1082	349	1995
	7A	1039	337	2138
5	5B	1035	459	1753
	10A	974	548	1595
6	6B	1262	878	2010
	10A	1510	642	2403
7	7B	1341	516	1994
	10A	1359	577	2135
8	7B	938	645	1245
	10A	903	675	1225

Table A11: Carbon dioxide data from B737 aircraft during the whole flight

Flight Number	Seat	Mean (ppm)	Min (ppm)	Max (ppm)
9	2F	1561	1246	2405
	20A	1391	876	1849
10	3F	1543	1105	2917
	22F	1405	1108	2602
11	7A	1626	1206	3300
	22A	1788	1505	2256
12	20B	1470	911	2434
	25F	1914	1071	2825
13	4A	1858	692	3508
	24F	1754	1401	2560
14	1F			
	24F	1678	701	2426

Table A12: Carbon dioxide data from B737 aircraft during cruise

Flight Number	Seat	Mean (ppm)	Min (ppm)	Max (ppm)
9	2F	1664	1494	1824
	20A	1578	1383	1849
10	3F	1411	1276	1520
	22F	1248	1108	1419
11	7A	1571	1374	2061
	22A	1810	1665	1970
12	20B	1500	1235	1722
	25F	2011	1539	2194
13	4A	1827	1662	1993
	24F	1695	1577	1831
14	1F			
	24F	1666	1527	1829

Table A13: Carbon dioxide data from B737 aircraft on the ground prior to departure

Flight Number	Seat	Mean (ppm)	Min (ppm)	Max (ppm)
9	2F	1587	1246	2405
	20A	1298	1113	1630
10	3F	2232	1471	2917
	22F	1943	1225	2602
11	7A	2494	1442	3300
	22A	1944	1581	2256
12	20B	1677	911	2434
	25F	1999	1071	2825
13	4A	2209	1479	3508
	24F	2064	1603	2560
14	1F			
	24F	1920	701	2423

Appendix B – Thermal comfort

To interpret the findings in terms of the likely effect on the comfort of passengers and cabin crew, we need to make reference to the theory of thermal comfort. Thermal comfort depends upon a combination of the environmental conditions to which an individual is exposed (principally air and radiant temperature, local air velocity/turbulence and relative humidity) together with the individual's clothing insulation level and metabolic rate, the latter varying mainly as a result of physical activity.

Individuals differ and, in consequence, not everyone will find a particular set of conditions satisfactory. Some will feel too cool, others too warm. However, it is possible to determine the proportion of the population who are likely to be dissatisfied with a given set of conditions, for example using the method set out in ISO 7730. In applying this method, it needs to be kept in mind that it has not been validated for the aircraft environment and it does not apply equally well to all indoor environments (for example it is more accurate for air-conditioned offices than it is for naturally ventilated buildings). Nevertheless, it is probably the best method of obtaining a first approximation.

Suitable ranges of temperature can be determined, using ISO 7730, for two levels of provision – (i) 10% of occupants dissatisfied and (ii) 15% of occupants dissatisfied. In this context, "dissatisfied" means "giving a thermal sensation rating outside the middle three categories on the seven-point ASHRAE scale (Slightly Cool, Neutral or Slightly Warm). It can be shown by theoretical calculations that there will always be a minimum of 5% of the population who are dissatisfied, when the average thermal sensation is neutral (some experts argue that the theoretical minimum is actually much higher, at 10% or even 20%).

In order to make the calculations, the values of some parameters have to be estimated, as follows.

Regarding clothing insulation (expressed in 'clo'), an insulation level of 0.77 clo would be achieved by wearing short socks, shoes, briefs, thin long-sleeved shirt, thin trousers and a light sweater. A very light ensemble (0.28 clo) would be short socks, shoes, briefs, shorts and T-shirt. A relatively heavy ensemble (1.20 clo) would be long socks, shoes, briefs, vest, long-sleeved shirt, heavy suit and tie. Passengers might cover this full range (and wider) but, in practice, some assumption must be made that passengers will adapt their clothing to the conditions, hence a narrower range of 0.50 – 1.00 is considered here. Cabin crew would be more restricted in their dress, and a range of 0.60 – 0.80 seems likely, based on typical uniforms and the only real flexibility being in the underwear worn.

A metabolic rate value of 1 met is equivalent to 58.2 Wm^{-2}, which is the typical metabolic rate of a seated relaxing adult. This would be a reasonable value to use for passengers. The typical metabolic rates associated with cabin crew activities could easily vary between 1.0 (sitting) and 3.0 (pushing trolley up a gradient). In practice, the range is likely to be much narrower because each activity is carried out for a short period. An estimate of 1.6 met is used here, which corresponds to standing and carrying out medium activity such as walking slowly or doing work at a rate similar to a shop assistant.

If surrounding surface temperatures differ little from air temperature, radiant temperature approximates to air temperature.

At the general levels of temperature in an aircraft cabin, relative humidity is expected to have little effect in the range 5-20% RH, and a figure of 15% is assumed here. Air velocity has been taken as 0.05-0.20 ms^{-1} for passengers and 0.05-0.30 $m\ s^{-1}$ for cabin crew.

The resulting temperature ranges (rounded to nearest 0.5°C) are shown in Table B1 and graphically in Figures B1 and B2.

This analysis suggests that it will be difficult to satisfy both passengers and crew in the same thermal environment. Only at about 24°C can both groups achieve the ideal temperature and this is dependent on having the maximum considered difference in air velocity and clo. However, this is to take a mechanistic view of comfort. Thermal comfort does not depend purely on an environment being imposed on people. It also depends on the response of people to adapt to the environment. Seen in this way, the question changes from “what temperature is comfortable” to “what is the range of temperatures to which people can easily adapt to achieve comfort”.

Table B1: Temperature ranges for 5%, 10% and 15% dissatisfied (°C)

Air velocity ($m\ s^{-1}$)	Clo	15% Dissatisfied (cool)	10% Dissatisfied (cool)	5% Dissatisfied (neutral)	10% Dissatisfied (warm)	15% Dissatisfied (warm)
Passengers						
0.05	0.5	25.0	25.5	26.8	28.2	28.8
	1.0	21.6	22.3	24.1	26.1	26.9
0.10	0.5	25.1	25.7	27.0	28.4	29.0
	1.0	21.7	22.5	24.3	26.3	27.1
0.15	0.5	25.6	26.1	27.5	28.7	29.3
	1.0	22.2	23.0	24.8	26.6	27.4
0.20	0.5	25.9	26.5	27.9	29.0	29.5
	1.0	22.5	23.3	25.1	26.9	27.6
Crew						
0.05	0.6	18.7	19.6	22.0	24.5	25.5
	0.8	16.6	17.7	20.5	23.3	24.4
0.10	0.6	18.8	19.7	22.2	24.7	25.7
	0.8	16.7	17.8	20.7	23.5	24.6
0.15	0.6	19.3	20.3	22.6	25.0	26.0
	0.8	17.2	18.3	21.2	23.9	25.0
0.20	0.6	19.8	20.8	23.0	25.4	26.3
	0.8	17.8	18.9	21.4	24.2	25.3
0.25	0.6	20.2	21.1	23.4	25.6	26.5
	0.8	18.2	19.2	22.0	24.4	25.5
0.30	0.6	20.5	21.4	23.7	25.8	26.7
	0.8	18.5	19.5	22.2	24.6	25.6

Figure B1: Temperature ranges for 5%, 10% and 15% dissatisfied (passengers)

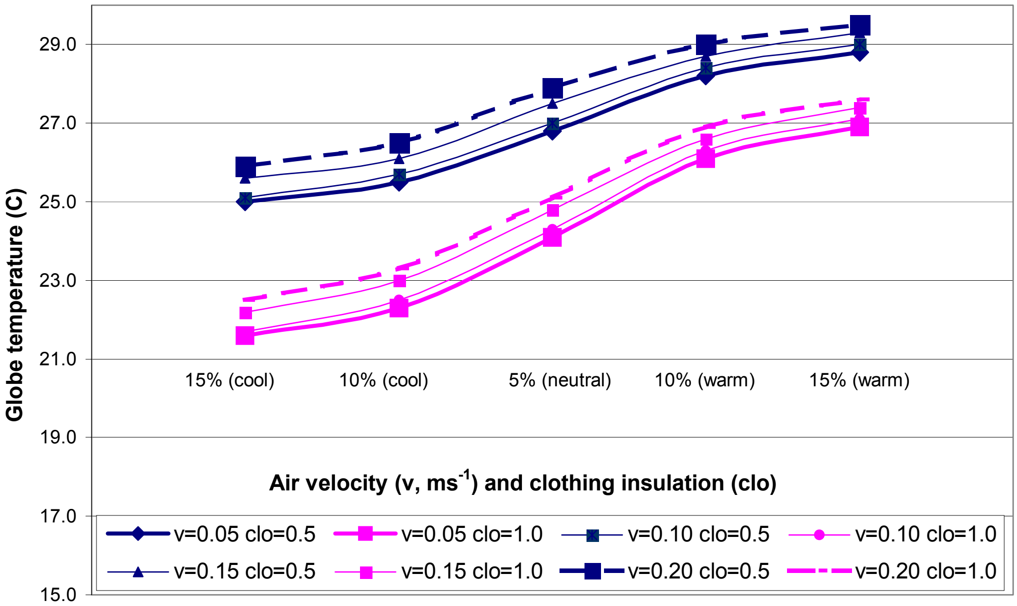
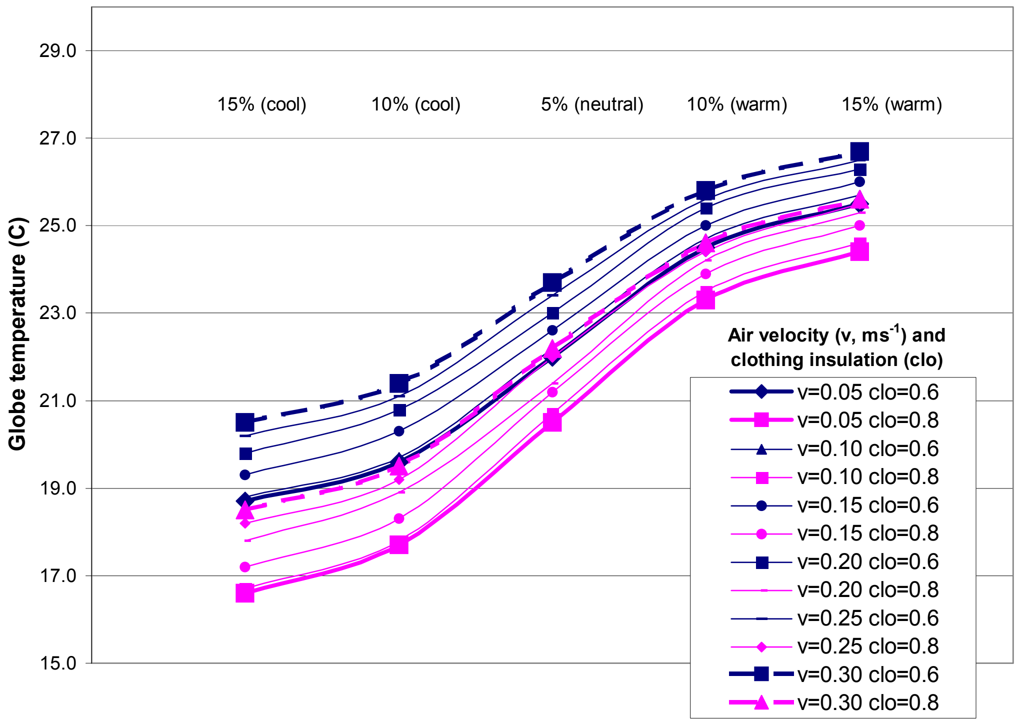


Figure B2: Temperature ranges for 5%, 10% and 15% dissatisfied (crew)



The data from the present study provide an excellent opportunity to illustrate this point. In Table B2, the relevant thermal data are presented, together with the calculated percentage people dissatisfied (PPD). Not all flights are shown because the necessary data were not available for all flights. The values of temperature and humidity shown are for passengers. For crew, temperatures have been reduced by 1.25°C for the B737 and 0.25°C for the BAe146, and air velocities have been increased by 0.15 $m.s^{-1}$ for the B737 and 0.025 $m.s^{-1}$ for the BAe146. This reflects the median differences between conditions for passengers and crew, based on measurements with portable instruments. Because this is a general correction, it may over-correct where the temperature is low and the air velocity is high, and under-correct where the temperature is high and the air velocity is low.

The shaded rows in Table B2 show where both passengers and crew could achieve a PPD of 10% or less, within the likely range of clo values. The more deeply shaded rows in Table 5.6 show where both passengers and crew could achieve a PPD of 7% or less, within the likely range of clo values. Not unexpectedly, this almost always requires the passengers to be at the upper end of their clo range and the crew to be at the lower end of their clo range.

Given the apparent challenge in achieving comfortable conditions for all, as shown in the theoretical analysis, it is notable that such low values of PPD are so often achieved. This would suggest that the crew are adjusting the temperature in response to the particular combination of thermal conditions that they are experiencing, so that something close to the optimum is achieved in the context of the humidity and air movement in the cabin. Furthermore, if cabin crew dress in 0.6 clo or perhaps a little less, then the thermal conditions that satisfy them are also likely to satisfy the passengers. The ideal balance appears to be easier to achieve on the B737, on account of the greater difference in temperature and air velocity between the aisle and the passenger seats.

As a final exercise, we took the mean of the PPD for passengers with clo=1 and crew with clo=0.6. This mean is related to the temperature among the seats by a quadratic function (r^2=0.96).

$$PPD = 1.3352T_g^2 - 64.93T_g + 794.44$$

According to this function, the mean PPD has a minimum (5.1%) at 24.3°C and is within 7% over the range 23.2-25.5°C and within 10% over the range 22.4-26.2°C. In round figures, the desirable range can be proposed as 23.0-25.5°C and the optimum as 24°C. The optimum will depend mainly on the air velocity if clo is fixed. This is based on the two aircraft studied and does not necessarily generalise to other aircraft, but is a useful starting point.

The aircraft appear to be capable of achieving these conditions, the major obstacles being (a) the need to ensure that crew have a light clothing ensemble while active in the cabin, and (b) the likelihood that passengers will wear a wide range of ensembles. The crew uniform is relatively easily controlled and modified if the analysis presented here is accepted. Passenger clothing cannot be dictated but, if a certain level of crew clothing became standard across the industry, temperatures could become more similar between flights and, in our view, recommendations on dress could more easily be made to passengers.

Table B2: PPD based on mean environmental conditions per flight

Aircraft	Flight No.	Seat	RH(%)	Air velocity (m.s^{-1})*	Globe temp (°C)	PPD Passengers: met=1 clo=0.5	PPD Passengers: met=1 clo=1.0	PPD Crew: met=1.6 clo=0.6	PPD Crew: met=1.6 clo=0.8
BAe146	2	10C	20.9	<0.05	23.4	37	6	6	10
	2	21A	17.2	<0.05	23.2	42	6	6	9
	3	6B	18.6	<0.05	23.5	36	6	6	10
	3	18A	11.2	0.22	25.5	23	5	8	13
	4	7A	17.6	<0.05	21.4	76	16	6	5
	4	8D	12.3	0.08	23.5	38	6	6	9
	5	5B	10.1	<0.05	25.2	14	6	12	17
	5	10A	9.7	<0.05	24.8	18	5	10	15
	6	6B	7.6	0.13	24.8	24	5	7	12
	6	10A	7.2	0.07	29.9	26	45	47	52
	7	10A	13.4	0.05	23.2	43	7	6	9
	8	10A	7.0	<0.05	24.0	30	5	7	11
B737	9	2F	15.0	0.07	25.1	14	6	5	8
	10	3F	18.9	0.05	24.3	23	5	5	7
	11	7A	19.9	0.05	23.9	28	5	5	6
	11	22A	20.2	0.09	23.7	32	5	6	5
	12	20B	25.1	0.18	20.3	97	36	28	12
	12	25F	24.2	0.05	23.5	34	5	5	6
	13	4A	12.8	0.10	25.3	13	6	5	8
	13	24F	24.8	0.10	21.1	80	18	16	7
	14	24F	21.8	0.10	22.6	52	9	9	5

*Limit of quantification is 0.05 (lower values have been replaced with 0.025 in calculations).

Appendix C - Microbiological measurements

Table C1: Bacteria measurements

Flight Number	Bacteria levels (cfu.m^{-3})			
	Before Boarding	During Boarding	Cruise	Disembarking
1	240	900	155	390
2	128	445	380	1905
3	243	345	235	490
4	60	945	445	1140
5	253	585	40	400
6	638	225	100	365
7	145	760	100	420
8	no sample[1]	no sample[1]	no sample[1]	no sample[1]
9	no sample[2]	285	220	1115
10	no sample[2]	735	400	1960
11	no sample[2]	595	65	345
12	no sample[2]	305	310	695
13	no sample[2]	310	95	350
14	no sample[2]	65	30	70

[1] No measurements taken as additional return flight (see Section 4.2)
[2] Insufficient time for monitoring team to make measurements on B737 aircraft

Table C2: Fungi measurements

Flight Number	Fungi levels (cfu.m^{-3})			
	Before Boarding	During Boarding	Cruise	Disembarking
1	123	50	0	60
2	53	35	10	25
3	13	10	0	30
4	8	175	5	35
5	63	45	0	15
6	48	10	0	10
7	78	30	10	35
8	no sample[1]	no sample[1]	no sample[1]	no sample[1]
9	no sample[2]	13	5	15
10	no sample[2]	80	0	10
11	no sample[2]	120	0	110
12	no sample[2]	30	15	110
13	no sample[2]	1360	110	70
14	no sample[2]	450	25	1230

[1] No measurements taken as additional return flight (see Section 4.2)
[2] Insufficient time for monitoring team to make measurements on B737 aircraft

Table C3: Composition of viable fungi from air samples expressed as mean percentage of total colonies appearing on plates

	Pre-boarding	Boarding	Cruise	De-boarding
Penicillium	22.3	70.8	8.6	63.7
Mycelia sterilia	38.5	5.2	57.1	4.8
Yeast	12.8	10.6	14.3	11.2
Cladosporium	16.2	6.6	11.4	14.3
Aureobasidium	0.7	1.4	2.9	2.0
Helminthosporium	0.7	-	2.9	0.4
Aspergillus	3.4	-	-	0.4
Acremonium	-	0.6	2.9	-
Geomyces	1.4	2.0	-	-
Tricoderma	2.0	-	-	-
White-rot basidiomycetes	0.7	0.6	-	-
Mucor	-	-	-	1.2
Fusarium	-	-	-	1.2
Phoma	-	1.1	-	-
Ulocladium	0.7	0.3	-	-
Eppicoccum	-	0.3	-	0.4
Verticillium	0.7	-	-	-
Rhizopus	-	-	-	0.4
Scopulariopsis	-	0.3	-	-
Botrytis	-	0.3	-	-

Table C4: Percentage of air samples yielding viable fungi at the different locations

	Pre-boarding	Boarding	Cruise	De-boarding
Penicillium	64	62	15	77
Mycelia sterilia	71	62	15	62
Yeast	64	92	39	77
Cladosporium	79	69	23	69
Aureobasidium	7	23	8	31
Helminthosporium	7	-	8	8
Aspergillus	29	-	-	8
Acremonium	-	8	8	-
Geomyces	7	15	-	-
Tricoderma	14	-	-	-
White-rot basidiomycetes	7	15	-	-
Mucor	-	-	-	23
Fusarium	-	-	-	23
Phoma	-	31	-	-
Ulocladium	7	8	-	-
Eppicoccum	-	8	-	8
Verticillium	7	-	-	-
Rhizopus	-	-	-	8
Scopulariopsis	-	8	-	-
Botrytis	-	8	-	-

Appendix D – Volatile organic compound measurements

Table D1: TVOC measurements

Flight Number	TVOC Concentrations (µg m^{-3})			
	Ground	Climb	Cruise	Descent
1	100		68	157
2	279		161	
3	607	444	204	
4	619	154	48	11
5	301	122	103	250
6	314	96	119	126
7	49	123	79	91
8	no sample[1]	no sample[1]	no sample[1]	no sample[1]
9	166	83	86	25
10	1140	194	145	101
11			162	
12	445	373	175	150
13	499	204	131	
14	251	192	156	86

[1] No measurements taken as additional return flight (see Section 4.2)

Table D2a: VOCs from BAe146 aircraft (µg m^{-3})

Flight No	Phase	Tetrachloromethane (carbon tetrachloride)	Benzene	1,2-dichloropropane	Pentanal (n-valeraldehyde)	Bromodichloromethane	cis-1,3 dichloropropene	Toluene	Tetrachloroethene	Trans-1,3-dichloropropene	1,1,2-trichloroethane	2-hexanone	Hexanal	Dibromochloromethane	1,2-dibromoethane	Chlorobenzene	Ethylbenzene	M+p-xylenes
1	Ground	<10.4	2	<0.7	<1.2	<1.3	<2.0	2.5	<1.2	<2.0	<2.3	<5.4	<0.4	<12.2	<3.6	<1.2	0.6	1.9
	Cruise	<12.9	0.2	<0.9	<1.5	<15.6	<2.4	0.8	<1.5	<2.4	<2.9	<6.7	0.9	<15.2	<4.5	<1.5	<0.2	0.2
	Descent	<26.6	0.5	<1.9	<3.1	<32.2	<5.0	1.5	<3.1	<5.0	<5.9	<13.8	1.3	<31.3	<9.4	<3.1	<0.3	0.4
2	Ground	<7.7	1.2	<0.5	<0.9	<9.4	<1.5	9.7	<0.9	<1.5	<1.7	<4.0	<0.3	<9.1	<2.7	<0.9	0.8	2.4
	Cruise	<6.6	0.4	<0.5	<0.8	<8.0	<1.3	2.8	1.1	<1.3	<1.5	<3.4	0.8	<7.8	<2.3	<0.8	0.3	1.1
3	Whole flight	<11	1	<0.8	<1.3	<14	<2.1	13.2	<1.3	<2.1	<2.5	<5.9	0.4	<13	<4.0	<1.3	<0.1	1.1
	Ground	<8	1.4	<0.6	<1.0	<10	<1.6	17.7	<1.0	<1.6	<1.9	<4.3	<0.3	<9.8	<2.9	<1.0	1.8	3.1
	Climb	<13	0.5	<0.9	<1.6	<16	<2.5	20.6	<1.6	<2.5	<3.0	<6.9	0.9	<16	<4.7	<1.5	<0.2	0.6
	Cruise	<13.3	0.2	<0.9	<1.6	<16	<2.5	7.8	<1.6	<2.5	<3.0	<6.9	1.1	<16	<4.7	<1.6	<0.2	<0.2
4	Whole flight	<13	0.9	<1.0	<1.5	<16	<2.4	1.1	<1.5	<2.4	<2.9	<6.7	<0.5	<15	<4.5	<1.5	<0.2	0.6
	Ground	<13	4.5	<1.0	<1.6	<15	<2.4	4.9	<1.5	<2.4	<2.8	<6.5	<0.4	<15	<4.4	<1.5	0.9	2.3
	Climb	<14	0.2	<1.0	<1.5	<17	<2.7	0.3	<1.7	<2.7	<2.9	<7.3	<0.5	<17	<5.0	<1.7	<0.2	<0.2
	Cruise	<12	0.2	<1.0	<1.7	<14	<2.2	0.3	<1.4	<2.4	<2.6	<6.1	<0.4	<14	<4.2	<1.4	<0.1	<0.1
	Descent	<13	0.2	<1.0	<1.5	<17	<2.7	<0.2	<1.7	<2.7	<2.9	<7.3	<0.5	<17	<5.0	<1.7	<0.2	<0.2

Table D2a: VOCs from BAe146 aircraft (μg m^{-3}) (cont)

Flight No	Phase	Styrene	Tibromomethane (bromoform)	1,1,2,2-tetrachloroethane	Limonene	Benzaldehyde	1,3-dichlorobenzene (m-dichlorobenzene)	1,4-dichlorobenzene (p-dichlorobenzene)	1,2-dichlorobenzene (o-dichlorobenzene)	p-tolualdehyde	4-methlpentan-2-one (MIBK)	Undecane	2-ethylhexan-1-ol	2-butoxyethanol (butyl glycol)	Decamethylcyclopenta-siloxane	1,2-propanediol (propylene glycol)	Hydrocarbon (retn 53.8 min)	Nonanal	Tetradecane
1	Ground	0.6	<1.8	<3.0	2.1	0.8	<0.6	<0.6	<0.6	<1.7	<1.2	2.1	1.1	22.6	(5.6)	—	—	—	—
	Cruise	<0.2	<2.3	<3.8	1.9	<1.1	<0.8	<0.8	<0.8	<2.1	<1.5	1.1	0.8	9.8	(2.9)	—	—	—	—
	Descent	<0.3	<4.7	<7.8	3.4	<2.2	<1.6	<1.6	<1.6	<4.4	<3.1	1.6	0.8	15.5	(6.1)	—	—	—	—
2	Ground	0.5	<1.4	<2.3	5.6	0.9	<0.5	<0.5	<0.5	<1.3	<0.9	3.8	1.6	39.1	(3.3)	—	—	—	—
	Cruise	<0.1	<1.2	<2.0	19.6	<0.5	<0.4	<0.4	<0.4	<1.1	<0.8	1.8	1.2	35.9	(6.0)	—	—	—	—
3	Whole flight	<0.1	<2.0	<3.3	7.7	1	<0.7	<0.7	<0.7	<1.9	<1.3	2.3	0.5	16.4	—	440	—	—	—
	Ground	<0.1	<1.5	<2.5	5.6	1.3	<0.5	<0.5	<0.5	<1.4	<1.0	<2.9	<1.1	27.8	—	1137	—	—	—
	Climb	<0.2	<2.3	<3.9	9.7	1	<0.8	<0.8	<0.8	<2.2	<1.6	1.8	<0.2	19	—	246	—	—	—
	Cruise	<0.2	<2.3	<3.9	13.6	<1.1	<0.8	<0.8	<0.8	<2.2	<1.6	0.9	1.1	8.4	—	43.5	—	—	—
4	Whole flight	<0.2	<2.3	<3.8	20.1	<1.1	<0.8	<0.8	<0.8	<2.1	<1.5	2.4	<0.2	5.2	—	191	—	—	—
	Ground	0.7	<2.2	<3.7	7.1	<1.0	<0.7	<0.7	<0.7	<2.1	<1.5	0.5	<0.1	29.6	—	1019	(8.2)	—	—
	Climb	<0.2	<2.5	<4.2	91	<1.2	<0.8	<0.8	<0.8	<2.3	<1.7	<0.2	0.8	—	—	8.7	—	—	—
	Cruise	<0.2	<2.1	<3.5	8	<1.0	<0.7	<0.7	<0.7	<1.9	<1.4	0.7	<0.1	—	—	29.9	—	—	—
	Descent	<0.2	<2.5	<4.2	0.2	<1.2	<0.8	<0.8	<0.8	<2.3	<1.7	<0.2	<0.2	—	—	—	—	—	—

Table D2a: VOCs from BAe146 aircraft (µg m^{-3}) (cont)

Flight No.	Phase	Tetrachloromethane (carbon tetrachloride)	Benzene	1,2-dichloropropane	Pentanal (n-valeraldehyde)	Bromodichloromethane	cis-1,3 dichloropropene	Toluene	Tetrachloroethene	Trans-1,3-dichloropropene	1,1,2-trichloroethane	2-hexanone	Hexanal	Dibromochloromethane	1,2-dibromoethane	Chlorobenzene	Ethylbenzene	M+p-xylenes
5	Whole flight	<13	0.4	<0.9	<1.6	<16	<2.5	1.1	<1.6	<2.5	<3.0	<6.9	<0.5	<16	<4.7	<1.6	<0.2	<0.1
	Ground	<13	0.7	<1.5	<1.5	<15	<2.4	2.4	16.4	<2.4	<2.8	<6.5	<0.4	<15	<4.4	<1.5	1.2	<0.1
	Climb	<22	0.3	<2.6	<2.6	<27	<4.2	0.7	<2.6	<4.2	<5.0	<11.6	<0.8	<26	<7.9	<2.6	<0.3	<0.3
	Cruise	<14	0.3	<1.6	<1.6	<17	<2.6	0.5	<1.6	<2.6	<3.1	<7.1	<0.5	<16	<4.8	<1.6	<0.2	<0.2
	Descent	<15	<0.2	<1.1	<1.8	<18	<2.9	<0.2	<1.8	<2.9	<3.4	<7.9	<0.5	<18	<5.4	<1.8	<0.2	<0.2
6	Whole flight	<13	0.7	<0.9	<1.6	<16	<2.5	2.3	<1.6	<2.5	<3.0	<6.9	<0.5	<16	<4.7	<1.6	<0.2	0.9
	Ground	<13	1.7	<0.9	<1.5	<15	<2.4	5.9	<2.0	<2.4	<2.8	<6.5	0.4	<15	<4.4	<1.5	<0.1	2.1
	Climb	<28	0.4	<2.0	<3.3	<34	<5.3	1.2	<3.3	<5.3	<6.3	<14.7	<1.0	<33	<10	<3.3	<0.3	<0.3
	Cruise	<13	0.3	<1.0	<1.6	<17	<2.6	0.8	<1.6	<2.6	<3.1	<7.1	<0.5	<16	<4.8	<1.6	<0.2	<0.2
	Descent	<15	0.3	<1.0	<1.6	<17	<2.6	0.6	<1.8	<2.9	<3.4	<7.9	<0.5	<18	<5.4	<1.8	<0.2	<0.2
7	Whole flight	<13	0.6	<1.0	<1.6	<16	<2.5	3.6	3.2	<2.5	<3.0	<7.0	<0.5	<16	<4.8	<1.6	<0.2	0.8
	Ground	<13	0.4	<0.9	<1.5	<16	<2.4	1.5	<1.5	<2.4	<2.9	<6.7	<0.5	<15	<4.5	<1.5	<0.2	<0.2
	Climb	<25	0.5	<1.8	<2.9	<30	<4.7	3	<2.9	<4.7	<5.6	<13	0.8	<29	<8.8	<2.9	<0.3	<0.3
	Cruise	<11	0.3	<0.8	<1.3	<13	<2.1	2.9	6.9	<2.1	<2.4	<5.6	0.3	<13	<3.8	<1.3	<0.1	<0.1
	Descent	<20	0.4	<1.4	<2.4	<25	<3.8	0.8	1.9	<3.8	<4.5	<11	0.6	<24	<7.1	<2.4	<0.2	<0.2

Table D2a: VOCs from BAe146 aircraft (µg m^{-3}) (cont)

Flight No.	Phase	Styrene	Tibromomethane (bromoform)	1,1,2,2-tetrachloroethane	Limonene	Benzaldehyde	1,3-dichlorobenzene (m-dichlorobenzene)	1,4-dichlorobenzene (p-dichlorobenzene)	1,2-dichlorobenzene (o-dichlorobenzene)	p-tolualdehyde	4-methlpentan-2-one (MIBK)	Undecane	2-ethylhexan-1-ol	2-butoxyethanol (butyl glycol)	Decamethylcyclopenta-siloxane	1,2-propanediol (propylene glycol)	Hydrocarbon (retn 53.8 min)
5	Whole flight	<0.1	<2.4	<3.9	3.5	<1.1	<0.8	<0.8	<0.8	<2.2	<1.6	2.8	0.5	18.3	—	172	—
	Ground	<0.1	<2.2	<3.7	5	<1.0	<0.7	<0.7	<0.7	<2.1	<2.1	2.3	<0.1	56.8	—	456	(5.5)
	Climb	<0.3	<3.9	<6.6	2.7	<1.8	<1.3	2.3	<1.3	<3.7	<2.6	1.1	0.7	12.7	—	152	—
	Cruise	<0.2	<2.4	<4.0	4.3	<1.1	<0.8	2.6	<0.8	<2.3	<1.6	0.7	<0.2	4	—	63	—
	Descent	<0.2	<2.7	<4.5	<0.2	<1.3	<0.9	<0.9	<0.9	<2.5	<1.8	<0.2	<0.2	—	—	—	—
6	Whole flight	<0.2	<2.3	<3.9	6.1	0.9	<0.8	3.1	<0.8	<2.2	<1.6	1.3	1	—	—	137	—
	Ground	2	<2.2	<3.7	10	0.8	<0.7	2.8	<0.7	1.2	<1.5	3	0.9	9.6	—	336	—
	Climb	<0.3	<5.0	<8.3	10.1	<2.3	<1.7	3	<1.7	<4.7	<3.3	0.9	0.7	—	—	67	—
	Cruise	<0.2	<2.4	<4.0	13	<1.1	<0.8	3.4	<0.8	<2.3	<1.6	1.1	0.4	—	—	44	—
	Descent	<0.2	<2.7	<4.5	2.3	<1.3	<0.9	3.2	<0.9	<2.5	<1.8	0.6	0.3	—	—	44	—
7	Whole flight	0.3	<2.4	<4.0	2.5	<1.1	<0.8	<0.8	<0.8	0.7	<1.6	3.4	0.6	30	(2.9)	—	—
	Ground	<0.2	<2.3	<3.8	0.9	<1.1	<0.8	<0.8	<0.8	<2.1	<1.5	1.2	0.2	12	(1.3)	—	—
	Climb	<0.3	<4.4	<7.4	7.7	<2.1	<1.5	<1.5	<1.5	<4.1	<2.9	4.1	<0.3	42	(3.5)	—	—
	Cruise	<0.3	<1.9	<3.2	2.5	<0.9	<0.6	<0.6	<0.6	<1.8	<1.3	2.1	<0.1	15	(2.8)	—	—
	Descent	<0.2	<3.6	<6.0	1.8	<1.7	<1.2	<1.2	<1.2	<3.3	<2.4	1.6	<0.2	8	(1.6)	—	—

Table D2b: VOCs from B737 aircraft (µg m^{-3})

Flight No.	Phase	Tetrachloromethane (carbon tetrachloride)	Benzene	1,2-dichloropropane	Pentanal (n-valeraldehyde)	Bromodichloromethane	cis-1,3 dichloropropene	Toluene	Tetrachloroethene	Trans-1,3-dichloropropene	1,1,2-trichloroethane	2-hexanone	Hexanal	Dibromochloromethane	1,2-dibromoethane	Chlorobenzene	Ethylbenzene	M+p-xylenes
9	Whole flight	<14	1.1	<1.0	<1.6	<17	<2.6	13.7	3.9	<2.6	<3.1	<7.1	4.3	<16	<4.8	<1.6	0.7	1.9
	Ground	<12	1.3	<0.8	<1.4	<14	<2.2	3.7	2	<2.2	<2.6	<5.9	0.4	<14	<4.1	<1.4	0.3	0.7
	Climb	<27	0.9	<1.9	<3.1	<32	<5.0	3	2.6	<5.0	<5.9	<13.8	0.7	<31	<9.4	<3.1	<0.3	<0.3
	Cruise	<12	0.2	<0.9	<1.5	<15	<2.4	2.3	2.3	<2.4	<2.8	<6.5	1	<15	<4.4	<1.5	<0.1	0.2
	Descent	<17	<0.2	<1.2	<2.0	<21	<3.2	0.7	<2.0	<3.2	<3.8	<8.8	<0.6	<20	<6.0	<2.0	<0.2	<0.2
10	Whole flight	<44	<0.5	<3.1	<5.1	<53	<8.2	1.4	15.4	<8.2	<9.7	<23	<1.5	<51	<15	<5.2	<0.5	<0.5
	Ground	<17	2.2	<1.2	<2.0	<21	<3.2	13.7	42.6	<3.2	<3.8	<8.8	3.2	<20	<6.0	<2.0	2.8	7
	Climb	<33	1.3	<2.3	5.9	<40	<6.2	3	21	<6.2	<7.3	<17	5.6	<39	<12	<3.8	0.9	1.1
	Cruise	<12	0.2	<0.8	<1.4	<14	<2.2	2.5	20.6	<2.2	<2.6	<5.9	1.7	<14	<4.1	<1.4	<0.1	0.7
	Descent	<16	0.3	<1.2	<1.9	<20	<3.1	1.7	16.3	<3.1	<3.7	<8.5	0.9	<19	<5.8	<1.9	<0.2	0.3
11	Whole flight	<9.6	0.3	<0.7	<1.1	<12	<1.8	58	3.5	<1.8	<2.1	<5.0	2.4	<11	<3.4	<1.1	0.2	0.6
	Ground [a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Climb [a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Cruise [c]	<4.8	0.1	<0.3	<0.6	<6	<0.9	57	3.2	<0.9	<1.1	<2.5	2.2	<6	<1.7	<0.6	0.2	0.5
	Descent [b]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table D2b: VOCs from B737 aircraft (µg m^{-3}) (cont)

Flight No.	Phase	Styrene	Tibromomethane (bromoform)	1,1,2,2-tetrachloroethane	Limonene	Benzaldehyde	1,3-dichlorobenzene (m-dichlorobenzene)	1,4-dichlorobenzene (p-dichlorobenzene)	1,2-dichlorobenzene (o-dichlorobenzene)	p-tolualdehyde	4-methlpentan-2-one (MIBK)	Undecane	2-ethylhexan-1-ol	2-butoxyethanol (butyl glycol)	Decamethylcyclopenta siloxane	1,2-propanediol (propylene glycol)	Hydrocarbon (retn 53.8 min)	Nonanal	Tetradecane	Siloxane retn 36.1
9	Whole flight	0.6	<2.4	<4.0	8.5	0.8	<0.8	<0.8	<0.8	<2.3	<1.6	2.7	3.4	—	(13)	83.1	—	—	—	—
	Ground	0.5	<2.0	<3.4	6	0.6	<0.7	<0.7	<0.7	<1.9	<1.4	1.8	0.8	—	(14.2)	168	—	—	—	—
	Climb	<0.3	<4.7	<7.8	3.4	<0.3	<1.6	<1.6	<1.6	<4.4	<3.1	1.8	0.8	—	(7.3)	11.7	—	—	—	—
	Cruise	<0.1	<2.2	<3.7	4.9	<0.1	<0.7	<0.7	<0.7	<2.1	<1.5	0.9	0.6	—	(8.5)	—	—	7.2	—	—
	Descent	<0.2	<3.0	<5.0	1.3	<0.2	<1.0	<1.0	<1.0	<2.8	<2.0	0.3	0.6	—	(4.1)	—	—	2.5	—	—
10	Whole flight	<0.5	<7.7	<13	6.8	<0.5	<2.6	<2.6	<2.6	<7.2	<5.1	2	0.9	—	—	—	—	8.7	—	—
	Ground	<0.2	<3.0	<5.0	12.7	<0.2	<1.0	<1.0	<1.0	<2.8	<2.0	6.9	2	—	(9.2)	267	—	—	—	—
	Climb	<0.4	<5.8	<9.6	5.5	<0.4	<1.9	<1.9	<1.9	<5.4	<3.8	18.8	1.6	—	—	82	—	—	14.1	—
	Cruise	<0.1	<2.0	<3.4	11.9	0.1	<0.7	<0.7	<0.7	<1.9	<1.4	2.5	1.2	—	(4.1)	69	—	7.7	—	—
	Descent	<0.2	<2.9	<4.8	9.3	<0.2	<1.0	<1.0	<1.0	<2.7	<1.9	1.8	0.8	—	(3.2)	40.4	—	5.4	—	—
11	Whole flight [#]	<0.1	<1.7	<2.8	18.2	<0.1	<0.6	<0.6	<0.6	<1.6	<1.1	1.4	0.7	—	(4.3)	30.2	—	—	—	—
	Ground [a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Climb [a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Cruise [c]	0.3	<0.9	<1.4	13.5	0.3	<0.3	<0.3	<0.3	<0.8	<0.6	1.5	0.6	—	(4.7)	23.5	—	—	—	—
	Descent [b]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table D2b: VOCs from B737 aircraft (µg m^{-3}) (cont)

Flight No.	Phase	Tetrachloromethane (carbon tetrachloride)	Benzene	1,2-dichloropropane	Pentanal (n-aleraldehyde)	Bromodichloromethane	cis-1,3 dichloropropene	Toluene	Tetrachloroethene	Trans-1,3-dichloropropene	1,1,2-trichloroethane	2-hexanone	Hexanal	Dibromochloromethane	1,2-dibromoethane	Chlorobenzene	Ethylbenzene	M+p-xylenes
12	Whole flight	<8.1	0.4	<0.6	<1.0	<10	<1.5	12.8	2.9	<1.5	<1.8	<4.2	2	<9.6	<2.9	<1.0	0.3	1.1
	Ground	<19	1.3	<1.3	<2.2	<22	<3.5	18.5	4.1	<3.5	<4.1	<9.6	2.1	<22	<6.5	<2.2	1.1	3.9
	Climb	<21	0.8	<1.5	<2.5	<26	<4.0	13.6	5.5	<4.0	<4.8	<11	1	<25	<7.5	<2.5	0.5	1.5
	Cruise [c]	<4.6	0.1	<0.3	<0.5	<5.5	<0.9	7.9	2.5	<0.9	<1.0	<2.4	1.4	<5.4	<1.6	<0.5	0.2	0.5
	Descent	<18	0.5	<1.3	<2.1	<22	<3.3	3.5	2.5	<3.3	<4.0	<9.2	0.9	<20.8	<6.3	<2.1	<0.2	0.5
13	Whole flight	<8.7	0.6	<0.6	<1.0	<11	<1.6	15	2	<1.6	<1.9	<4.5	2.6	<10	<3.1	<1.0	0.5	1.2
	Ground	<30	1.8	<2.1	<3.6	<37	<5.7	64	5.5	<5.7	<6.8	<16	10	<36	<11	<3.6	1.6	4
	Climb	<12	2.2	<0.8	<1.4	<14	<2.2	23	2.6	<2.2	<2.6	<5.9	1.4	<14	<4.1	<1.4	0.7	2.2
	Cruise [c]	<4.1	<0.1	<0.3	<0.5	<5.0	<0.8	7.7	1.5	<0.8	<0.9	<2.1	0.3	<4.8	<1.4	<0.5	0.2	0.4
	Descent [b]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
14	Whole flight [b]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Ground	<24	0.9	<1.7	<2.8	<29	<4.4	5.8	14.1	<4.4	<5.3	<12.2	3.4	<28	<8.3	<2.8	0.5	0.9
	Climb	<28	<0.3	<2.0	<3.3	<34	<5.3	23	94.6	<5.3	<6.3	<14.7	<1.0	<33	<10	<3.3	<0.3	<0.3
	Cruise [c]	<4.7	0.1	<0.3	<0.5	<5.7	<0.9	12.1	43.5	<0.5	<1.0	<2.4	2.3	<5.5	<1.6	<0.5	0.1	0.2
	Descent	<11	0.3	<0.8	<1.3	<13.2	<2.1	1.5	15.4	<1.3	<2.4	<5.6	0.4	<12.8	<3.8	<1.3	0.2	0.2

Table D2b: VOCs from B737 aircraft (µg m^{-3}) (cont)

Flight No.	Phase	Styrene	Tibromomethane (bromoform)	1,1,2,2-tetrachloroethane	Limonene	Benzaldehyde	1,3-dichlorobenzene (m-dichlorobenzene)	1,4-dichlorobenzene (p-dichlorobenzene)	1,2-dichlorobenzene (o-dichlorobenzene)	p-tolualdehyde	4-methlpentan-2-one (MIBK)	Undecane	2-ethylhexan-1-ol	2-butoxyethanol (butyl glycol)	Decamethylcyclopentasiloxane	1,2-propanediol (propylene glycol)	Hydrocarbon (retn 53.8 min)	Nonanal	Tetradecane	Siloxane retn 36.1
12	Whole flight	<0.1	<1.4	<2.4	11.4	0.4	<0.5	2.3	<0.5	<1.3	<1.0	2.4	1.4	—	(7.1)	465	—	—	—	—
	Ground	3.2	<3.3	<5.4	12.6	1	<1.1	3	<1.1	<3.0	<2.2	4.2	2.7	—	(9.3)	410	—	—	—	—
	Climb	<0.3	<3.8	<6.3	8.6	0.4	<1.3	3.5	<1.3	<3.5	<2.5	3.3	1.7	—	(7.2)	452	—	—	—	—
	Cruise [c]	1	<0.8	<1.3	11.3	<0.1	<0.3	1.9	<0.3	<0.8	<0.5	1.6	1	—	(6.1)	160	—	—	—	—
	Descent	<0.2	<3.1	<5.2	8.8	<0.2	<1.0	1.9	<1.0	<2.1	<2.1	1.8	0.9	—	(7.3)	94	—	—	—	—
13	Whole flight	0.6	<1.5	<2.6	12.1	1.1	<0.5	<0.5	<0.5	<1.4	<1.0	2.5	1.2	—	(7.2)	41	—	—	—	(5.3)
	Ground	<0.4	<5.4	<8.9	32.2	0.4	<1.8	<1.8	<1.8	<5.0	<3.6	4.9	2.8	—	(18.2)	—	—	—	—	(13.9)
	Climb	0.6	<2.0	<3.4	13.8	0.6	<0.7	<0.7	<0.7	<1.9	<1.4	2.8	1.1	—	(7.8)	69	—	—	—	(6.3)
	Cruise [c]	0.1	<0.7	<1.2	10.1	0.2	<0.2	<0.2	<0.2	<0.7	<0.5	1.4	0.8	—	(8)	13	—	—	—	(4.3)
	Descent [b]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
14	Whole flight [b]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Ground	0.5	<4.2	<6.9	10.6	<0.3	<1.4	<1.4	<1.4	<3.9	<2.8	2.8	2.6	—	(3.9)	152	—	12.9	—	—
	Climb	<0.3	<5.0	<8.3	9.4	<0.3	<1.7	<1.7	<1.7	<4.7	<3.3	1.5	1.6	—	(2.4)	137	—	8.5	—	—
	Cruise [c]	<0.1	<0.8	<1.4	6.7	0.2	<0.3	<0.3	<0.3	<0.8	<0.5	0.9	0.7	—	(3.1)	104	—	10.6	—	—
	Descent	0.3	<1.9	<3.2	6.4	<0.1	<0.6	<0.6	<0.6	<1.8	<1.3	0.6	0.7	—	5.3	34	—	7.3	—	—

VOC notes

( ) Quantified as toluene as no calibration factor available

—Not a major peak in this sample

Pump for "continuous" samplers only turned on during cruise, so sampling only undertaken for last 39 minutes of flight

[a] No sampling undertaken due to shortage of time

[b] sampling or analysis difficulty and results not available

[c] Volume of air sampled significantly greater than 6 litres so results for the more volatile components trapped on each sampler may be subject to underestimate. This applies to the following compounds: tetrachloromethane, benzene, 1,2-dicholorpropane and pentanal.

Table D3a: VVOCs from BAe146 aircraft (µg m^{-3})

Flight No.	Phase	Hexane	1,1,1-trichloroethane	Trichloromethane	1,2-dichloroethane	Trichloroethene	Trans-1,2-dichloroethene	Propan-2-ol (isopropanol-IPA)[a]	Vinyl acetate	Cis-1,2-dichloroethene	Butan-2-one (methyl ethyl ketone-MEK)	Ethanol[b]	Acetonitrile[b]
1	Ground	2.4	<2.8	<15.5	<2.6	4.3	<2.6	560.2	<1.9	<2.6	7.3	>289.9	#
	Cruise	<1.7	<3.3	<18.8	<3.2	<3.2	<3.2	89.7	<2.3	<3.2	<2.0	>91.5	>51.3
	Descent	<3.4	<6.9	<38.7	<6.6	<7.5	<6.6	432.5	<4.7	<6.6	<4.1	>3822.3	>199.6
2	Ground [c]	5.1	<2.0	<11.3	<1.9	<2.2	<1.9	909.2	<1.4	<1.9	3.3	>852.0	#
	Cruise [c]	4.3	<1.6	<9.2	<1.6	<1.8	<1.6	122.9	<1.1	<1.6	2.5	>752.7	>31.5
	Descent [d]												
3	Whole flight	<1.5	<2.9	<17	<2.8	<3.2	<2.8	>2620	<2.0	<2.8	3.8	>40	#
	Ground	1.1	<2.2	<12	<2.1	<2.4	<2.1	224.5	<1.5	<2.1	3.8	>22.7	#
	Climb	<1.7	<3.4	<19	<3.3	<3.8	<3.3	>3070	<2.3	<3.3	2.1	>162	#
	Cruise	<1.7	<3.4	<19	<3.3	<3.8	<3.3	2960	<2.3	<3.3	<2.1	>12.3	#
4	Whole flight	<1.7	<3.3	<19	<3.2	<3.6	<3.2	336	<2.3	<3.2	<2.0	>295	#
	Ground	<1.6	<3.2	<18	<3.1	<3.5	<3.1	706	<2.2	<3.1	3.4	>37.6	#
	Climb	<1.8	<3.7	<21	<3.5	<4.0	<3.5	117	<2.5	<3.5	2.0	>419	>23.3
	Cruise	<1.5	<3.1	<17	<2.9	<3.3	<2.9	30.7	<2.1	<2.9	<1.8	>24.8	>8.8
	Descent	<1.8	<3.7	<21	<3.5	<4.0	<3.5	27.7	<2.5	<3.5	<2.2	>41.4	#

Table D3a: VVOCs from BAe146 aircraft (µg m^{-3}) (cont)

Flight No.	Phase	Hexane	1,1,1-trichloroethane	Trichloromethane	1,2-dichloroethane	Trichloroethene	Trans-1,2-dichloroethene	Propan-2-ol (isopropanol-IPA)[a]	Vinyl acetate	Cis-1,2-dichloroethene	Butan-2-one (methyl ethyl ketone-MEK)	Ethanol[b]	Acetonitrile[b]
5	Whole flight	<1.7	<3.5	<20	<3.3	<3.8	<3.3	353	<2.4	<3.3	2.1	>14.4	>54.8
	Ground	<1.6	<3.2	<18	<3.1	<3.5	<3.1	316	<2.2	<3.1	3.7	>54.1	>74.7
	Climb	<2.9	<5.8	<33	<5.5	<6.3	<5.5	412	<3.9	<5.5	<3.4	>37.1	#
	Cruise	<1.8	<3.5	<20	<3.4	<3.9	<3.4	372	<2.4	<3.4	2.1	>14.5	>93.8
	Descent	<2.0	<3.9	<22	<3.8	<4.3	<3.8	52.3	<2.7	<3.8	<2.3	>12.7	>280
6	Whole flight	<1.7	<3.4	<19	<3.3	<3.8	<3.3	340	<2.3	<3.3	3.1	>120	>61.7
	Ground	<1.6	<3.2	<18	<3.1	<3.5	<3.1	328	<2.2	<3.1	1.9	>134	>127
	Climb	<3.7	<7.3	<41	<7.0	<8.0	<7.0	183	<5.0	<7.0	<4.3	>76.2	>65.2
	Cruise	<1.8	<3.5	<20	<3.4	<3.9	<3.4	413	<2.4	<3.4	2.5	>486	>108
	Descent	<2.0	<3.9	<22	<3.8	<4.3	<3.8	405	<2.7	<3.8	<2.3	>93.4	>259
7	Whole flight	<1.7	<3.5	<20	<3.3	<3.8	<3.3	327	<2.4	<3.1	<2.1	>171	>101
	Ground	<1.7	<3.3	<19	<3.2	<3.6	<3.2	59.6	<2.3	<3.2	<2.0	>160	>36.4
	Climb	<3.2	<6.5	<37	<6.2	<7.1	<6.2	375	<4.4	<6.2	<3.8	>47.7	>71.9
	Cruise	<1.4	<2.8	<16	<2.7	<3.1	<2.7	129	<1.9	<2.7	<1.7	>178	>17.8
	Descent	<2.6	<5.2	<30	<5.0	<5.7	<5.0	382	<3.6	<5.0	<3.1	>229	>70.2

Table D3b: VVOCs from B737 aircraft (µg m^{-3})

Flight No.	Phase	Hexane	1,1,1-trichloroethane	Trichloromethane	1,2-dichloroethane	Trichloroethene	Trans-1,2-dichloroethene	Propan-2-ol (isopropanol-IPA)[a]	Vinyl acetate	Cis-1,2-dichloroethene	Butan-2-one (methyl ethyl ketone-MEK)	Ethanol[b]	Acetonitrile[b]
9	Whole flight	<1.8	<3.5	<20	<3.4	<3.9	<3.4	159.4	<2.4	<3.4	2.4	>14.4	>54.0
	Ground	<1.5	<3.0	<17	<2.8	<3.2	<2.8	61.3	<2.0	<2.8	<1.8	>8.0	>12.5
	Climb	<3.4	<6.9	<39	<6.6	<7.5	<6.6	98.4	<4.7	<6.6	<4.1	>20.1	>46.8
	Cruise	<1.6	<3.2	<18	<3.1	<3.5	<3.1	134.3	<2.2	<3.1	<1.9	>15.5	>41.4
	Descent	<2.2	<4.4	<25	<4.2	<4.8	<4.2	50.2	<3.0	<4.2	<2.6	>11.5	>478
10	Whole flight	<5.6	<11	<64	<11	<12	<11	29.6	<7.7	<11	6.7	>822	>152
	Ground	<2.2	<4.4	<25	<4.2	<4.8	<4.2	300.2	<3.0	<4.2	3.0	>319	>47.4
	Climb	<4.2	<8.5	<48	<8.1	<9.2	<8.1	57	<5.8	<8.1	<5.0	>439	>55.0
	Cruise	<1.5	<3.0	<17	<2.8	<3.2	<2.8	18.9	<2.0	<2.8	2.7	>350	>13.1
	Descent	<2.1	<4.2	<24	<4.0	<4.6	<4.0	15.4	<2.9	<4.0	3.5	>198	>33.0
11	Whole flight	<1.2	<2.5	<14	<2.4	<2.7	<2.4	38.1	<1.7	<2.4	3.5	>290	>12.5
	Ground [d]												
	Climb [d]												
	Cruise [c]	<0.6	<1.3	<7.0	<1.2	<1.4	<1.2	232.2	<0.9	<1.2	1.7	>137	#
	Descent [e]												

Table D3b: VVOCs from B737 aircraft (µg m^{-3}) (cont)

Flight No.	Phase	Hexane	1,1,1-trichloroethane	Trichloromethane	1,2-dichloroethane	Trichloroethene	Trans-1,2-dichloroethene	Propan-2-ol (isopropanol-IPA)[a]	Vinyl acetate	Cis-1,2-dichloroethene	Butan-2-one (methyl ethyl ketone-MEK)	Ethanol[b]	Acetonitrile[b]
12	Whole flight	<1.1	<2.1	<12	<2.0	<2.3	<2.0	124.9	<1.4	<2.0	3.8	>72.5	>34.4
	Ground	<2.4	<4.8	<27	<4.6	<5.2	<4.6	88.3	<3.3	<4.6	6.4	>435	>88.2
	Climb	<2.8	<5.5	<31	<5.3	<6.0	<5.3	290.3	<3.8	<5.3	4.1	>201	>55.9
	Cruise [c]	<0.6	<1.2	<6.7	<1.1	<1.3	<1.1	63	<0.8	<1.1	3.0	>69.6	>16.2
	Descent	<2.3	<4.6	<26	<4.4	<5.0	<4.4	67.7	<3.1	<4.4	5.2	>87.3	>261
13	Whole flight	<1.1	<2.2	<13	<2.1	<2.4	<2.1	160.9	<1.5	<2.1	4.6	>28.4	>83.1
	Ground	<3.9	<7.9	<44	<7.5	<8.6	<7.5	169.6	<5.4	<7.5	25	>127	>1115
	Climb	<1.5	<3.0	<17	<2.8	<3.2	<2.8	86.6	<2.0	<2.8	3.8	>55.5	>14.3
	Cruise [c]	<0.5	<1.1	<6.0	<1.0	<1.2	<1.0	81.7	<0.7	<1.0	1.9	>13.0	#
	Descent	<2.9	<5.8	<33	<5.5	<6.3	<5.5	189.2	<3.9	<5.5	4	>43.0	>60.4
14	Whole flight [e]												
	Ground	<3.1	<6.1	<34	<5.8	<6.7	<5.8	77	<4.2	<5.8	5.0	>494	>74.1
	Climb	<3.7	<7.3	<41	<7.0	<8.0	<7.0	9.5	<5.0	<7.0	5.1	>620	>108
	Cruise [c]	<0.6	<1.2	<6.8	<1.2	<1.3	<1.2	6	<0.8	<1.2	2.6	>161	>7.8
	Descent	<1.4	<2.8	<16	<2.7	<3.1	<2.7	9.9	<1.9	<2.7	<1.7	>158	>9.4

Notes to VVOC Tables D3a and D3b

[a] Propan-2-ol used in operation of P-Trak particle counter while sampling undertaken. Possibility exists that some of the propan-2-ol measure
ɔm this process.

[b] All ethanol and acetonitrile values are likely to be underestimates as the method is not optimised for these compounds, but reported as observed as significant peaks in the chromatogram.

[c] Volume of air sampled significantly greater than 6 litres so results for the more volatile components trapped on each sampler may be subject to underestimate. This applies to the following compounds: trans-1,2-dichloroethene, vinyl acetate and cis-1,2-dichloroethene.

[d] No sample taken due to shortage of time

[e] Sampling or analysis difficulty and no results available

possibly a small amount of acetonitrile obscured by large propan-2-ol peak

Table D4a: Carbonyl Compounds from BAe 146 Aircraft (µg m^{-3})

Flight No.	Phase	Formaldehyde	Acetaldehyde	Acrolein	Propionaldehyde	Acetone	Crotonaldehyde	Butyraldehyde	Methacrolein
1	Ground	14.5	9.5	4	<1	95	<1	<3	<1
	Climb	1.5	3	<1	<2	53.5	<2	<4	<2
	Cruise	2	3	<1	<3	88	<3	<5	<3
	Descent	2	4	<1	<3	87	14	<5	<3
2	Ground	7	6.5	<0.5	<1	188	<1	<2	<1
	Climb-Cruise	2.5	7.5	<0.7	<2	197.5	<2	<3.5	<2
	Descent	3.5	11.5	<0.6	<1.5	243	<1.5	<3	<1.5
3	Whole flight	8	11	<0.2	13	24	<0.4	<0.8	<0.4
	Ground	15	24	<0.5	32	23	<1	<3	<1
	Climb	5	4	<0.6	<1	16	<1	<3	<1
	Cruise	3	2	<1	<2	18	<2	<4	<2
4	Whole flight	6	7	<0.2	<0.5	22	<0.4	<1	<0.5
	Ground	10	11	<0.6	<1	20	<1	<3	<1
	Climb	1	3	<0.7	<2	16	<2	<4	<2
	Cruise	2	2	<0.7	<2	16	<2	<4	<2
5	Whole flight	3	3	<0.2	<0.5	13	<0.5	<1	<0.5
	Ground	8	5	<0.6	<1	20	<1	<3	<1
	Climb	<1	<1	<1	<3	<3	<3	<6	<3
	Cruise	3	2	<0.6	<2	9	<2	<4	<2
	Descent	2	2	<0.8	<2	7	<2	<4	<2
6	Whole flight	4	5	<0.2	<0.5	13	<0.5	<1	<0.5
	Ground	6	5	<0.5	<1	19	<1	<2	<1
	Climb	6	7	<1	<3	6	<3	<7	<3
	Cruise	3	6	<1	<2	9	<2	<3	<2
	Descent	2	3	<1	<2	7	<2	<4	<2
7	Whole flight	4	6	<0.2	<0.5	16	<0.5	<1	<0.5
	Ground	5	7	<0.8	<2	18	<2	<4	<2
	Climb	3	3	<1	<3	13	<3	<5	<3
	Cruise	<0.6	6	<0.6	<1	12	<1	<3	<1
	Descent	2	5	<1	<3	17	<3	<6	<3

Table D4b: Carbonyl Compounds from B737 aircraft (µg m^{-3})

Flight No.	Phase	Formaldehyde	Acetaldehyde	Acrolein	Propionaldehyde	Acetone	Crotonaldehyde	Butyraldehyde	Methacrolein
9	Whole flight	4	5	<0.2	1	36	<0.5	<1	<0.5
	Ground	7	7	<0.6	1	30	<2	<3	<2
	Climb	2	9	<1	<4	33	<4	<7	<4
	Cruise	2	6	<0.7	<2	42	<2	<4	<2
	Descent	1	5	<1	<2	38	<2	<5	<2
10	Whole flight	5	9	<0.2	1	38	<0.5	<1	<0.5
	Ground	6	10	<1	3	55	<3	<5	<3
	Climb	2	11	<2	3	31	<4	<8	<4
	Cruise	14	8	<0.6	<1	33	<1	<3	<1
	Descent	1	6	<1	<2	31	<2	<5	<2
11	Whole flight	5	9	<0.1	1	37	<0.3	<0.7	<0.3
	Ground	14	31	<4	4	160	<4	<7	<4
	Cruise	<0.5	<0.5	<0.5	<1	<1	<1	<2	<1
	Descent	3	8	<0.6	<1	36	<1	<3	<1
12	Whole flight	6	8	<0.1	1	33	<0.3	<0.6	<0.3
	Ground	10	8	<0.7	2	33	<2	<3	<2
	Climb	7	<1	<1	<4	25	<4	<7	<4
	Cruise	11	16	<0.6	2	81	<1	<3	<1
	Descent	4	4	<1	4	25	<2	<4	<2
13	Whole flight	7	5	<0.1	<0.3	29	<0.3	<0.6	<0.3
	Ground	10	1	<2	<4	51	<4	<8	<4
	Climb	13	6	<0.6	7	28	<1	<3	<1
	Cruise	3	3	<0.2	<0.6	24	<0.6	<1	<0.6
	Descent	7	<2	<2	<6	50	<6	<10	<6
14	Whole flight	4	9	<0.1	1	54	<0.3	<0.6	<0.3
	Ground	7	6	<2	<4	43	<4	<8	<4
	Climb	4	5	<1	<3	38	<3	<6	<3
	Cruise	3	10	<0.3	<0.6	54	<0.6	<1	<0.6
	Descent	3	4	<0.5	<1	47	<1	<3	<1

Table D5a: SVOCs from BAe146 aircraft (µg m^{-3})

Flight No	Phase	Exxon 2380 determined using Tri tolyl phosphate isomer eluting at 30.4 min	Exxon 2380 determined using compound eluting at 32.8 min	Exxon 2380 determined using compound eluting at 34.7 min	Skydrol determined using Tri butyl phosphate	Skydrol determined using Dibutylphenyl phosphate
1	Ground	ND (<68)	ND (<68)	ND (<68)	ND (<3)	
	Cruise	ND (<68)	ND (<68)	ND (<68)	ND (<3)	
	Descent	ND (<130)	ND (<130)	ND (<130)	ND (<4)	
2	Ground	ND (<40)	ND (<40)	ND (<40)	ND(<2)	
	Cruise	ND(<70)	ND(<70)	ND(<70)	ND(<3)	
	Descent	ND(<70)	ND(<70)	ND(<70)	ND(<3)	
3	Continuous	ND (<16)	ND (<16)	ND (<16)	ND (<10)	ND (<10)
	Ground	ND (<60)	ND (<60)	ND (<60)	ND (<20)	ND (<20)
	Climb	ND (<70)	ND (<70)	ND (<70)	ND (<20)	ND (<50)
	Descent	ND (<100)	ND (<100)	ND (<100)	ND (<20)	ND (<50)
4	Continuous	ND (<20)	ND (<20)	ND (<20)	*ND (<20)	ND (<10)
	Ground	ND (<80)	ND (<80)	ND (<80)	ND (<10)	ND (<10)
	Climb	ND (<80)	ND (<80)	ND (<80)	ND (<20)	ND (<10)
	Cruise	ND (<80)	ND (<80)	ND (<80)	ND (<10)	ND (<10)
	Descent	ND (<80)	ND (<80)	ND (<80)	ND (<20)	ND (<10)

Table D5a: SVOCs from BAe146 aircraft (μg m^{-3})

Flight No	Phase	Exxon 2380 determined using Tri tolyl phosphate isomer eluting at 30.4 min	Exxon 2380 determined using compound eluting at 32.8 min	Exxon 2380 determined using compound eluting at 34.7 min	Skydrol determined using Tri butyl phosphate	Skydrol determined using Dibutylphenyl phosphate
1	Ground	ND (<68)	ND (<68)	ND (<68)	ND (<3)	
	Cruise	ND (<68)	ND (<68)	ND (<68)	ND (<3)	
	Descent	ND (<130)	ND (<130)	ND (<130)	ND (<4)	
2	Ground	ND (<40)	ND (<40)	ND (<40)	ND(<2)	
	Cruise	ND(<70)	ND(<70)	ND(<70)	ND(<3)	
	Descent	ND(<70)	ND(<70)	ND(<70)	ND(<3)	
3	Continuous	ND (<16)	ND (<16)	ND (<16)	ND (<10)	ND (<10)
	Ground	ND (<60)	ND (<60)	ND (<60)	ND (<20)	ND (<20)
	Climb	ND (<70)	ND (<70)	ND (<70)	ND (<20)	ND (<50)
	Descent	ND (<100)	ND (<100)	ND (<100)	ND (<20)	ND (<50)
4	Continuous	ND (<20)	ND (<20)	ND (<20)	*ND (<20)	ND (<10)
	Ground	ND (<80)	ND (<80)	ND (<80)	ND (<10)	ND (<10)
	Climb	ND (<80)	ND (<80)	ND (<80)	ND (<20)	ND (<10)
	Cruise	ND (<80)	ND (<80)	ND (<80)	ND (<10)	ND (<10)
	Descent	ND (<80)	ND (<80)	ND (<80)	ND (<20)	ND (<10)

Notes to SVOC Tables D5a

ND – not detected

*ND – not quantifiable amount as insufficient analyte to give positive “fingerprint” identification of analyte, but single ion response indicates trace amount present.

Calibration is for reference samples supplied of Skydrol 00000919 QB-21202 and Exxon 2380. These are fluids and both are mixtures of several components. Quantification of the amound in air assumes that the composition of the mixture trapped by the PUF is the same as the reference fluids.

Detection limits for Exxon 2380 are better than 20μg on the PUF tube.

Detection limits for Skydrol as tributylphosphate and dibutylphenylphosphate are better than 0.5μg on the PUF tube. However some of the blanks have produced interferences, equivalent of up to 7μg Skydrol as tributylphosphate and 5μg Skydrol as dibutylphenylphosphate on the PUF tube. This has limited the level at which the presence of Skydrol can be confirmed.

Detection limits for other SVOCs are expected to fall within these ranges.

Table D5a: SVOCs from BAe146 aircraft (μg m^{-3})

Flight No	Phase	Exxon 2380 determined using Tri tolyl phosphate isomer eluting at 30.4 min	Exxon 2380 determined using compound eluting at 32.8 min	Exxon 2380 determined using compound eluting at 34.7 min	Skydrol determined using Tri butyl phosphate	Skydrol determined using Dibutylphenyl phosphate
1	Ground	ND (<68)	ND (<68)	ND (<68)	ND (<3)	
	Cruise	ND (<68)	ND (<68)	ND (<68)	ND (<3)	
	Descent	ND (<130)	ND (<130)	ND (<130)	ND (<4)	
2	Ground	ND (<40)	ND (<40)	ND (<40)	ND(<2)	
	Cruise	ND(<70)	ND(<70)	ND(<70)	ND(<3)	
	Descent	ND(<70)	ND(<70)	ND(<70)	ND(<3)	
3	Continuous	ND (<16)	ND (<16)	ND (<16)	ND (<10)	ND (<10)
	Ground	ND (<60)	ND (<60)	ND (<60)	ND (<20)	ND (<20)
	Climb	ND (<70)	ND (<70)	ND (<70)	ND (<20)	ND (<50)
	Descent	ND (<100)	ND (<100)	ND (<100)	ND (<20)	ND (<50)
4	Continuous	ND (<20)	ND (<20)	ND (<20)	*ND (<20)	ND (<10)
	Ground	ND (<80)	ND (<80)	ND (<80)	ND (<10)	ND (<10)
	Climb	ND (<80)	ND (<80)	ND (<80)	ND (<20)	ND (<10)
	Cruise	ND (<80)	ND (<80)	ND (<80)	ND (<10)	ND (<10)
	Descent	ND (<80)	ND (<80)	ND (<80)	ND (<20)	ND (<10)

Table D5a: SVOCs from BAe146 aircraft (µg m^{-3}) (cont)

Flight No	Phase	Exxon 2380 determined using Tri tolyl phosphate isomer eluting at 30.4 min	Exxon 2380 determined using compound eluting at 32.8 min	Exxon 2380 determined using compound eluting at 34.7 min	Skydrol determined using Tri butyl phosphate	Skydrol determined using Dibutylphenyl phosphate
5	Continuous	ND (<20)	ND (<20)	ND (<20)	* ND(<20)	ND (<10)
	Climb	ND<130)	ND<130)	ND<130)	ND(<10)	ND (<10)
	Cruise	ND (<70)	ND (<70)	ND (<70)	ND (<10)	ND (<10)
	Descent	ND (<90)	ND (<90)	ND (<90)	ND (<20)	ND (<10)
6	Continuous	ND (<20)	ND (<20)	ND (<20)	*ND (<20)	ND (<10)
	Ground	ND (<60)	ND (<60)	ND (<60)	ND (<20)	ND (<10)
	Climb	ND (<150)	ND (<150)	ND (<150)	ND (<20)	ND (<50)
	Cruise	ND (<80)	ND (<80)	ND (<80)	ND (<20)	ND (<50)
7	Continuous	ND (<20)	ND (<20)	ND (<20)	ND (<10)	ND (<10)
	Ground	ND(<1300)	ND(<1300)	ND(<1300)	ND (<10)	ND (<10)
	Climb	ND (<90)	ND (<90)	ND (<90)	ND (<10)	ND (<10)
	Cruise	ND (<60)	ND (<60)	ND (<60)	ND (<10)	ND (<10)
	Descent	ND (<120)	ND (<120)	ND (<120)	ND (<20)	ND (<50)

Notes to SVOC Tables D5a

ND – not detected

*ND – not quantifiable amount as insufficient analyte to give positive “fingerprint” identification of analyte, but single ion response indicates trace amount present.

Calibration is for reference samples supplied of Skydrol 00000919 QB-21202 and Exxon 2380. These are fluids and both are mixtures of several components. Quantification of the amound in air assumes that the composition of the mixture trapped by the PUF is the same as the reference fluids.

Detection limits for Exxon 2380 are better than 20µg on the PUF tube.

Detection limits for Skydrol as tributylphosphate and dibutylphenylphosphate are better than 0.5µg on the PUF tube. However some of the blanks have produced interferences, equivalent of up to 7µg Skydrol as tributylphosphate and 5µg Skydrol as dibutylphenylphosphate on the PUF tube. This has limited the level at which the presence of Skydrol can be confirmed.

Detection limits for other SVOCs are expected to fall within these ranges.

Table D5b SVOCs from Boeing 737 aircraft (µg m^{-3})

Flight No	Phase	Aeroshell 560 determined using Tri tolyl phosphate isomer eluting at 29.7 min	Aeroshell 560determined using compound eluting at 32.7min	Aeroshell 560determined using compound eluting at 33.5min	Skydrol 500 B-4 determined using Tri butyl phosphate	Skydrol 500 B-4 determined using Dibutylphenyl phosphate
9	Continuous	ND (<30)	ND* (<5)	ND* (<5)	ND (<2)	ND (<2)
	Ground	ND (<110)	ND (<20)	ND<20	ND (<10)	ND (<10)
	Cruise	ND (<120)	ND (<20)	ND (<20)	ND (<8)	ND (<8)
10	Continuous	ND (<30)	ND (<5)	ND (<5)	ND (<2)	ND (<2)
	Climb	ND (<300)	ND (<50)	ND (<50)	ND (<20)	ND (<20)
	Cruise	ND (<100)	ND (<20)	ND (<20)	ND (<7)	ND (<7)
11	Continuous	ND (<20)	ND (<3)	ND (<3)	ND (<1)	ND (<1)
	Cruise	ND (<70)	ND (<10)	ND (<10)	ND (<4)	ND (<4)
12	Continuous	ND (<20)	ND (<3)	ND (<3)	ND (<1)	ND (<1)
	Cruise	ND (<200)	ND (<30)	ND (<30)	ND (<10)	ND (<10)
13	Continuous	ND (<20)	ND (<3)	ND (<3)	ND (<1)	ND (<1)
	Cruise	ND (<40)	ND (<6)	ND (<6)	ND (<2)	ND (<2)
14	Continuous	ND (<20)	ND (<3)	ND (<3)	ND (<1)	ND (<1)
	Cruise	ND (<40)	ND (<7)	ND (<7)	ND (<3)	ND (<3)

Notes to SVOC Table D5b

ND – not detected

*ND – not quantifiable amount as insufficient analyte to give positive “fingerprint” identification of analyte, but single ion response indicates trace amount present.

Calibration is for reference samples supplied Skydrol 500 B-4 and Aeroshell Turbine oil 560. These are fluids and both are mixtures of several components. Quantification of the amount in air assumes that the composition of the mixture trapped by the PUF is the same as the reference fluids.

Detection limits for Aeroshell 560 are better than 3µg on the PUF tube.

Detection limits for Skydrol as tributylphosphate and dibutylphenylphosphate are better than 0.5µg on the PUF tube. However some of the blanks have produced interferences, equivalent of up to 5µg Skydrol as tributylphosphate and 5µg Skydrol as dibutylphenylphosphate on the PUF tube. This has limited the level at which the presence of Skydrol can be confirmed.

Detection limits for other SVOCs are expected to fall within these ranges.

Appendix E – Ultrafine particle measurements

Table E1: Ultrafine particle data from BAe146 aircraft during the whole flight

Flight Number	Mean (pt cm^{-3})	Min (pt cm^{-3})	Max (pt cm^{-3})
1	10949	26	48963
2	8990	64	51266
3	19136	32	249633
4	21107	52	231233
5	26536	35	256183
6	29705	44	185616
7	3873	13	32845
8	11441	44	126333

Table E2: Ultrafine particle data from BAe146 aircraft during cruise

Flight Number	Mean (pt cm^{-3})	Min (pt cm^{-3})	Max (pt cm^{-3})
1	45	26	109
2	195	64	558
3	4985	32	94848
4	458	52	10296
5	793	35	8986
6	632	48	4442
7	29	13	182
8	1080	44	25810

Table E3: Ultrafine particle data from BAe146 Aircraft on the ground prior to departure

Flight Number	Mean (pt cm^{-3})	Min (pt cm^{-3})	Max (pt cm^{-3})
1	25859	12113	46421
2	21427	11753	51266
3	20986	4156	47185
4	32057	12823	85483
5	57183	24690	135733
6	75369	17043	185616
7	14416	6055	32845
8	38844	11266	126333

Table E4: Ultrafine particle data from B737 aircraft during the whole flight

Flight Number	Mean (pt cm^{-3})	Min (pt cm^{-3})	Max (pt cm^{-3})
9	9040	11	112970
10	8938	8	129976
11	2418	18	74351
12	1292	8	34733
13	5280	15	96346
14	5317	29	382416

Table E5: Ultrafine particle data from B737 aircraft during cruise

Flight Number	Mean (pt cm^{-3})	Min (pt cm^{-3})	Max (pt cm^{-3})
9	28	22	39
10	50	20	136
11	93	18	714
12	38	13	204
13	49	15	104
14	85	29	652

Table E6: Ultrafine particle data from B737 aircraft on the ground prior to departure

Flight Number	Mean (pt cm^{-3})	Min (pt cm^{-3})	Max (pt cm^{-3})
9	40635	68	112970
10	37883	2325	129976
11	11511	1770	74351
12	6816	655	34733
13	17684	232	63378
14	57020	1198	382416