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Ventilation of enclosures for removal of asbestos containing materials

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Ventilation of enclosures for removal of asbestos containing materials

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When removal of high-risk asbestos-containing materials takes place, the work should be carried out inside a specially constructed ventilated enclosure to prevent the spread of asbestos outside the work area. The aim of this research project was to investigate the factors that affect the containment potential of temporary ventilated enclosures. The work covered; the way that air moves within ventilated enclosures, how the construction of enclosures and airlocks affects air movement and containment, and how the positioning of extraction points and air inlets affect air movement and containment. Work was done to investigate the relationship between air flow and negative pressure, and containment. The study also examined factors which affect the ability of enclosures to contain asbestos, such as unplanned openings. In addition to this the effect of removing ceiling tiles and the size of ceiling void relative to the enclosure was investigated.

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EXECUTIVE SUMMARY

Background

Many buildings in GB contain asbestos; this can include pipe lagging, wall insulation, fire doors, ceiling tiles, floor material, fire- and sound-proofing. Asbestos fibres are often mixed with other materials such as cement, which are known as asbestos containing materials (ACMs). Asbestos is classified as a category 1 human carcinogen, under GB health and safety regulations therefore exposure to carcinogenic substances should be controlled to a level that is as low as is reasonably practicable (ALARP). Removal of asbestos or ACMs can release asbestos fibres, which can become airborne, a proportion of which will be respirable.

Any work in Great Britain involving asbestos should be controlled in accordance with the Control of Asbestos Regulations 2012 (CAR 2012). The removal work should be strictly controlled using dust suppression techniques to mitigate fibre release. The prevention of the spread of asbestos fibres is achieved by the use of temporary ventilated enclosures. Guidance on the specification, construction and operation of these enclosures is currently available in the HSE guidance document HSG 247.

Following the introduction of CAR 2012 HSE's guidance is due to be reviewed and rewritten. The purpose of this work was to investigate the airflow characteristics of ventilated enclosures and the factors that affect their containment potential, in order to provide robust information on which the new guidance could rely. Additional work undertaken during the project was to investigate the effect on the airflow characteristics and containment potential of ventilated enclosures during the removal of ceiling tiles.

Objectives

- Investigate the factors that affect the airflow characteristics of ventilated enclosures, these to include;
  - Ventilation rate
  - Location of extract position
  - Number of airlock inlets
- Investigate the factors that affect the containment potential of enclosures, these to include;
  - Pressure difference between the interior of the enclosure and the surrounding space (ΔP) and the how various factors affect it such as volume flow rate/ventilation rate, airlock configuration and airlock door/door opening shape and area.
  - Airlock door deflection and how various factors affect this such as volume flow rate, weight of door, and overlap of door and opening.
  - The effect of adding inlet filters in the enclosure walls.
  - The effect of unplanned openings in the enclosure walls on ΔP and containment effectiveness.

- Investigate the effect upon the volume flow rate of a hired negative pressure unit (NPU) by adding ducting to the inlet and exhaust sides and also the effect of adding 90° bends to the additional ducting.

- Investigate the effects upon enclosure containment potential in an enclosure when simulating the removal of ceiling tiles, this to include;

    - The effects when voids are sealed with a volume smaller than the enclosure and unsealed voids where the volume is much greater than the enclosure.

    - Above assessed by measuring effects upon ΔP, by using tracer gas to quantitatively investigate containment effectiveness and the use of smoke to qualitatively show the effects of removing ceiling tiles.

Main Findings

- A ventilation rate of 8 air changes per hour (ach) in Enclosure 1 produced a poor vertical mixing regardless of the extraction position; this led to an effective ventilation rate of less than 10 % of the calculated rate at high-level positions. This meant that the air at the top of the enclosure was poorly mixed with the rest of the air in the enclosure, if the top of the enclosure was treated as a separate space the ventilation rate was less than 0.8 ach. This would mean that any airborne fibres could potentially remain suspended in the air for longer than the standard 1-hour ventilation overrun.

- The location of the extract position had some effect upon the horizontal mixing within Enclosure 1 at the lower ventilation rate of 8 ach (384 m^3h^{-1}). Specifically NPU position 4, which was raised above floor level, produced the best mixed atmosphere at the low level sampling positions.

- Having two airlocks open in Enclosure 1 increased horizontal mixing.

- A ventilation rate of 8ach in the larger Enclosure 2 produced a well-mixed atmosphere both horizontally and vertically regardless of NPU position. This showed that when considering mixing, volume flow rate is the determining factor not the air change rate.

- Visualisation using smoke confirmed these findings, clearly showing the stratification within Enclosure 1 at 8 ach. The smoke visualisation showed that when considering the clearance time of an enclosure both the degree of mixing and the ventilation rate need to be considered. A smoke test should be carried out as a matter of course on enclosures before they are put into operation.

- However it should be noted that a large volume flow rate is more important in achieving a well-mixed atmosphere than NPU position or number of airlocks. The smoke visualisation was very informative in that it demonstrated the fallacy of the common belief that *n* ach means that smoke will be cleared in 1/*n* hours by showing that it can take 4 – 5 air changes before the air is cleared.

- For standard airlock chambers volume flow rates in excess of 1900 m^3h^{-1} caused the airlock doors to impinge on the far side of the chamber, making it difficult to work inside the chamber.

- Adding additional inlet filters to the enclosure wall was found to reduce ΔP and the airlock door deflection. However, this approach could have other problems such as potentially compromising containment.

- ΔP was found to be proportional to volume flow rate through the enclosure, the open area of the airlock doors, and the weight of the airlock doors.

- It was also found that ΔP could vary by up to 1 Pa as the ambient temperature changed throughout a day, which is one of the reasons that ΔP is an unreliable indicator of volume flow rate.

- The effect of unplanned openings in the enclosure walls upon ΔP was investigated; only large (~2 m) vertical slits and holes with areas of 100 cm^2 had a significant effect.

- The effect of unplanned openings upon containment potential was assessed using a tracer gas challenge in the presence of a working Class-H vacuum cleaner exhaust and without. Tracer gas was detected outside of the enclosure for all of the unplanned openings tested except the small hole with an area of 4 cm^2. When tested without the presence of the vacuum cleaner exhaust no tracer gas was detected outside of the enclosure for any of the unplanned openings. This indicates that in the absence of any external disturbing airflows ΔP was sufficient to maintain enclosure integrity.

- Results showed that ΔP was not a reliable indicator of containment integrity, the position of the airlock doors as airflow indicators may be a more suitable indicator.

- The addition of flexible ducting to the NPU with 90° bends reduced the volume flow rate by approximately 1 % per metre of duct and 2 % per 90° bend. These reductions should be taken into account when calculating required ventilation rates for the 355 mm diameter ducting tested.

- The effect of removing ceiling tiles was found to be dependent upon the volume of the void above the false ceiling compared to the enclosure.

- When the volume of the void was much larger than the enclosure, for instance a small enclosure in a large room where the void is unsealed, removing a ceiling tile caused ΔP and the airlock door deflection to fall to zero.

- Tracer gas and smoke tests showed that once the tile was removed air was able to enter the void and therefore potentially spread contamination to surrounding areas.

- When the volume of the void was less than the enclosure, removal of a ceiling tile caused a reduction of ΔP but the airlock door deflection was unchanged. Tracer gas and smoke tests showed that once the pressure between the two spaces had equalised air could move freely between the two. This means that in this situation the whole void would potentially be contaminated and would require cleaning after completion of the work.

- These results were interesting and should be considered, especially in cases where the void is small compared to the enclosure. The results have shown that once the tile is removed the void becomes part of the enclosure and contaminated air can move freely between the spaces. This means that upon completion of the work the whole void should be considered to be contaminated and be cleaned.

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1. INTRODUCTION

Many buildings in GB contain asbestos products including pipe lagging, wall insulation, fire doors, ceiling tiles, floor material, fire- and sound-proofing. Asbestos is a naturally occurring silicate material composed of long fibrous crystals with typical aspect ratios of approximately 1:20. Asbestos fibres are often mixed with other materials such as cement, which are known as asbestos containing materials (ACMs). Asbestos is classified as a category 1 human carcinogen[1], under GB health and safety regulations therefore exposure to carcinogenic substances should be controlled to a level that is as low as is reasonably practicable (ALARP). Any work in Great Britain involving asbestos must be controlled in accordance with the Control of Asbestos Regulations 2012 (CAR 2012)[2]. Asbestos or ACMs in buildings in good condition and properly managed do not present a risk to occupants and should be left in place. However, ACMs are removed for various reasons e.g. they are damaged, for refurbishment and prior to demolition.

Respirable asbestos fibres are generally invisible to the naked eye with typical lengths of 3 – 20 μm and diameters less than 1 μm. Once released they easily become airborne. Respirable particles tend to have settling velocities less than 1 mms^{-1}; they therefore become suspended in and move with the air into which they are released [3]. ACM removal will potentially give rise to airborne fibres and the potential for spread. The removal work should be strictly controlled using dust suppression techniques to mitigate fibre release. Workers must also wear high efficiency respiratory protective equipment (RPE) and personal protective equipment (PPE) such as disposable overalls and boots. Workers must also decontaminate themselves before leaving the contaminated areas. Asbestos fibre release during removal work has the potential to spread into other areas. Therefore it is necessary to control the movement of the air in the vicinity of the work in order to prevent the spread of asbestos to uncontaminated areas.

The prevention of the spread of asbestos fibres for high risk work is normally achieved by the use of temporary ventilated enclosures. Guidance on the specification, construction and operation of these enclosures is currently available in the HSE guidance document HSG 247[4]. In summary this document states that enclosures should be constructed of 1000 gauge polythene (250 μm), sealed and as airtight as possible with planned openings via three-stage airlocks, have sacrificial flooring and ventilated at a minimum rate of 8 air changes per hour (ach). Ventilation is provided by means of a device called a negative pressure unit (NPU); the unit includes a fan to extract air from the enclosure and is fitted with a high efficiency particulate air (HEPA) filter. NPUs are typically used with a disposable paper pre-filter in line that is changed every day. The NPU should provide a negative differential pressure (ΔP) of –5 Pa between the enclosure and atmosphere.

Following the introduction of CAR 2012 HSE guidance is due to be reviewed and rewritten. The purpose of this study was to investigate the airflow characteristics of ventilated enclosures and the factors that affect their containment potential, in order to provide robust information on which the new guidance could rely. The study was also designed to assess the containment potential and airflow characteristics of ventilated enclosures during the removal of ceiling tiles. The aims and objectives are set out in Section 2.

2. AIMS AND OBJECTIVES

Aims

The aims of the project were

- To obtain more robust information on the ventilation of asbestos enclosures to facilitate revision of Chapter 6 of the guidance HSG 247.

- To provide training materials for HSE inspectors and others on the airflow characteristics of ventilated asbestos enclosures.

Objectives

- Investigate the factors that affect the airflow characteristics of ventilated enclosures, these to include;
    - Ventilation rate
    - Location of extract position
    - Number of airlock inlets
- Investigate the factors that affect the containment potential of enclosures, these to include;
    - Pressure difference between the interior of the enclosure and the surrounding space (ΔP) and the how various factors affect it such as volume flow rate/ventilation rate, airlock configuration and airlock door/door opening shape and area.
    - Airlock door deflection and how various factors affect this such as volume flow rate, weight of door, and overlap of door and opening.
    - The effect of adding inlet filters in the enclosure walls.
    - The effect of unplanned openings in the enclosure walls on ΔP and containment effectiveness.
- Investigate the effect upon the volume flow rate of a hired negative pressure unit (NPU) by adding ducting to the inlet and exhaust sides and also the effect of adding 90° bends to the additional ducting.
- Investigate the effects upon enclosure containment potential in an enclosure when simulating the removal of ceiling tiles, this to include;
    - The effects when voids are sealed with a volume smaller than the enclosure and unsealed voids where the volume is much greater than the enclosure.
    - Above assessed by measuring effects upon ΔP, by using tracer gas to quantitatively investigate containment effectiveness and the use of smoke to qualitatively show the effects of removing ceiling tiles.

3. METHODOLOGY

3.1 ENCLOSURES STUDIED

Three enclosures were studied, see Figure 3.1 below. The enclosures and airlocks were constructed of timber frames with a skin of 1000 gauge polythene in line with the guidance in HSG 247[4]. Enclosure 1 was a regularly shaped simple cuboid (4 x 4 x 3 m) fitted with two three-stage airlocks. Each airlock was constructed of three chambers measuring 1 x 1 x 2 m each, the door openings were approximately 0.8 x 1.8 m. The total internal volume of the enclosure was 60 m^3 including the airlocks. Enclosure 2 was L-shaped; 6 m on the long edges 3 m on the short edges and 3 m high with an internal volume of 87 m^3 including one airlock. Enclosure 3 was a cube 3 x 3 x 3 m and had an internal volume of 33 m^3 including the airlock; the ceiling was fitted with 4 ceiling tiles, measuring 1.2 x 1.2 m, for simulating the process of replacing them and investigating the effect that this had on containment.

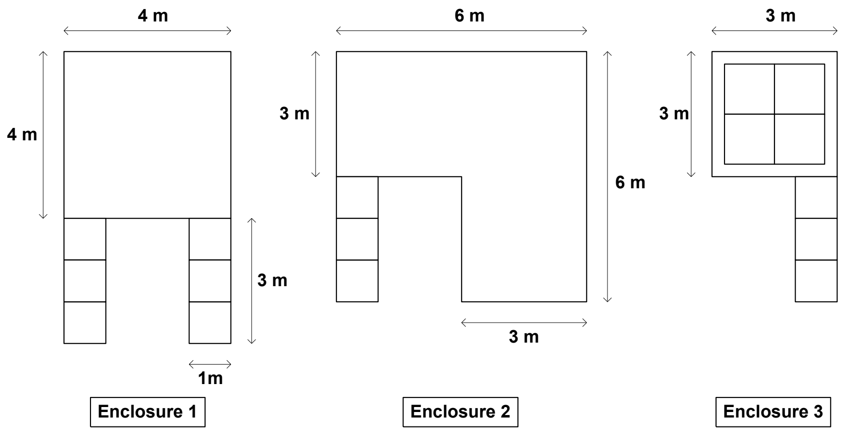

Figure 3.1 Plan view of the enclosures studied. All three enclosures were 3 m high.

The airlock doors that separated each chamber were constructed from weighted polythene sheets and acted as non-return valves, preventing contaminated air from exiting and to allow replacement air to enter, see Figure 3.2 below. The geometry of the doors and arrangement of the airlock chambers were varied to investigate the effects on the differential pressure (ΔP) across the enclosure when the NPU was operated.

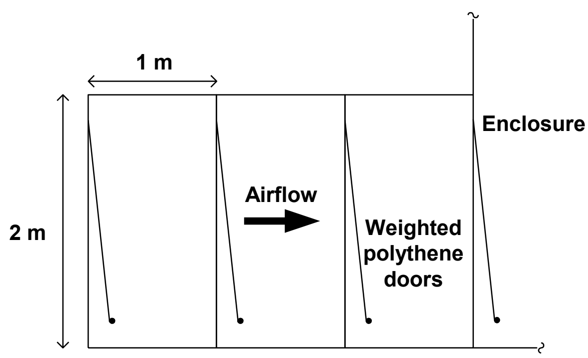

Figure 3.2 Diagram showing side view of a three stage airlock

Extracting air from the enclosure creates a negative pressure relative to atmosphere; this entrains air into the enclosure through the airlock(s). The pressure difference creates a force against the airlock doors and causes them to be deflected inwards allowing air to enter. As there was no asbestos or ACMs present in any of the test enclosures, for the majority of this project the NPU was replaced by a standard fan and pre filter. Some tests were performed using NPUs hired from an equipment supply company; these tests are detailed in Section 3.4.

3.2 ENCLOSURE 1

3.2.1 Airflow patterns

The internal airflow patterns within the enclosure and the effects of NPU extract position and airlock geometry were investigated using a tracer gas technique. Sulfur hexafluoride (SF_6), was released and then mixed using two axial fans to tag the air in the enclosure until the average concentration of SF_6 was approximately 100 parts per million (ppm). The mixing fans were deactivated and the ventilation was then activated, the concentration of SF_6 was monitored at a series of predetermined positions in sequential tests, shown below in Figure 3.3, using an infrared spectrophotometer (Miran 1a S/N 407051). Position 1 was 1.5 m from the floor, positions 2 and 4 were 0.75 m from the floor, and 3 and 5 were 2.75 m from the floor. Comparing the rate of decay of tracer gas concentration at each position indicates the degree of mixing that occurs inside the enclosure under various ventilation conditions. These experiments were repeated with the NPU extract located at four different positions and at a variety of ventilation rates and with one or both airlocks open.

The effect on the internal airflow patterns by adding inlet filters was also investigated. A further set of tests was performed measuring the concentration of tracer gas at one of the high level positions for an extended period to determine the time taken for the air at this high level position to clear of contamination. During all tests using tracer gas the air extracted from the enclosure was exhausted outside and away from the building to prevent re-entraining tracer gas back into the enclosure.

A series of tests was carried out using smoke to demonstrate the clearance time of the enclosure and to further investigate the airflow patterns under various ventilation rates. These tests were performed at two ventilation rates. Two additional tests were performed introducing smoke into the airlock chambers to visualise how air enters the enclosure. These tests are discussed in Section 5.

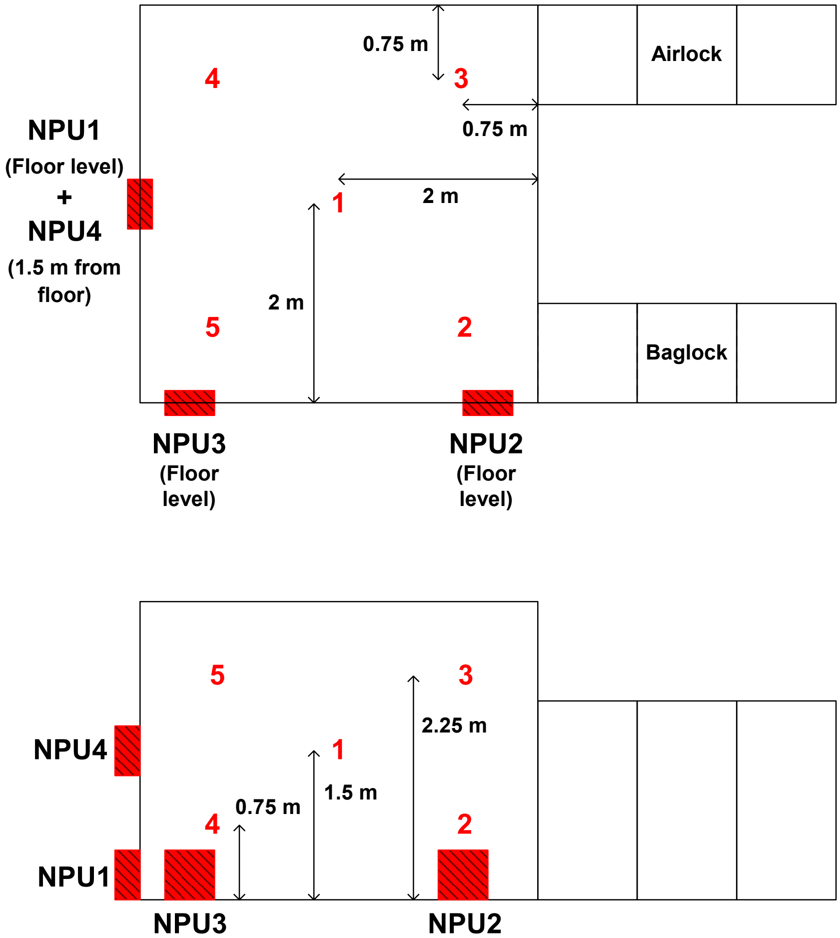

Figure 3.3 Side and plan view of Enclosure 1 showing extract/NPU positions and tracer gas concentration decay test positions.

3.2.2 Differential pressure, additional inlet filters and unplanned openings

The current guidance (HSG247) states that the enclosure should be maintained at a negative pressure with respect to atmosphere to ensure that any leaks are into the enclosure to prevent the spread of asbestos and that this ΔP should be –5 Pa. The factors that affect ΔP were investigated; these included extract volume flow rate, number of airlocks open, configuration of airlock chambers and design of door openings and doors. ΔP was measured using a micromanometer (TSI S/N TA4601007001) at four positions; these were located at the centre of each wall, 2.0 m from each corner and 1.5 m from the floor, as shown in Figure 3.4 below.

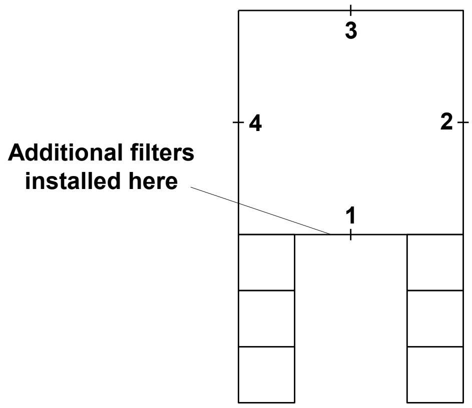

Figure 3.4 ΔP measurement positions in the walls of Enclosure 1.

These measurements were made with the extraction point at NPU position 1 (see Figure 3.3). The mean value of ΔP is reported. Four measurement positions were selected to determine whether or not there was significant variation of pressure throughout the enclosure. The current HSE guidance states that where possible enclosures should be fitted with two airlocks, one for personnel and one for bagged waste to be removed (also known as the baglock). The current guidance also states that during normal operations, unless waste is being removed, the baglock should be sealed meaning that air can only enter the enclosure via the personnel airlock. ΔP was measured with one airlock and with both airlocks open at nine ventilation rates.

Some enclosures can be very large, hundreds or even thousands of cubic meters. In these cases it can be difficult to supply sufficient replacement air through an airlock. One suggested method to overcome this problem is to install additional inlet filters directly into the enclosure walls.

In order to investigate the effects of additional inlet filters, four NPU 380 x 380 mm pre filters were installed in the wall between the two airlocks (see Figure 3.4). If this were done on a real enclosure some method would have to be employed to prevent asbestos contaminated air from exiting the enclosure because pre filters do not have sufficiently high filtration efficiency in the size range of asbestos fibres. For this reason the filters were fitted with flaps on the enclosure side similar to the doors in the airlock chambers. With the enclosure ventilated and with one airlock open, ΔP was measured as each filter was opened in sequence. This was repeated both with and without non-return flaps fitted to the filters. At the same time the volume flow rate of air passing through each filter was measured using a direct volume flow rate measurement device (TSI Model 8373-M-GB S/N 00090343).

Because the walls of enclosures are made from polythene they can tear or puncture easily. This can potentially affect the containment potential of an enclosure. To investigate the effects of breaches to the enclosure, a series of unplanned openings consisting of vertical and horizontal slits of various lengths and holes of various open areas were introduced into the walls and the effect upon ΔP was measured. This was performed at two ventilation rates.

The effect of unplanned openings on containment potential was also assessed using a tracer gas challenge. SF_6 was released and mixed with the air inside the enclosure to create a uniform concentration of approximately 100 ppm. A Class-H vacuum cleaner was positioned inside the enclosure near to the site of the unplanned opening and the ventilation activated. After a period of 5 minutes the unplanned opening was uncovered, air was sampled outside of the enclosure from a position 300 mm from the unplanned opening and analysed using a Miran 1a gas analyser to determine if any tracer gas could be detected. Air was exhausted from the vacuum cleaner through a cylindrical port on top surface of the unit, the exhausted air was emitted horizontally through 360°. The vacuum cleaner was placed against the wall of the enclosure with the centre of the exhaust port approximately 115 mm from the wall emitting air in all directions. A photograph of the vacuum cleaner used and a diagram showing the position within the enclosure and sample position are shown below in Figure 3.5. The air exhausted from the enclosure by the extraction fan was discharged outside of the building via lengths of rigid and flexible 300 mm diameter duct to prevent reentrainment of tracer gas into the building.

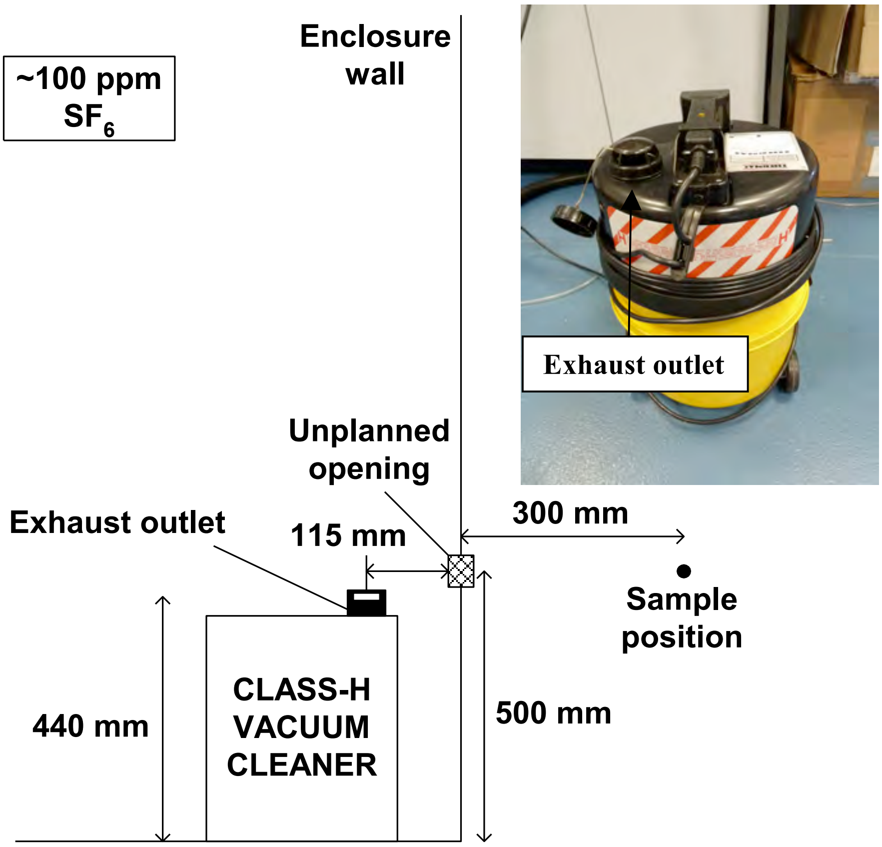

Figure 3.5 Tracer gas sampling position outside of enclosure for testing enclosure integrity

3.2.3 Airlock configuration and door deflection

Several elements of the construction of the airlocks were suspected of influencing the way air enters enclosures and particularly ΔP. One of these was the arrangement of the airlock chambers themselves, i.e. three chambers in a straight line or arranged in an L-shape. The enclosure was ventilated at two different rates and ΔP was measured. Three configurations were tested, which are shown below in Figure 3.6. The second variable investigated was the size of the door in the airlock chamber wall with a constant door width. Again, the enclosure was ventilated at two different rates and ΔP measured with two different values of the overlap. The final variable investigated was the shape of the door opening; the three door-opening configurations are shown in Figure 3.6.

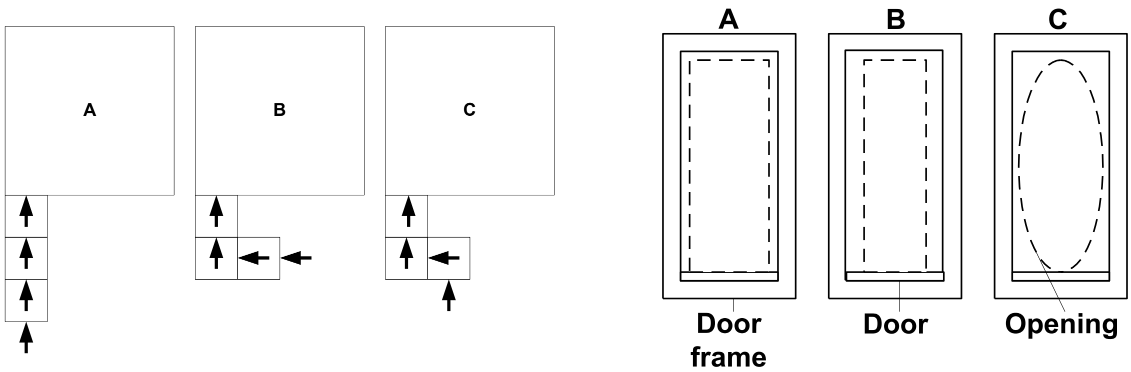

Figure 3.6 Three airlock arrangements investigated (left) and door size/door opening overlap and shapes investigated (right).

The movement of air through the airlocks caused the doors to deflect inwards, as shown in Figure 3.2. This deflection was measured at two volume flow rates with one and both airlocks open.

The design of airlock doors varies in industry; a "weight" is usually added to the bottom of the door. A piece of wood or metal (a chain or rod) or plastic sheeting can be used. A design that is often used is to cut a strip of polythene from the roll used to clad the enclosure to the required width and then roll up the excess to form the weight. This was adopted as the standard and used throughout the study. Using a standard 4 m wide roll of 1000-gauge polythene the weight of the rolled excess was approximately 380 g when the length of excess sheeting rolled up to form the weight is equal to the length of the door.

3.3 ENCLOSURE 2

In practice enclosures are not always regular shapes. Enclosure 2 was an L-shape 6 m on the long sides, 3 m on the short sides and 3 m high; it had an internal volume of 81 m^3 (not including the airlock). The degree of mixing within the enclosure was assessed by measuring the concentration decay of SF_6 at eight positions. This was performed at a single ventilation rate with the extraction unit at two different positions located at floor level. A higher ventilation rate was assessed by using a hired NPU that provided a volume flow rate of approximately 1500 m^3h^{-1}. ΔP was monitored during each test. The two extract positions were selected as a good practice position and a compromised position that could be the result of limited access to the walls of the enclosure. The extract positions are shown below in Figure 3.7 along with the tracer gas sampling positions.

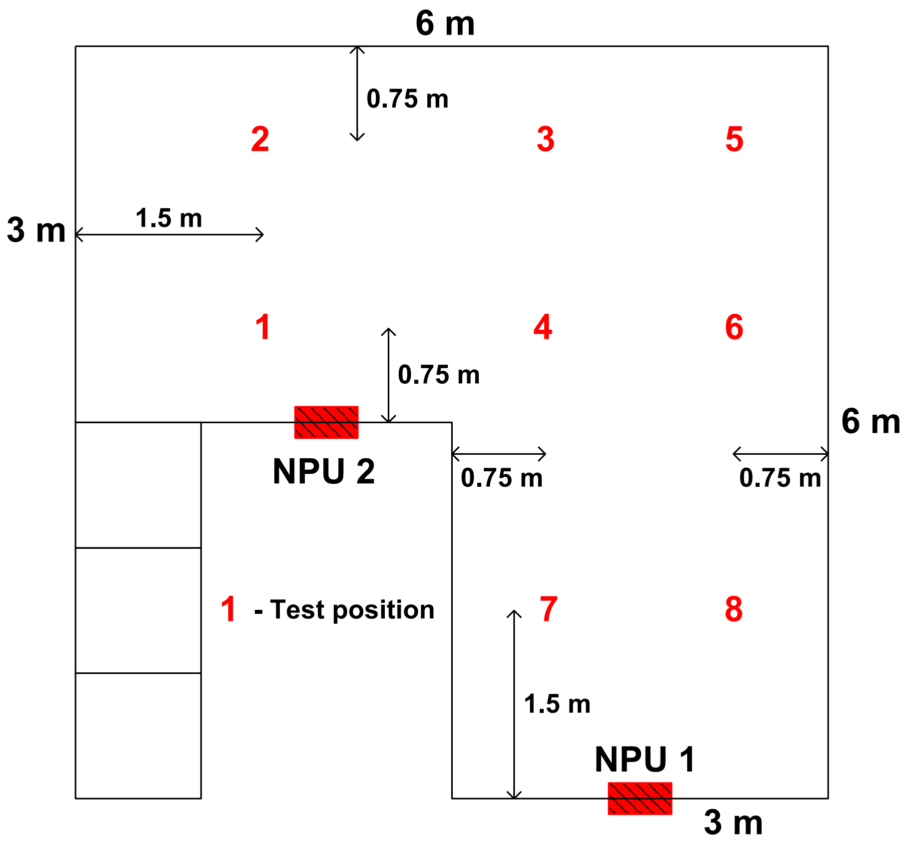

Figure 3.7 Plan view of Enclosure 2 showing NPU/extract positions and tracer gas concentration decay positions. Positions 1, 3, 6 & 7 were at low-level 0.75 m from the floor. Positions 2, 4, 5 & 8 were at high-level 2.25 m from the floor.

In practice it is sometimes necessary to add lengths of ducting and a 'roving head' to the inlet side of the NPU to manage air movements within enclosures. In addition HSG 247 states that air extracted from enclosures should be exhausted outside to atmosphere[4], which will usually involve adding ducting to the exhaust side of the NPU. During the work on Enclosure 2, a NPU was rented from a decontamination equipment supplier. The volume flow rate was measured and compared to the certificate supplied with the NPU. The effect on the volume flow rate of the NPU of adding lengths of ducting and bends in the ducting both on the inlet and exhaust sides of the NPU was investigated. The volume flow rate was measured with 6 m and 12 m of straight length of spiral wound flexible ducting of diameter 355 mm on the inlet and exhaust and with 12 m of flexible ducting with a single 90° bend on the inlet and exhaust side. These are all shown below in Figure 3.8.

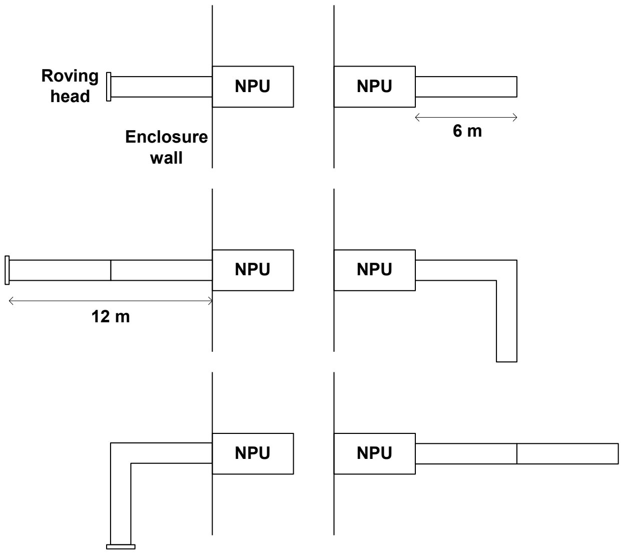

Figure 3.8 Flexible spiral wound ducting added to inlet and exhaust of NPU

3.4 ENCLOSURE 3 – CEILING TILE REPLACEMENT

3.4.1 The enclosure

A common process during refurbishment or installation work particularly in commercial premises, is replacing ceiling tiles made from ACMs with non-asbestos containing tiles. As the ceiling tiles form part or all of the ceiling, removing them modifies the physical structure and shape of a space, as well as the effective volume of the enclosed area. These changes potentially compromise the integrity and therefore the containment potential of the enclosure.

A series of experiments was performed to investigate the effects of removing ceiling tiles and the associated cleaning tasks in the areas around the tiles. The purpose of these tests was to ascertain whether removing tiles could allow potentially contaminated air to leave the enclosure and spread into the ceiling void. When investigating spread into the ceiling void, two scenarios were investigated; one where the volume of the void was much greater than the volume of the enclosure, and a second where the volume of the void was smaller than the enclosure.

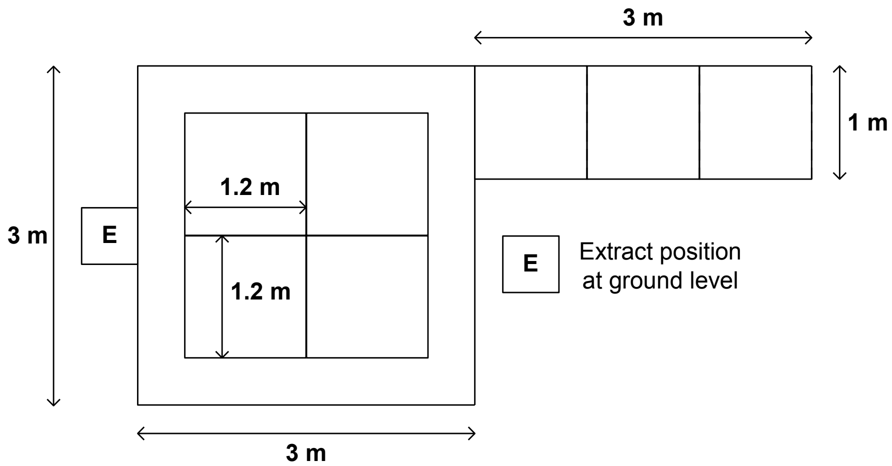

Figure 3.9 Plan view of Enclosure 3.

Enclosure 3 was a cube 3 x 3 x 3 m and was fitted with one airlock. Instead of being made from polythene sheet as in Enclosure 1 the ceiling was made from hardboard and 4 removable tiles each measuring 1.2 x 1.2 m. There was also a hardboard layer positioned 1 m above the false ceiling simulating the roof void found above false ceilings. Figure 3.9 above shows a plan view of Enclosure 2. In order to avoid using any asbestos the tiles were made from Supalux®, which is a typically used replacement material. As with real ceiling tiles, the tiles were attached with screws from below to the roof frame so that it was not necessary to lift and twist to remove them.

3.4.2 Volume of void much greater than volume of enclosure

The first case investigated was where the volume of the ceiling void was much greater than the volume of the enclosure. This is typical for offices and commercial premises including department stores, supermarkets and retail units. These floor spaces are typically large and the ceiling void usually covers the whole floor area and sometimes beyond. Often in this situation a small enclosure is created around a number of tiles for them to be removed and replaced with non-ACM tiles. In this scenario the volume of the roof void is much greater than the volume of the enclosure. This was simulated by not sealing the sides of the void above Enclosure 3, in effect making the whole room containing the enclosure the volume of the void. The hardboard panel 1 m above the false ceiling represents the top of the roof void and an additional panel 1 m wide was added to the perimeter of the enclosure ceiling to allow air to travel over a simulated portion of ceiling, see Figure 3.10 below.

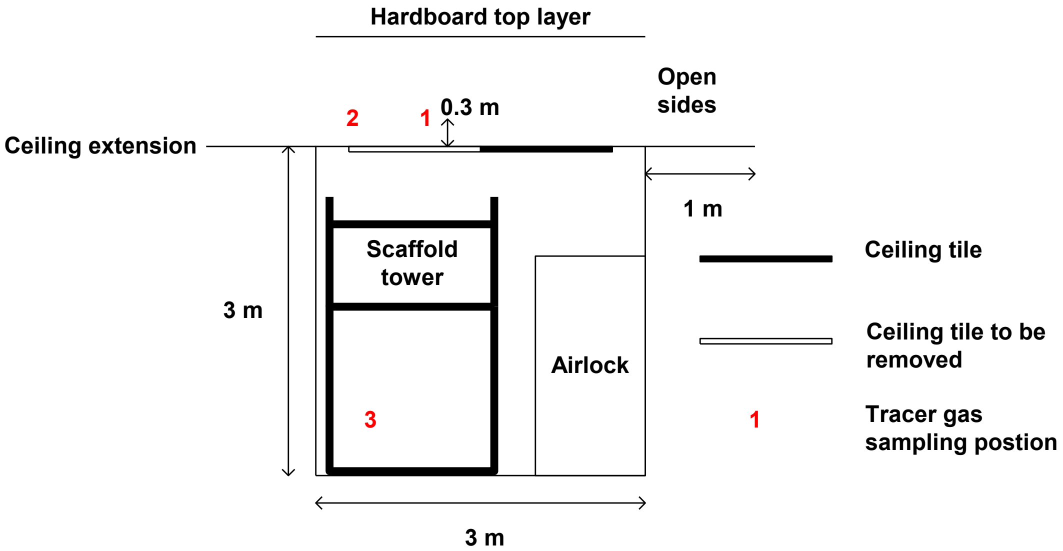

Figure 3.10 Diagram showing layout of Enclosure 3 in the unsealed void configuration and tracer gas sampling positions.

These tests involved injecting sulfur hexafluoride (SF_6) as a tracer gas into the enclosure and mixing to produce a uniform concentration of SF_6 in the enclosure of approximately 100 parts per million (ppm). The gas injection then remained on throughout the test period and the steady state concentration inside the enclosure was monitored by sampling gas at position 3 and measuring the concentration using an infrared spectrometer. The mixing fan was deactivated when the process of removing the tile was started, so after this time the concentration measured at position 3 was not the average concentration in the enclosure. The tile was removed by an operator standing on the scaffold tower; once the retaining screws had been removed the tile was gently lowered to the tower platform. A second infrared spectrometer was used to sample air at positions 1 or 2 to detect any tracer gas that escaped the enclosure. Position 1 was 0.30 m above the centre of the tile to be removed; position 2 was located 0.30 m above and half way along one edge of the tile to be removed. With the ventilation running a tile was removed and the task of vacuuming around the frame where the tile was attached was simulated. This was performed at four ventilation rates. ΔP was also monitored during every test before and after the tile was removed. The concentration of tracer gas was stabilised with the ventilation running, the test was started at t = 0 s, the tile was removed at t = 300 s, the simulated vacuuming task was carried out between t = 540 s and t = 600 s, at t = 660 s the operator left the enclosure and the test was stopped.

3.4.3 Volume of void is much less than the volume of the enclosure

The second case involved a void with a volume less than that of the enclosure. This may occur where the roof void is temporarily partitioned as part of the asbestos work or where the enclosure is an entire room. This case was simulated by sealing the edges of the void in line with the walls of the enclosure creating a sealed void measuring 3 x 3 x 1 m above the enclosure. The tests removing a tile and simulating the cleaning of the area surrounding the removed tile were repeated at two ventilation rates sampling air at position 1 only, shown in Figure 3.11 below.

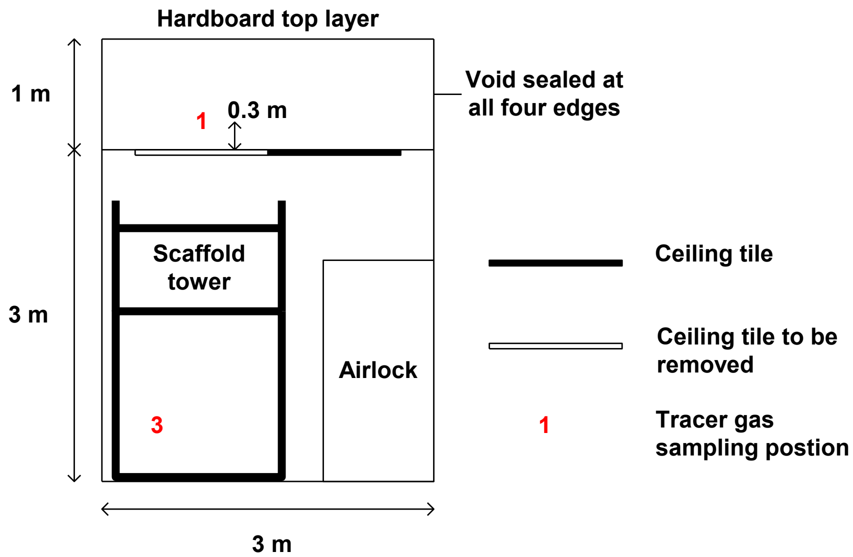

Figure 3.11 Diagram showing layout of Enclosure 3 in the sealed void configuration and tracer gas sampling position.

3.5 VIDEO TRAINING MATERIALS

A series of videos were produced to be used as training aids. These included footage of smoke tests in Enclosure 1 at 8ach and 20 ach to demonstrate the time taken for the air to be cleared at these ventilation rates. Additionally a test was filmed in Enclosure 1 with the ventilation operating releasing smoke into the airlock chamber to demonstrate how air entering the enclosure mixes with the air in the enclosure. Several videos were also filmed in Enclosure 3 with both the sealed and unsealed voids to show how contaminated air can escape the enclosure into the void, and also to show the initial inrush of air from the void into the enclosure as the pressures equalise when a tile is removed.

4. RESULTS

4.1 CALCULATION AND MEASUREMENT OF AIR CHANGE RATES

Ventilation rates can be expressed in a number of ways. The simplest way is stating a volume flow rate of air; this can be extracted air, supplied air or air passing through a room. Volume flow rates are expressed as a volume of air per unit time; the SI units are cubic metres per second (m^3s^{-1}), however in GB it is commonly expressed as cubic metres per hour (m^3h^{-1}). Other common units are cubic feet per minute (cfm) and litres per minute ($lmin^{-1}$). Another method for specifying a room ventilation rate is as an air change rate; this is defined as the volume flow rate of air moving through the room (Q) divided by the volume of the room (V). The air change rate represents the number of room volumes of air that passes through a room per unit time and is most commonly expressed as air changes per hour (ach). An air change rate of 1 ach does not mean that all of the air in a room is changed once per hour, as ambient air enters the room it mixes with the air diluting the concentration of any contaminants exponentially. Assuming that the air in a room is well mixed the proportion of the original air that remains after one air change will be $1/e^1$ (0.367) and after 2 air changes $1/e^2$ (0.135) and so on.

A common method for measuring the air change rate of a room is the modified step-down method based on the method specified by Etheridge and Sandberg [5]. This method is used in building services and ventilation systems design studies and is common in a wider scientific context but would not typically be used in the asbestos removal industry. In this method a tracer gas is introduced and uniformly mixed with the air in a room, the rate at which the concentration of the tracer gas decreases gives a direct measure of the air change rate. The concentration of tracer gas decreases in an exponential manner according to the equation;

$$C_t = C_0.e^{-nt}$$

Where C_t is the concentration of tracer gas at time t, C_0 is the initial concentration of tracer gas and n is the air change rate in air changes per unit time. Plotting the concentration of tracer gas against time allows this equation to be derived giving the air change rate. This method does not require knowledge of the room volume (V), which is linked to the air change rate (n) and extraction volume flow rate (Q) by the equation;

$$Q = n.V$$

The method for calculating the air change rate as described in HSG246 is to calculate the volume of the enclosure including the airlock(s) and then multiply this by the desired number of air changes per hour, e.g. 8 to give the required volume flow rate. However, because the airlock chambers are separated from the enclosure by the door they are therefore a separate space. This means that if the air change rate were measured directly using a tracer gas in this situation the result would give an air change rate of n air changes per hour where

$$n = 8 \times (V_e + V_a))/V_e)$$

Where V_e is the volume of the enclosure, V_a is the volume of the airlock. The result of this would be that the true air change rate of the enclosure would be greater than 8. In order to avoid any confusion, during this study the volume flow rates were calculated to set the true air change rate of the enclosure, i.e. using the volume of the enclosure only. In practice it would be sensible to continue adding the volume of the airlocks to the volume of the enclosure as this will add an extra margin of safety.

4.2 AIRFLOW PATTERNS AND MIXING

4.2.1 Enclosure 1

The concentration decay of tracer gas was measured at five positions in Enclosure 1 with both airlocks open, ventilated at 8 ach (384 m^3h^{-1}) and 18.8 ach (900 m^3h^{-1}) with the extract located at each of the four positions shown in Figure 3.3. 18.8 ach was the maximum attainable ventilation rate with the equipment available. Figure 4.1 below shows the concentration decay of tracer gas at the five sample positions in Enclosure 1 with the extract located at NPU positions 1 to 4. For instantaneous and perfect mixing the concentration of tracer gas decreases at an exponential rate following the general equation:

$$C_t = C_0.e^{-nt}$$

Where C_t is the concentration at time t, C_0 is the starting concentration and n is the decay constant or air change rate. By fitting this equation to the data curves shown in Figure 4.1, the ratio of the mean decay constant at the five test positions to the decay constant for a perfectly mixed atmosphere at 8 ach gives a rough approximation of the degree of mixing within the enclosure for each NPU position. This ratio also gives some information of the overall airflow within the enclosure. The further away from 100 % the poorer the overall degree of mixing within the enclosure. Table 4.1 below gives the ratio of the mean decay constant to the decay constant for perfect mixing for the four NPU positions in Enclosure 1 ventilated at 8.1 ach with both airlocks open.

Table 4.1 *Ratio of the mean decay constant to the decay constant for a perfectly mixed atmosphere at 8 ach for the four NPU positions in Enclosure 1 ventilated at 8 ach with both airlocks open*

NPU Position	Ratio of the mean decay constant to the decay constant for perfectly a mixed atmosphere at 8 ach %
1	77
2	73
3	60
4	144

The degree of mixing was investigated with only one airlock open in Enclosure 1 ventilated at 8 ach (384 m^3h^{-1}) for NPU positions 1, 2 and 3, the airlock was open and the baglock sealed. Plots of the results are shown in Figure 4.1 below alongside the results with two airlocks open. The ratio of the mean decay constant at the five test positions to the decay constant for a perfectly mixed atmosphere at 8 ach with one airlock open for NPU positions 1, 2 and 3 are given below in Table 4.2.

Table 4.2 *Ratio of the mean decay constant to the decay constant for a perfectly mixed atmosphere at 8 ach for NPU positions 1, 2 and 3 in Enclosure 1 ventilated at 8 ach with one airlock open*

NPU Position	Ratio of the mean decay constant to decay constant for perfectly mixed atmosphere at 8 ach %
1	77
2	74
3	61

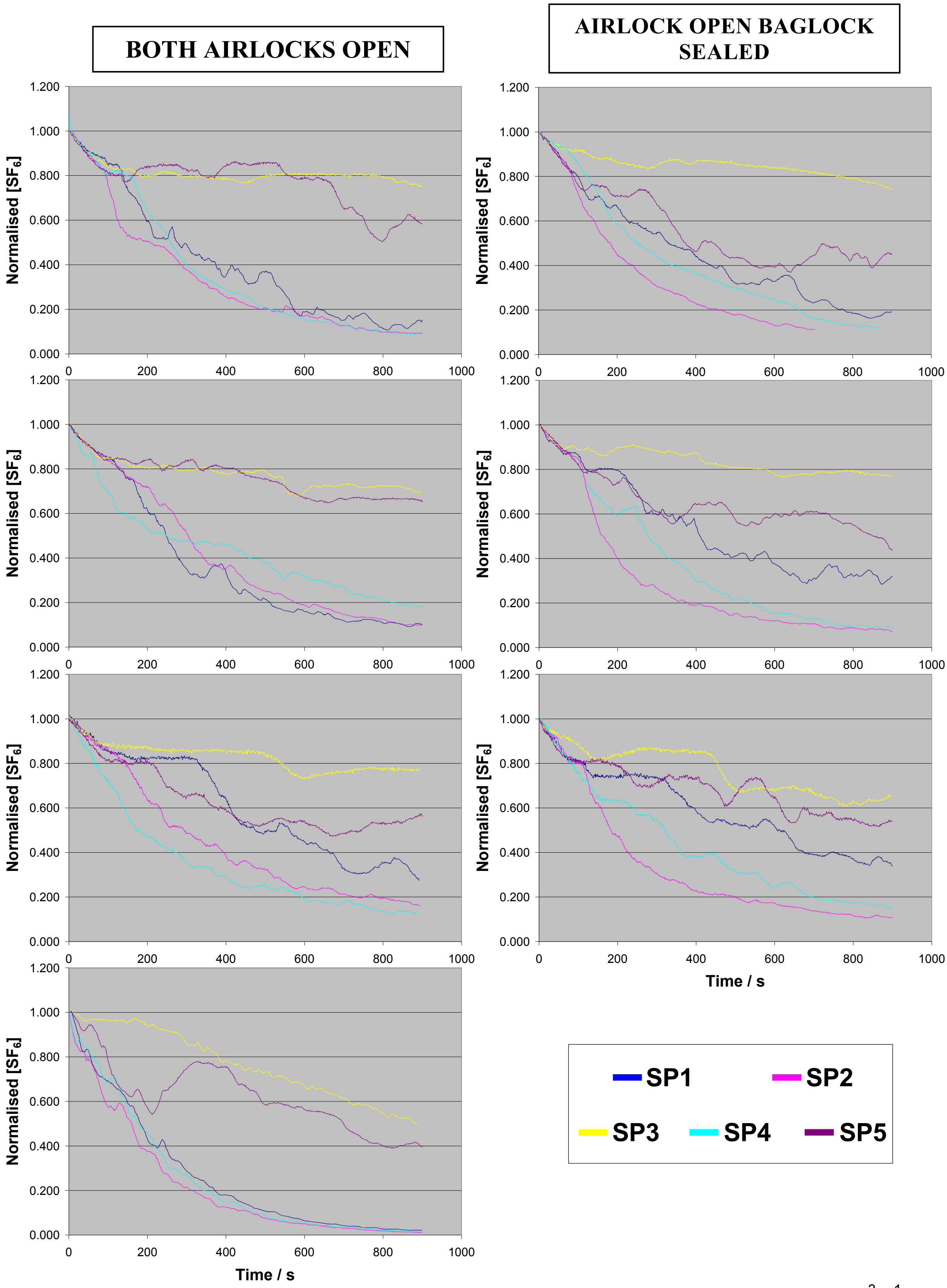

Figure 4.1 Tracer gas concentration decay plots for Enclosure 1 at 8 ach, 384 m^3h^{-1}. Left hand column two airlocks open, right hand column one airlock open. Top row NPU position 1, second row NPU position 2, third row NPU position 3 bottom row NPU position 4.

Figure 4.2 below shows the tracer gas concentration decay plots at a ventilation rate of 19.2 ach. It can be seen that all the plots follow a similar curve indicating only small concentration differences at each sampling position at any point in time. The ratio of the standard deviation of the decay constants to the mean for Enclosure 1 ventilated at 19.2 with one and both airlocks open are shown below in Table 4.3. The results show that at the higher ventilation rate the air is well mixed with one or two airlocks open.

Table 4.3 *Ratio of the mean decay constant to the decay constant for a perfectly mixed atmosphere at 19.2 ach for one and both airlocks open in Enclosure 1 ventilated at 19.2 ach with extract at NPU position 1*

Airlocks open	Ratio of the mean decay constant to decay constant for perfectly mixed atmosphere at 19.2 ach %
Both	101
One	99

From the plots it can be seen that at the lower air change rate positions 3 and 5 take the longest to clear. An extended test was carried out to determine more information of the decay rate at the high level position 5. Enclosure 1 was ventilated at 8 ach with one airlock open and the concentration of tracer gas at position 5 was measured for approximately 90 minutes, a plot of the results are shown in Figure 4.3 below. For ventilation rate of 8 ach assuming a perfectly mixed atmosphere the decay constant is 0.00222 s^{-1}, the measured decay constant at position 5 was 0.00019 s^{-1} equivalent to approximately 0.7 ach. At that ventilation rate it would take over 3 hours for the concentration of an airborne contaminant to fall to 10 % of its initial concentration.

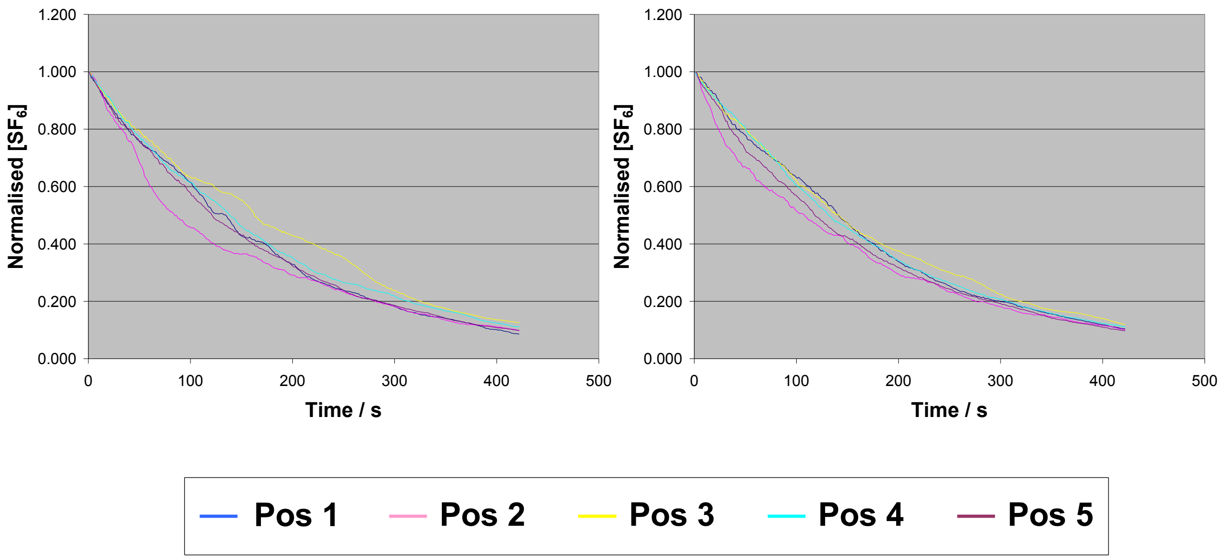

Figure 4.2 Tracer gas concentration decay plots for Enclosure 1 at 19.2 ach (920 m^3h^{-1}) and extraction at NPU position 1, both airlocks open (left) and one airlock open (right).

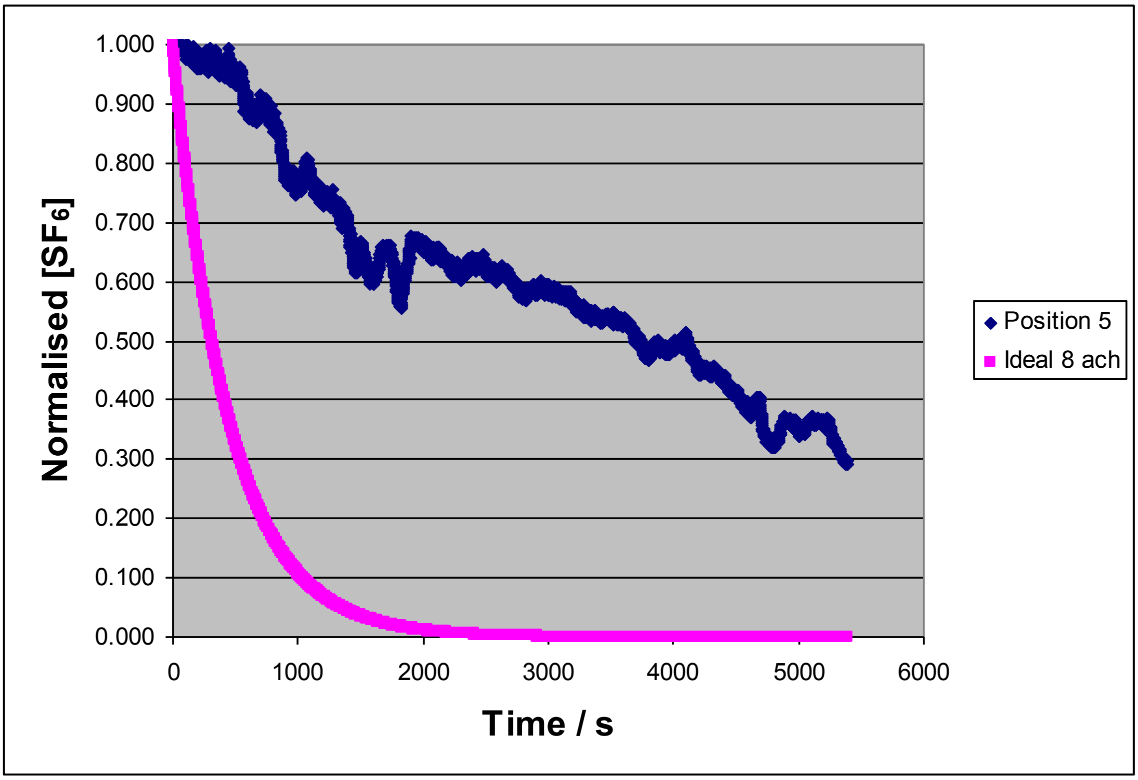

Figure 4.3 Tracer gas concentration decay plot for position 5 in Enclosure 1 ventilated at 8 ach with airlock open and baglock sealed, extract located at NPU position 1, also shows the ideal decay curve for 8 ach assuming a perfectly mixed atmosphere.

4.2.2 Enclosure 2

The degree of mixing in Enclosure 2 was investigated by measuring the concentration decay of tracer gas at 8 positions, at two ventilation rates and with the extraction located at two positions, see Figure 3.7. The results are shown in Figure 4.4 and Table 4.4 below. As well as showing the ratio of the mean decay constant to the decay constant for perfect mixing at the relevant ventilation rate, the ratio of the standard deviation of the decay constants to the mean is also shown to show the spread of the decay constants.

Table 4.4 *Ratio of the standard deviation of the decay constants to the mean for two air change rates and two NPU positions in Enclosure 2*

Ventilation Rate ach	NPU Position	Ratio of standard deviation of decay constants to mean %	Ratio of the mean decay constant to decay constant for perfectly mixed atmosphere at relevant ventilation rate %
8	1	5	133
8	2	9	96
19.3	1	2	102
19.3	2	2	66

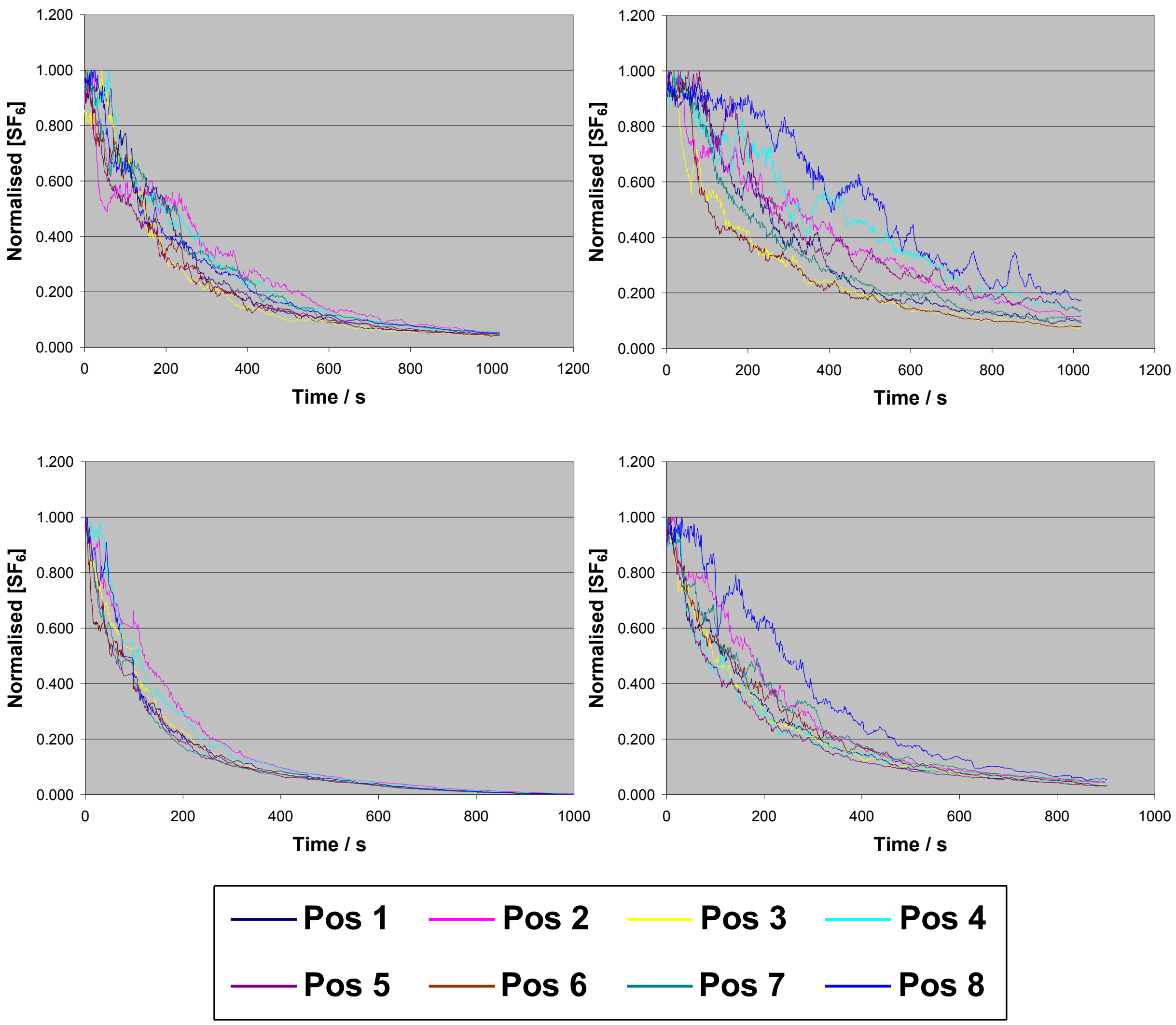

Figure 4.4 Tracer gas concentration decay plots at 8 positions in Enclosure 2 at 8 ach extraction at NPU position 1 (top left), 8 ach extraction at NPU position 2 (top right), 19.3 ach extraction at NPU position 1 (bottom left) and 19.3 ach extraction at NPU position 2 (bottom right).

4.3 FACTORS AFFECTING CONTAINMENT POTENTIAL

4.3.1 Differential pressure (ΔP)

The differential pressure between the enclosure and atmosphere was measured in Enclosure 1 at a range of volume flow rates with one and two airlocks open. The results are shown in summary in Table 4.5 and plotted in Figure 4.5 below.

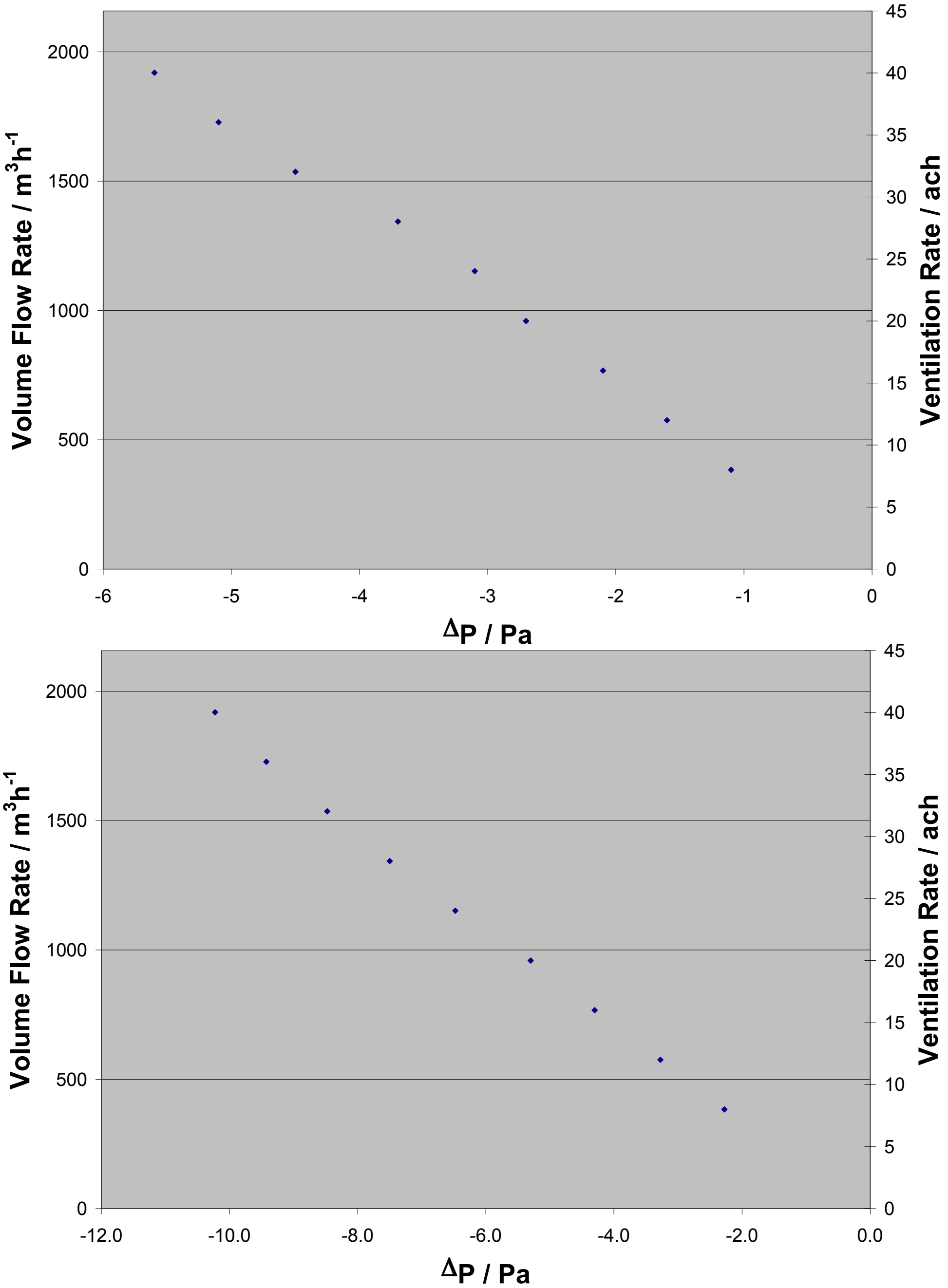

Figure 4.5 ΔP in Enclosure 1 at various volume flow rates/ventilation rates; ΔP is plotted on the x-axis to allow both volume flow rate and ventilation rate in air changes per hour to be shown, two airlocks open (top) and one airlock open (bottom).

__Table 4.5__ ΔP in Enclosure 1 at various ventilation rates with both airlocks open

Ventilation Rate ach	Volume Flow Rate m^3h^{-1}	ΔP 2 airlocks open Pa	ΔP 1 airlock open Pa
8	384	-1.1	-2.3
12	575	-1.6	-3.3
16	767	-2.1	-4.3
20	959	-2.7	-5.3
24	1152	-3.1	-6.5
28	1344	-3.7	-7.5
32	1536	-4.5	-8.5
36	1728	-5.1	-9.4
40	1920	-5.6	-10.2

The pressure was measured at four separate positions in Enclosure 1 to determine whether or not ΔP varied with position. The full set of results is shown in full in Tables 4.6 and 4.7 below.

Table 4.6 *ΔP at four positions in Enclosure 1 at various ventilation rates with two airlocks open*

Test	Position	ΔP Pa	Mean ΔP Pa	Volume Flow Rate m3h-1	Ventilation Rate ach
1	1	-1			
2	2	-1.1			
3	3	-1.1			
4	4	-1.2	-1.1	384	7.1
5	1	-1.7			
6	2	-1.6			
7	3	-1.6			
8	4	-1.6	-1.6	575	10.6
9	1	-2.1			
10	2	-2.1			
11	3	-2.1			
12	4	-2.1	-2.1	767	14.2
13	1	-2.8			
14	2	-2.7			
15	3	-2.6			
16	4	-2.6	-2.7	959	17.8
17	1	-3.3			
18	2	-3.2			
19	3	-3.2			
20	4	-2.6	-3.1	1152	21.3
21	1	-2.8			
22	2	-2.9			
23	3	-2.8			
24	4	-2.7	-3.7	1344	24.9
25	1	-3.6			
26	2	-3.7			
27	3	-3.6			
28	4	-3.6	-4.5	1536	28.4
29	1	-5.2			
30	2	-5.2			
31	3	-5.1			
32	4	-4.9	-5.1	1728	32.0
33	1	-5.7			
34	2	-5.7			
35	3	-5.5			
36	4	-5.4	-5.6	1920	35.6

Table 4.7 *ΔP at four positions in Enclosure 1 at various ventilation rates with one airlock open*

Test	**Position**	**ΔP Pa**	**Mean ΔP Pa**	**Volume Flow Rate m^3h^{-1}**	**Ventilation Rate ach**
1	1	-10.5			
2	2	-10			
3	3	-10.2			
4	4	-10.2	-10.2	1920	7.1
5	1	-9.7			
6	2	-9.4			
7	3	-9.3			
8	4	-9.3	-9.4	1728	10.6
9	1	-8.6			
10	2	-8.4			
11	3	-8.5			
12	4	-8.4	-8.5	1536	14.2
13	1	-7.7			
14	2	-7.5			
15	3	-7.5			
16	4	-7.3	-7.5	1344	17.8
17	1	-6.6			
18	2	-6.6			
19	3	-6.4			
20	4	-6.3	-6.5	1152	21.3
21	1	-5.4			
22	2	-5.3			
23	3	-5.3			
24	4	-5.2	-5.3	959	24.9
25	1	-4.4			
26	2	-4.3			
27	3	-4.2			
28	4	-4.3	-4.3	767	28.4
29	1	-3.3			
30	2	-3.4			
31	3	-3.2			
32	4	-3.2	-3.3	575	32.0
33	1	-2.3			
34	2	-2.3			
35	3	-2.3	-2.3	384	35.6
36	4	-2.2			

4.3.2 Airlock and airlock door configurations

The differential pressure ΔP was measured with a single airlock in three configurations, A, B and C as shown in Figure 3.5 for Enclosure 1 ventilated at 8 ach and 40 ach, the results are shown below in Table 4.8.

Table 4.8 *ΔP in Enclosure 1 at two ventilation rates with one airlock in three configurations*

Airlock Arrangement	**Ventilation Rate Ach**	**ΔP Pa**
A	8	-2.3
A	40	-10.2
B	8	-2.5
B	40	-10.7
C	8	-2.4
C	40	-10.1

ΔP was measured with a single airlock with three different door openings, two rectangular and one oval with two open areas at 8 ach and 40 ach in Enclosure 1, the results are shown below in Table 4.9.

Table 4.9 *ΔP in Enclosure 1 at two ventilation rates with one airlock and three door-opening designs*

Door opening	**Ventilation Rate Ach**	**ΔP Pa**
A	8	-2.3
A	40	-10.2
B	8	-3.1
B	40	-11.2
C	8	-3.0
C	40	-11.0

4.3.3 Door deflection

The degree of deflection of the airlock doors was measured in Enclosure 1 at a variety of ventilation rates. Measurements were taken from the weight of the door to the vertical. The doors were the standard design and opening A was used, this was a rectangular opening with dimensions 0.7 m by 1.7 m, giving an open area of 1.19 m^2. The doors from the final airlock chamber into the enclosure were generally deflected to a lesser degree than the internal airlock doors; the results are shown below in Table 4.10.

Table 4.10 *Deflection of internal and final airlock doors in Enclosure 1 at a variety of ventilation rates*

Ventilation Rate ach	**Volume Flow Rate m^3h^{-1}**	**Two Airlocks Open**		**One Airlock Open**	
		Final Door m	**Internal Doors m**	**Final Door m**	**Internal Doors m**
8	384	0.10	0.10	0.11	0.20
12	575	0.11	0.17	0.15	0.29
16	767	0.13	0.20	0.18	0.36
20	959	0.15	0.22	0.22	0.44
24	1152	0.17	0.25	0.26	0.50
28	1344	0.19	0.28	0.30	0.58
32	1536	0.21	0.35	0.34	0.66
36	1728	0.23	0.36	0.37	0.71
40	1920	0.25	0.42	0.42	0.79

4.3.4 Additional inlet filters

Four inlet filters were installed in the wall of Enclosure 1. The ventilation rate was set at 37.5 ach (1800 m^3h^{-1}) and ΔP was measured at the four positions with and without non-return flaps fitted to the inside of the filters. The volume flow rate of air passing through each filter was measured with and without the non-return flap fitted to the inside of the filters. The results are shown in Table 4.11 below.

Table 4.11 *Volume flow rate through additional filters fitted to Enclosure 1 ventilated at 37.5 ach (1800 m^3h^{-1})*

Additional Filters	Non-return flaps	ΔP Pa	Filter No.	Volume flow rate per filter m^3h^{-1}	Total volume flow rate m^3h^{-1}
0	N/A	-9.6	-	-	-
1	N	-8.7	1	265	265
2	N	-7.9	1	239	474
			2	235	
3	N	-6.5	1	181	543
			2	219	
			3	143	
4	N	-5.6	1	197	691
			2	177	
			3	137	
			4	180	
0	N/A	-9.2	-	-	-
1	Y	-9.8	1	175	175
2	Y	-8.5	1	167	353
			2	186	
3	Y	-7.7	1	154	456
			2	172	
			3	130	
4	Y	-6.8	1	144	560
			2	158	
			3	103	
			4	155	

It is not known why the volume flow rate through individual filters varies; it may be due to differences in the filter construction such as density and thickness.

4.3.5 Effect of unplanned openings

A series of unplanned openings were introduced into the walls of Enclosure 1 at ventilation rates of 7.1 and 20 ach to measure the effect on ΔP. There were 8 unplanned openings; these are described in Table 4.12 below.

Table 4.12 *Unplanned opening used in Enclosure 1*

Opening	Description
Slit 1	Horizontal slit 0.45 m at ground level where wall meets floor
Slit 2	Horizontal slit 0.90 m at ground level where wall meets floor
Slit 3	Vertical slit 1m approximately 0.7 – 1.7 m from ground
Slit 4	Vertical slit 2 m approximately 0.2 – 2.2 m from ground
Slit 5	Horizontal slit 2 m at ground level where wall meets floor
Hole 1	Square hole 4 cm^2 (2 x 2 cm) approximately 0.5 m from ground
Hole 2	Square hole 25 cm^2 (5 x 5 cm) approximately 0.5 m from ground
Hole 3	Square hole 100 cm^2 (10 x 10 cm) approximately 0.5 m from ground

Enclosure 1 was ventilated at either 20 or 8 ach and then ΔP was measured when the unplanned openings were introduced into the enclosure walls, the results are shown below in Table 4.13.

Table 4.13 *ΔP in Enclosure 1 when unplanned openings are introduced into the walls at two ventilation rates*

Test	Unplanned opening	Ventilation rate ach	ΔP Pa	Reduction of ΔP Pa
1	None	20	-4.6	-
2	None	8	-2.0	-
3	Slit 1	8	-1.9	0.1
4	Slit 1	20	-4.7	-0.1
5	Slit 2	20	-4.5	0.1
6	Hole 1	20	-4.5	0.1
7	Hole 2	20	-4.7	-0.1
8	Slit 3	20	-4.5	0.1
9	Slit 4	20	-3.4	1.2
10	Slit 5	20	-4.4	0.2
11	Hole 3	20	-4.2	0.4
12	None	20	-4.6	-
13	None	8	-2.0	-
14	Slit 4	8	-1.5	0.5

When challenged with tracer gas and the exhaust of a vacuum cleaner, the containment of the enclosure was compromised by the presence of unplanned openings in the enclosure walls. Table 4.14 below shows the concentration of tracer gas measured at a position 300 mm outside of the enclosure from the site of the unplanned openings (see Figure 3.5). The limit of detection (L.O.D.) of the analyser was 0.01 ppm.

Table 4.14 *Maximum concentration of tracer gas detected 300 mm outside of the enclosure wall from unplanned openings at a ventilation rate of 20 ach*

Unplanned Opening	Maximum [SF_6] ppm
Slit 1	0.21
Slit 2	0.08
Slit 3	10.18
Slit 4	9.76
Slit 5	0.65
Hole 1	< L.O.D.
Hole 2	9.87
Hole 3	11.19

4.3.6 NPU Airflow

The volume flow rate of a hired NPU 1500 was measured using a flow grid connected to a micromanometer. The effect upon the volume flow rate of adding lengths of flexible ducting and 90° bends was measured. The results are shown below in Table 4.15. These measurements were made with the NPU freestanding, i.e. not fitted to an enclosure. The test certificate supplied with the unit is shown in Figure A1 in Appendix A.

Table 4.15 *Volume flow rate of hired NPU and effects of adding flexible ducting*

NPU Arrangement	Volume flow rate m^3h^{-1}	Reduction %
As found	1565	0
6 m added to NPU exhaust	1472	6
12 m added to NPU exhaust	1384	12
12 m + 90° bend added to NPU exhaust	1340	14
12 m + 2 x 90° bends added to NPU exhaust	1293	17
6 m added to NPU exhaust + 6 m added to NPU inlet	1411	10
6 m added to NPU inlet	1500	4
12 m added to NPU inlet	1433	8
12 m + 90° bend added to NPU inlet	1410	10
12 m + 2 x 90° bends added to NPU inlet	1383	12

4.4 ENCLOSURE 3 – CEILING TILE REPLACEMENT

4.4.1 Unsealed Void

Experiments were carried out by removing a single tile from the ceiling and performing a simulated vacuuming exercise (simulation of vacuuming without the vacuum cleaner present) around the rim of the open space. For this exercise the operator would stand on the scaffold platform, shown in Figure 3.10, p.11, with their head and shoulders above the level of the roof and would then simulate the motions of vacuuming any dust and debris from the frame surrounding the removed tile. The results of the tracer gas measurements and differential pressure measurements are shown below in Table 4.16.

Table 4.16 *Tracer gas and differential pressure results for removing a single tile from Enclosure 3 with an unsealed void as shown in Figure 3.10 on p.10*

Ventilation rate ach	Sample position	Mean[1] [SF_6] ppm	Max[2] [SF_6] ppm	ΔP Before Pa	ΔP After Pa
8	1	2.7	11.2	-1.4	-0.1
8	2	1.0	6.3	-1.5	0.0
12	1	0.23	1.21	-1.8	-0.1
16	1	0.04	0.19	-2.2	-0.1
20	1	0.01	0.15	-2.9	-0.1
20	2	<L.O.D.	0.20	-3.0	-0.3

An example of the tracer gas concentrations are shown below in Figure 4.6, this shows tracer gas concentration at the external sample position 1 and the internal sample position 3.

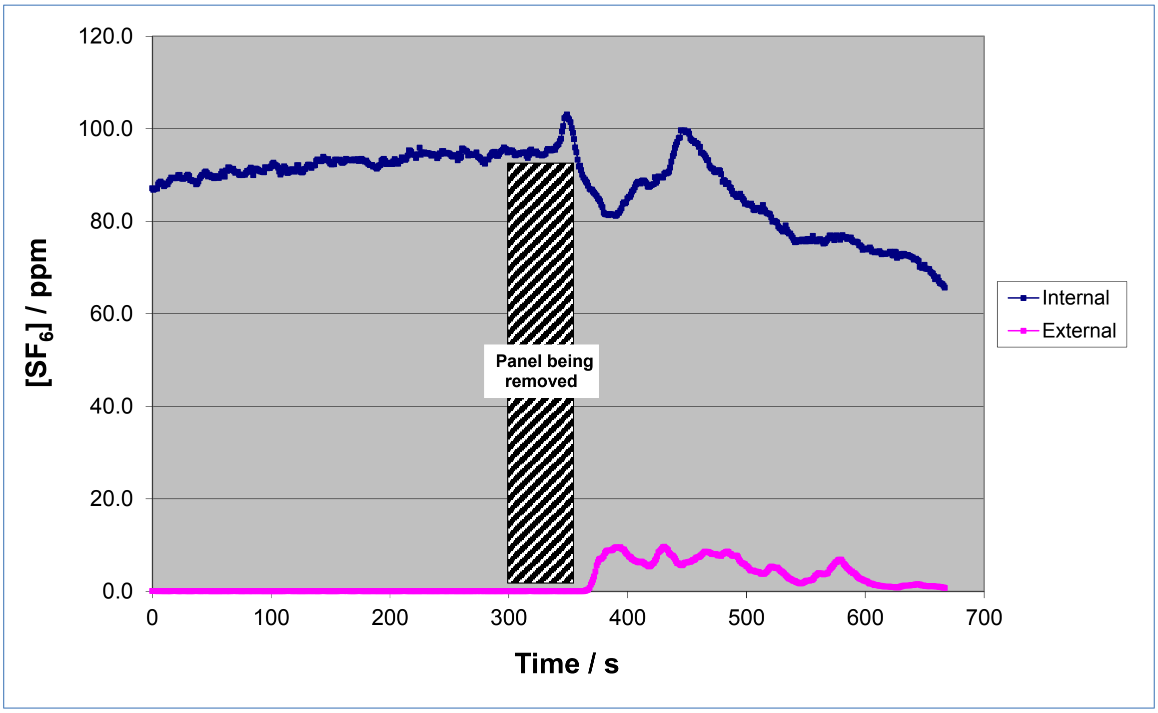

Figure 4.6 Tracer gas concentrations at sample positions 1 (external) and 3 (internal) at a ventilation rate of 8 ach with an unsealed void

To study the effects that an operational vacuum cleaner would on leakage from the enclosure a set of experiments was performed using a Class-H vacuum cleaner positioned on the scaffold tower when the tile had been removed. Vacuuming was carried out whilst air was sampled from position 1 and analysed for tracer gas. The results are shown below in Table 4.17.

---

[1] *Mean concentration of tracer gas at external sample position between removal of tile at t = 300 s and end of test at t = 660 s. Sample frequency 1 Hz*

[2] *Maximum recorded concentration of tracer gas at external sample position between removal of tile at t = 300 s and end of test at t = 660 s. Sample frequency 1 Hz*

Table 4.17 *Tracer gas concentrations at sample position 1 with a Class-H vacuum cleaner positioned on the scaffold tower with an unsealed void.*

Ventilation rate ach	Mean [SF_6] ppm	Maximum [SF_6] ppm
8	1.65	7.44
12	0.43	0.83
16	0.06	0.14
20	0.05	0.26

4.4.2 Sealed Void

Experiments were carried out removing a single tile from the ceiling and performing a simulated vacuuming exercise around the rim of the open space (no vacuum cleaner present). The results of the tracer gas and differential pressure measurements are shown below in Table 4.18.

Table 4.18 *Tracer gas and differential pressure results for removing a single tile from Enclosure 2 with a sealed void*

Ventilation rate ach	Mean[3] [SF_6] ppm	Max[4] [SF_6] Ppm	ΔP Before Pa	ΔP After Pa
8	1.19	1.66	-1.3	-0.9
20	0.80	1.50	-2.7	-2.3

[3] *Mean concentration of tracer gas at external sample position between removal of tile at t = 300 s and end of test at t = 660 s.*
[4] *Maximum concentration of tracer gas at external sample position between removal of tile at t = 300 s and end of test at t = 660 s.*

5. DISCUSSION

5.1 AIR MOVEMENT AND DEGREE OF MIXING WITHIN ENCLOSURES

The concentration decay plots shown in Figure 4.1 on p.15 shows that at 8 ach in Enclosure 1 the air was poorly mixed vertically. This is shown by the rate of decay of concentration of the tracer gas at the two high level positions 3 and 5 being slower than the other three. Position 3 was consistently the poorest mixed position; this was at high level next to the airlock door. Position 1, located at the centre of the enclosure, was generally well mixed along with the two low level positions, 2 and 4.

The two low level positions were well mixed horizontally at all extraction positions including NPU position 2, which was directly next to one of the airlocks. Increasing the height of the extract position, NPU position 4, did not improve mixing significantly. With the extract at NPU position 4 the two low level and central sampling positions were better mixed than for the high level positions and tracer gas was cleared from the two high level positions at a slightly higher rate than for the other three NPU positions. The results presented in Table 4.1 and Figure 4.1 support the conclusion that the air in Enclosure 1 was poorly mixed at a ventilation rate of 8 ach. The ratio of the mean decay constant at the five sample positions to the decay constant for a perfectly mixed atmosphere at 8 ach for NPU positions 1 – 4 with both airlocks open were 77 %, 73 %, 60 % and 144 % respectively: if the air in the enclosure were well mixed this ratio would be 100 %.

The mixing experiments were repeated in Enclosure 1 at 8 ach with only one airlock open, as sometimes occurs, at extract positions NPU 1 – 3, the data is presented in Figure 4.1 and Table 4.2. The same vertical inhomogeneity is shown with the concentration of tracer gas at the two high level positions decreasing at the slowest rate and a more marked difference between the central position at 1.5 m from the floor from the two low level positions. Results with only one airlock also show a greater difference between horizontal positions with little difference between NPU positions. However the overall degree of mixing is similar to that with both airlocks open. The ratio of the mean decay constant at the five sample positions to the decay constant for a perfectly mixed atmosphere at 8 ach for NPU positions 1 – 3 were 77 %, 73 % and 61 % respectively virtually identical to the results with two airlocks open.

The concentration decay of tracer gas was measured at the five positions in Enclosure 1 ventilated at 19.2 ach (equivalent to approximately 900 m^3h^{-1} or 530 cfm) with one and two airlocks open, with the extraction at NPU position 1. The results are shown in Table 4.3 in Section 4 and Figure 4.2 on p16. The ratio of the mean decay constant at the five test positions to the decay constant for a perfectly mixed atmosphere at 8 ach for one and two airlocks open were 99 % and 101 % respectively. This and the traces shown in Figure 4.2 show that at the higher ventilation rate of 19.2 ach the air inside the enclosure had a much higher degree of mixing than at 8 ach.

The extended test at the high level position 5 showed that it would take over three hours to reduce the concentration of an airborne contaminant to less than 10 % of its starting value once emission had ceased. This is important because with a fully mixed atmosphere at a ventilation rate of 8 ach the concentration should have decreased to less than 10 % of the initial value after approximately 17.3 minutes and to less than 0.1 % after approximately 1 hour. If the ventilation were allowed to run on for only 1 hour after work was complete in Enclosure 1 there could still be significant concentrations of airborne fibres present.

The degree of mixing in Enclosure 2 was investigated using two extraction positions. NPU position 1 was at what would be considered to be the ideal position with the maximum separation between the NPU and the airlock and NPU position 2 was what would be considered the worst position with the NPU located adjacent to the airlock inlet. The results presented in Table 4.4 and the concentration decay plots in Figure 4.4 show that at the lower ventilation rate of 8 ach the air is well mixed in Enclosure 2, even with the extraction located at what would be considered the unfavourable position 2. The ratios of the mean decay constant at the eight sample positions to the decay constant for a perfectly mixed atmosphere are interesting. They suggest that there is some short circuiting with the extraction at the good position and the lower volume flow rate but not at the higher volume flow rate. But, with the extraction at the poor position there is some short circuiting at the higher volume flow rate but not at the lower. Another way of comparing the degree of mixing is to use the ratio of the standard deviation of the decay constants at the measurement positions to the mean decay constant. This data gives information on the uniformity within the enclosure or the spread of the decay constants and shows that at the higher volume flow rate this ratio is approximately 2 % for both extraction positions and at the lower extraction rate 5 % and 9 % for positions 1 and 2 respectively. This suggests that in larger enclosures with more complex geometry as well as the importance of a high volume flow rate the position of the NPU is important, every effort should be made to site the extraction point in a good position. This is borne out by the fact that the best mixed atmosphere by both measures was at the high volume flow rate with the NPU located in the best position.

In these enclosures the replacement air enters through the airlock at low level and the NPU is typically sited at low level, which is a likely explanation for the lack of vertical mixing observed at low volume flow rates. These results indicate that the most important factor when considering the degree of mixing within an enclosure is the total volume flow rate of air rather than the air change rate. At higher volume flow rates the turbulence created by the movement of air into the enclosure is likely to promote the observed higher degree of mixing.

Smoke was used to visualise air movements within enclosure 1 and to demonstrate the time taken by the ventilation to clear contaminants from the air. A commonly held misconception is that a ventilation rate of 8 ach means that all of the air will be exchanged and all of the airborne contaminants will be cleared in 1/8 of an hour or 7.5 minutes. In practice because the air movement through the enclosure is not plug flow but dilution, the concentration of airborne contaminants would decrease exponentially, assuming that the air is perfectly mixed. This means that after one air change, or 7.5 minutes, the concentration of an airborne contaminant would be reduced to 1/e or approximately 37 % of the initial concentration and after 2 air changes the concentration would be $1/e^2$ or approximately 13 %. To reduce the initial concentration to less than 1 % would require 5 air changes and to reduce it to less than 0.1 % would require 7 air changes or approximately 1 hour assuming perfect mixing. The experiments determining the degree of mixing within Enclosure 1 showed that the air was poorly mixed vertically and that the effective air change rate at high level was considerably less than 8 ach. This was borne out in the smoke tests, Figure 5.1 below shows four screenshots from a smoke test in Enclosure 1 ventilated at 8 ach. The first photo at top left was taken just as the injection of smoke began for comparison; the second photo at top right is a time zero when the ventilation was activated. The third photo at bottom left was taken after 1 air change or 8.4 minutes; this shows that a considerable quantity of smoke is still visible. The final photograph taken after 20 minutes and 2.4 air changes showed that smoke was still visible, especially at high level, which was consistent with the results of the mixing experiments.

Figure 5.2 shows screenshots from a smoke test in Enclosure 1 ventilated at 20 ach. The first photo on the left was taken 200 s after the ventilation was activated or after 1 air change, the quantity of smoke visible is comparable to that after 1 air change at 8 ach. Likewise the photo on the right is after 2.4 air changes (the same as the photo at bottom right of Figure 5.1) and again there is a similar quantity of smoke visible. When considering the clearance time of an enclosure both the air change rate and degree of mixing should be considered. If the air is well mixed the clearance time of an enclosure will depend upon the air change rate regardless of volume. If the air is not well mixed, which has been shown to occur when the volume flow rate is less than 500 m^3h^{-1}, stratification or the creation of ventilation dead spots can occur which will have the effect of increasing the clearance time.

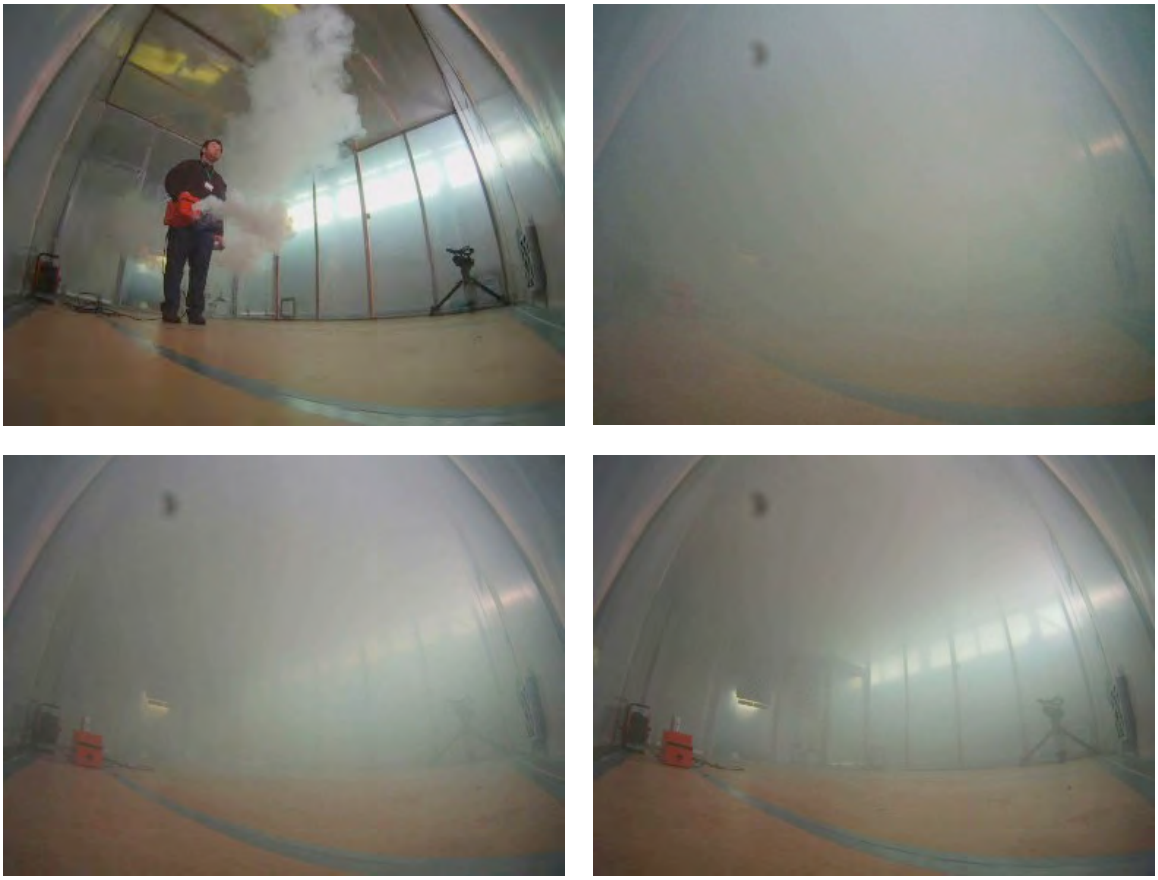

Figure 5.1 Screenshots of smoke test in Enclosure 1 ventilated at 8 ach, t = -60 s (top left), ventilation activated at t = 0 s (top right), after 1 air change t = 507 s (bottom left) and after 20 minutes or 2.4 air changes t = 1200 s (bottom right).

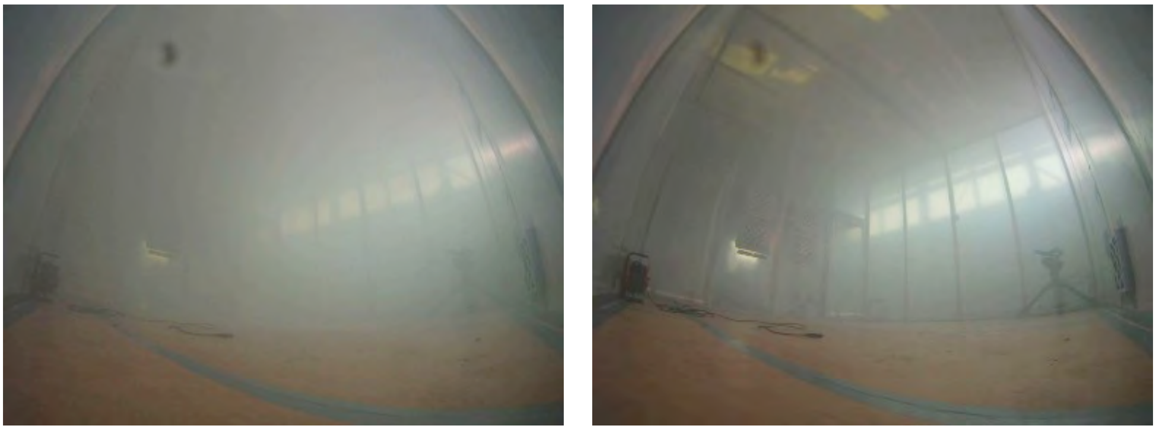

Figure 5.2 Screenshots of smoke test in Enclosure 1 ventilated at 20 ach, after 1 air change t = 200 s (left) and after 2.4 air changes t = 472 s (right).

5.2 ΔP AND THE FACTORS AFFECTING CONTAINMENT POTENTIAL OF ENCLOSURES

5.2.1 Volume Flow Rate

An important parameter used to assess the containment potential of an enclosure is the differential pressure between the enclosure and atmosphere or ΔP. The results of the ΔP measurements in Enclosure 1 are presented in summary in Table 4.5 in Section 4 and in full in Tables 4.6 and 4.7 on pages 20 and 21. For all ventilation rates with one and two airlocks open, except one, the standard deviation of ΔP measured at the four positions was 0.2 Pa or less, noting that the resolution of the manometer used to measure the pressure was 0.1 Pa. Similar results were found for Enclosure 3 as well. This indicates that pressure was essentially homogeneous throughout the enclosures and therefore for enclosures with simple shapes ΔP can be measured at any position. However it would still be sensible to avoid positioning the ΔP measurement position too close to the extraction point or airlock inlets unless necessary.

As a comparison to this variation, several ΔP measurements were repeated at different times of day in Enclosure 1 when the ambient temperature had changed. When measured early in the morning when the ambient temperature was the lowest, ΔP was found to be lower than when measured at higher temperatures in the mid afternoon by between 0.5 and 1.1 Pa for the same ventilation rate. This is not unexpected as the pressure of a gas is directly proportional to the temperature but nevertheless this became important when considering the variation of ΔP caused by various design parameters of the enclosure. The results clearly showed that the relationship between ventilation rate and ΔP was directly proportional over the range of ventilation rates investigated excluding the effect of ambient temperature. The ΔP results for one and two airlocks open showed that whilst the relationship between the open area of inlets was not directly proportional, it was close to linear (1:1) with ΔP for one airlock open, and was approximately 1.9 times ΔP with two airlocks open. Despite this correlation there are too many other factors that can affect ΔP that it cannot be considered a reliable indicator of air change rate.

Another factor to consider when planning the volume flow rate for an enclosure is to check which units are used to define the volume flow rate of a hired NPU. During the course of the project two NPUs were hired from the same company, the test certificates supplied with the units are shown in Figures A1 and A2 in Appendix A. Both units were identified as an NPU 1500 however the certificates show that one had an operating volume flow rate of 1580 m^3h^{-1} (~930 cfm) and the other had a volume flow rate of 2560 m^2h^{-1} (1510 cfm). This was clearly shown on the test certificate but not in the company's brochure, thus operators should be clear on the units of the volume flow rate of the NPUs they intend to use.

5.2.2 Airlock configuration and door design

Differential pressure in Enclosure 1 was measured with three different configurations of a single three-stage airlock: linear, L-shaped with a single 90° bend and L-shaped with two 90° bends. The results presented in Table 4.8 showed no significant difference between any of the three with a maximum variation at 8 ach of 0.2 Pa and at 40 ach of 0.6 Pa. Considering the fact that the enclosures and airlocks are constructed and then sealed by hand this was not considered significant.

The design of the airlock doors was investigated by measuring ΔP in Enclosure 1 at two ventilation rates with three different door designs. A and B were rectangular with the overlap between the door and the airlock wall being greater for B than A, the area of the openings were 1.19 m^2 for A and 0.85 m^2 for B and the doors themselves were identical. C had an oval opening with approximately the same open area as B. The results presented in Table 4.9 showed no significant difference between B and C indicating that the shape of the opening was not an important factor at the flow rates studied. The results for A and B showed a difference of 0.8 Pa at 8 ach and 1.0 Pa at 40 ach although this difference could have been caused by the increased overlap of the door or the difference in open area. A series of tests also showed that increasing the weight at the bottom of the door increased ΔP. These factors are discussed further in the following sections.

5.2.3 Airlock door deflection and additional inlet filters

As air passed through the airlock it caused the doors to deflect inwards. This deflection was measured in Enclosure 1 for a range of ventilation rates from 8 to 40 ach, and these results are presented in Table 4.10. The relationship between the degree of door deflection and ventilation rate was linear. The final door from the inner stage of the airlock into the enclosure was found to deflect approximately half as much as the internal doors. When only one airlock was open the internal doors were found to deflect by approximately 0.8 m at a volume flow rate of 1920 m^3h^{-1} (40 ach). In an airlock chamber measuring 1 m^2 this would make it next to impossible to carry out any task within the airlock such as decontamination of personnel without touching the chamber walls. Whilst this is not likely to be an issue in the smaller enclosures investigated in this study, in much larger enclosures, where the extraction volume flow rates would be higher and similar higher ventilation rates described here, problems are likely to occur.

There are several ways to reduce the airlock door deflection if this was deemed necessary. Previous results in this study have shown that increasing the size of the door opening and reducing the overlap of the door reduce the deflection however the degree to which this can be put into practice may be limited. An easier method would be to increase the weight of the door; this would also have the added effect of increasing ΔP.

Another method of reducing the deflection of the airlock doors would be to introduce some of the incoming air via another route. This could be achieved by adding inlet filters directly to the enclosure wall. Four pre-filters were positioned into the wall of Enclosure 1 ventilated at 36 ach.

It was found that each additional filter reduced ΔP by approximately 1 Pa and allowed between approximately 100 – 265 m^3h^{-1} of air to pass through each filter depending upon the number fitted. In this case adding four filters would reduce the internal airlock door deflection to approximately 0.5 m. However it should be noted that adding pre-filters to the walls in this manner would allow a potential pathway out of the enclosure. This pathway would not be HEPA filtered as the ventilation extract does not provide the same degree of containment as the more robust physical obstruction provided by the three-stage airlock. It should also be noted that the use of filters in this way would increase the number of seams that would need to be sealed and increase the number of potential failure points in enclosures. For these reasons their use should be carefully considered and alternative methods of reducing the airlock door deflection such as opening a second lock or increasing the door weights should considered.

It may be worth considering the use of the airlock doors as airflow indicators. For example, once the enclosure is constructed, the ventilation would be activated and the deflection of one of the airlock doors could be marked. As previously noted using the 'standard' door, approximately 0.9 m wide and 1.8 m long with an additional 1.8 m rolled up to act as the weight was displaced by approximately 0.5 m by a volume flow rate of 1000 m^3h^{-1}. The degree of deflection is affected by many factors such as door weight and overlap, opening size, DP as well as volume flow rate. A suitable method would be to mark the deflection when the enclosure is first constructed and NPU(s) activated and use this as a benchmark. This mark could be used as an indicator that could highlight any large breaches of the enclosure walls; this is demonstrated in Figure 5.3 below.

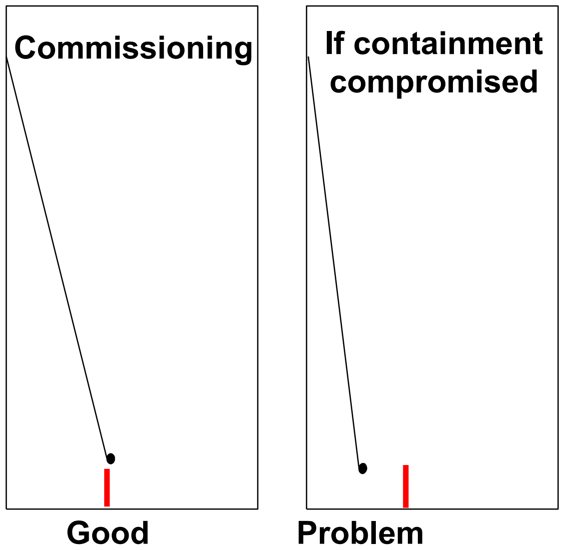

Figure 5.3 Use of the airlock doors as an airflow indicator

5.2.4 Unplanned openings

The effects of unplanned openings such as holes or slits unintentionally introduced into the enclosure walls were investigated by measuring the effect on ΔP and by using a tracer gas challenge. The results presented in Table 4.13 showed that only a 2 m vertical slit in the enclosure wall and a hole with an area of 100 cm^2 showed a measurable change in ΔP. Slit 4, a 2 m vertical cut extending from approximately 0.2 m to 2.2 m caused a decrease of ΔP from –4.6 Pa to –3.4 Pa at a ventilation rate of 20 ach and from –2.0 Pa to –1.5 Pa at 8 ach. Hole 3, a square hole measuring 10 cm by 10 cm caused a decrease of ΔP from –4.6 Pa to – 4.2 Pa at an air change rate of 20 ach. The largest change produced by any of the other unplanned openings was 0.2 Pa, and therefore none of these openings were considered significant, which was a relatively surprising result. Even 1 m and 2 m cuts at the join between the walls and the floor did not show a noticeable effect upon ΔP. The explanation for this may be that cuts along the bottom of the wall do not open up due to the tension of the polythene wall holding it in place. This would be supported by earlier results that showed that ΔP was proportional to the open area of inlets; if the cuts do not open up, they will not allow significant quantities of air to enter. Conversely the tension placed upon the walls by the negative pressure caused the large vertical cut to open up explaining the noticeable decrease of ΔP at both the higher and lower ventilation rates. The conclusion of these results is that ΔP is not a reliable indicator of enclosure integrity except for gross breaches in the walls. This is especially important along the seam of the wall and floor where it would be relatively easy for large openings to appear either by accident or through poor sealing. These sorts of unplanned openings should be relatively easy to identify at the construction stage using the smoke test described in HSE guidance HSG 247 [4] but harder to spot once the enclosure is in use. This highlights the importance of carrying out the daily checks of the enclosure's integrity to ensure that these types are breaches are resealed quickly.

The effect upon the containment potential of these sorts of unplanned openings on the enclosure was investigated by using a tracer gas challenge. SF_6 was released into the enclosure and mixed with the air to create a homogeneous concentration of approximately 100 ppm SF_6. With the ventilation running at a rate of 20 ach, the unplanned openings were introduced whilst the exhaust from a Class-H vacuum cleaner was directed toward the openings. Air was sampled from a position 300 mm outside of the enclosure at the site of the opening and analysed for the presence of tracer gas. The results presented in Table 4.14 showed that for the two vertical slits (1 m and 2 m) and the two larger holes (25 cm^2 and 100 cm^2) significant concentrations of tracer gas, from 9.76 – 11.19 ppm, were detected outside of the enclosure. For the three horizontal slits of 0.45 m, 0.90 m and 2 m concentrations of 0.21, 0.08 and 0.65 ppm respectively were detected. Whilst these latter concentrations are not high, all represent less than 1 % of the concentration inside the enclosure; they are significantly higher than the limit of detection of the instrument. The results demonstrate that it was possible for contaminated air to escape from the enclosure if the exhaust jet of a vacuum cleaner impinged upon or close to an unplanned opening. This is a real risk as these vacuum cleaners are routinely used within enclosures.

It should be noted that these results demonstrate that monitoring ΔP alone is not a reliable indicator of enclosure integrity and that it is possible for significant holes or gaps to appear in the enclosure walls without a significant decrease in ΔP. The experiments were repeated without the use of the vacuum cleaner and no tracer gas was detected outside of the enclosure for any of the unplanned openings. This indicates that unless an energetic jet such as a vacuum cleaner exhaust is near to an unplanned opening, the negative pressure induced by the ventilation is sufficient to maintain containment integrity.

5.3 CEILING TILE REPLACEMENT

5.3.1 Unsealed void

Experiments removing a ceiling tile where the volume of the void is much larger than the volume of the enclosure showed that at 8, 12 and 16 ach tracer gas was detected outside of the enclosure; the results are presented in Table 4.16. At 20 ach the mean concentration of tracer gas over the period of the test, approximately 6 minutes including removal of the tile and a simulated vacuuming task around the edges of the frame, were at or close to the limit of detection of the gas analyser (0.01 ppm). However, peak concentrations of greater than ten times the L.O.D. were detected which would seem to indicate that removal of the tile allowed contaminated air to exit the enclosure which could potentially lead to contamination of the ceiling void and surrounding areas.

Screen shots of a smoke test during removal of a ceiling tile at a ventilation rate of 20 ach are shown below in Figure 5.4 and support the above statement. Similar results were observed at lower ventilation rates with greater volumes of smoke observed leaving the enclosure.

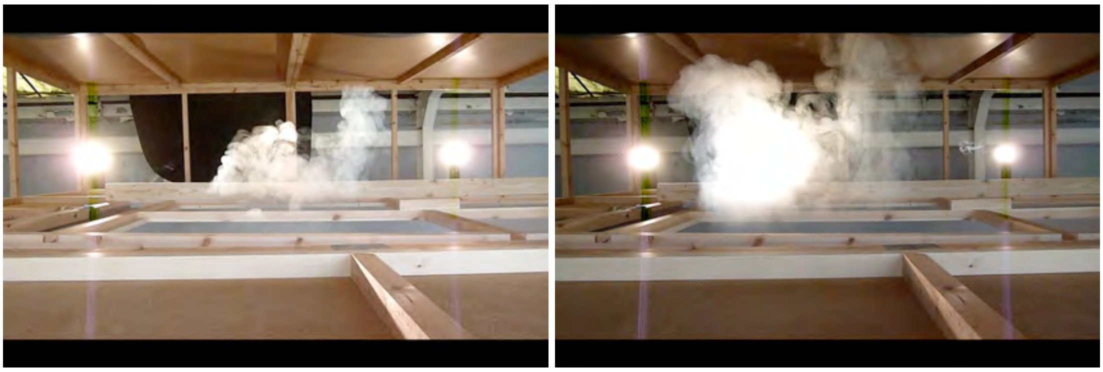

Figure 5.4 Screenshots from video showing removal of a ceiling tile in an unsealed ceiling void at a ventilation rate of 16.4 ach

With an unsealed void removing the ceiling tile resulted in ΔP falling to zero and the airlock door deflection also falling to zero. This indicated that all of the air being extracted from the enclosure was entering the enclosure through the gap left by the removed ceiling tile. Results of experiments using tracer gas and a Class-H vacuum cleaner on the scaffold tower presented in Table 4.17 showed that at all ventilation rates significant concentrations of tracer gas were detected in the void outside of the enclosure.

5.3.2 Sealed void

Removing a ceiling tile when the void was sealed and the volume of the void was less than the volume of the enclosure showed that with respect to the void, containment was less compromised; these results are presented in Table 4.18. At 20 ach, a significant concentration of tracer gas was detected in the void. However, ΔP did not decrease to zero but decreased from –2.7 Pa to –2.3 Pa and the airlock door deflection did not change. This indicated that the integrity of the enclosure was not compromised but that the ceiling void itself had become part of the enclosure. Figure 5.5 below shows screen shots from a video showing tile removal at 16.4 ach. This video showed that smoke from inside the enclosure slowly filled the void. Similar results were obtained at the lower ventilation rate of 8 ach.

Figure 5.5 Screen shots from a video showing ceiling tile removal from a sealed void at a ventilation rate of 8 ach, 10 s after tile removal (left) and 3 minutes after tile removal (right)

This work showed that for sealed voids removing ceiling tiles incorporates the volume of the void into the enclosure allowing mixing of the air between the two spaces. When the tile is removed there is an initial movement of air from the void into the enclosure but once the pressures have equalised they essentially become the same space. This means that any contamination within the enclosure can potentially spread into the void and the void will need to be decontaminated after work is complete.

6. CONCLUSIONS

6.1 VOLUME FLOW RATE AND VENTILATION RATE

- Volume flow rates of less than 500 m^3h^{-1} produce poorly mixed atmospheres regardless of other factors.
- This inhomogeneity can lead to poorly mixed areas at high level within enclosures, at 8 ach in Enclosure 1 the effective ventilation rate at the high level positions was less than 10 % of the calculated rate, this can have important implications when calculating how long to allow the ventilation to run on after work is completed to remove any airborne fibres.
- Volume flow rate is the important factor not air change rate, 8 ach per hour produced poor mixing in Enclosure 1 but good mixing in Enclosure 2.
- The position of NPU has some effect on mixing but volume flow rate is more important, NPU position is more important in irregularly shaped enclosures.
- Smoke visualisation highlighted the poor mixing within Enclosure 1 and demonstrated that ventilation can take longer than is commonly assumed to clear airborne contaminants.

The important parts of these findings are that low volume flow rates lead to poorly mixed atmospheres. This is likely only to be an issue in smaller enclosures as operators in practice use NPUs to provide air movement and these devices do not have adjustable volume flow rates. One of the most commonly used sizes of NPU is the 1500; this can be either 1500 cfm or 1500 m^3h^{-1} both of which would produce a well-mixed atmosphere in Enclosure 1. It is an issue that is worth consideration, however, as if it were to occur it could lead to unintentional spread of contamination if the air inside an enclosure were not fully cleared before it was dismantled. This would have the dual effect of identifying any potential areas of poor mixing within the enclosure and demonstrating how long it will take to clear any airborne fibres from the air at the end of the day or upon completion of work.

Although the position of the NPU was not found to be a major factor in either Enclosure 1 or 3 it should still be positioned in the 'best' location to promote good mixing, as the enclosures assessed were relatively simple shapes. However it should be noted that a large volume flow rate is more important in achieving a well-mixed atmosphere than NPU position. The smoke visualisation was very informative in regards that it demonstrated the fallacy of the common belief that n ach means that smoke will be cleared in $1/n$ hours by showing that it can take 4 – 5 air changes before the air is cleared.

6.2 CONTAINMENT POTENTIAL

- For standard airlock chambers, volume flow rates in excess of 1900 m^3h^{-1} cause the airlock doors to impinge on the far side of the chamber; this could make it difficult to work inside the airlock chamber.
- ΔP is proportional to volume flow rate and the open area of the airlock inlet doors.
- ΔP can change by up to 1 Pa with changes in ambient temperature.
- The shape of the airlock door openings or the arrangement of the airlock chambers does not have a significant effect upon ΔP.

- Only large slits in the enclosure walls and holes with areas of at least 100 cm^2 caused a detectable decrease in ΔP.

- Unplanned openings that could allow contaminated air to escape the enclosure are possible with no significant decrease of ΔP. However, no breaches of containment were found from unplanned openings unless artificial air movements such as the exhaust of a Class-H vacuum cleaner were positioned nearby inside the enclosure.

- ΔP may not be a reliable indicator of containment integrity: the position of the airlock chamber doors may be more suitable indicator.

- The addition of flexible ducting with 90° bends to NPUs reduced the volume flow rate by approximately 1 % per metre of duct and 2 % per bend for the ducting tested; potential reductions in volume flow rate caused by lengths of ducting should be taken into account when calculating ventilation rates.

6.3 CEILING TILE REPLACEMENT

- Removal of ceiling tiles in enclosures where the volume of the void was much larger than the enclosure caused ΔP to fall to zero and allowed contaminated air to exit the enclosure potentially contaminating the surrounding areas.

- Removal of ceiling tiles in the test enclosure where the volume of the void was less than or similar to the enclosure equalised the pressure between the two spaces allowing the air to mix freely, tests showed that contaminated air spread from the enclosure into the ceiling void.

These results were interesting and should be considered, especially in cases where the void is small compared to the enclosure. The results have shown that once the tile is removed the void becomes part of the enclosure and contaminated air can move freely between the spaces. This means that upon completion of the work the whole void should be considered to be contaminated and be cleaned.

7. REFERENCES

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8. APPENDIX A

[redacted]

TEST CERTIFICATE

EQUIPMENT DETAILS

CUSTOMER: [redacted]

TEST DATE: 28/05/2012

MODEL: NPU1500

MANUFACTURER: [redacted]

VOLTAGE: 110

CERTIFICATE NUMBER: NID/2263

RE-TEST DATE: 27/11/2012

SERIAL NUMBER: 7437

MANUFACTURE DATE: -

CURRENT: 16

PAT TEST

TEST EQUIPMENT: SEAWARD PAT

VISUAL CHECKS: PASS

EARTH BOND: PASS

INSULATION: PASS

SERIAL NUMBER: SN27A-0163

LEAKAGE: PASS

LOAD: PASS

RESULT: PASS

DOP TEST

TEST EQUIPMENT: ATI Photometer TDA-2G

AEROSOL: ODINA OIL

PENETRATION (%)

SERIAL NUMBER: ATIS/N20808

RESULT: PASS

AIRFLOW

TEST INSTRUMENT: ATI HOTWIRE

ACTUAL AIRFLOW CFM: 929

SERIAL NUMBER: S/NTA4300933006

UNIT RATING: (m3/h) 1581

RESULT: 0.0027

Note: Actual airflow results must be within 20% of the units airflow rating

TESTED BY: [redacted]

SIGNED:

THIS MACHINE MUST BE RE-TESTED:

1 EVERY 6 MONTHS

2 AFTER CHANGING HEPA FILTER

3 AFTER ANY DAMAGE

4 IF THE UNIT HAS BEEN DROPPED

We hereby certify that the tests carried out are in accordance with current guidelines for Filt[redacted] and PAT testing. The results are recorded at the time of the test.

Figure A1 Test certificate for NPU 1500 used in trials. NB. Flow rate as measured by the hire company; 1581 m^3h^{-1} (929 cfm).

[redacted]

ACAD

arca

[redacted]

TEST CERTIFICATE

Customer: [redacted]
Address:

Certificate No: MAN/06931
Test Date: 11/03/2011
Re-Test Date: 11/09/2011

Model:		NPU 1500		**Serial Number:**	5575
Manufacturer:		SMH		**Year of Manufacture:**	N/K
Voltage:	110V	**Current:**	14AMP	**Motor Power:**	50HZ
Measured Airflow		2560.65 M3/HR			

ELECTRICAL TEST

Tested:	YES	**Result:**	PASS

DOP TEST

Particle:	ODINA EL OIL	**Test Machine:**	TDA- 2H S/N 13870
Tested:	YES	**Result:**	0.0010

Tested By: [redacted] **Name:**

This machine should be re-tested:

1. Every 6 Months
2. After changing the Hepa Filter
3. After any damage
4. If the unit has been dropped

THIS UNIT CONFORMS TO BS 8520-2:2009

[redacted]

[redacted]

Figure A2 Test certificate for first NPU 1500 hired, NB. Flow rate as measured by hire company; 2561 m^3h^{-1} (1507 cfm)

Published by the Health and Safety Executive 09/13

HSE

Health and Safety Executive

Ventilation of enclosures for removal of asbestos containing materials

When removal of high-risk asbestos-containing materials takes place, the work should be carried out inside a specially constructed ventilated enclosure to prevent the spread of asbestos outside the work area. The aim of this research project was to investigate the factors that affect the containment potential of temporary ventilated enclosures. The work covered; the way that air moves within ventilated enclosures, how the construction of enclosures and airlocks affects air movement and containment, and how the positioning of extraction points and air inlets affect air movement and containment. Work was done to investigate the relationship between air flow and negative pressure, and containment. The study also examined factors which affect the ability of enclosures to contain asbestos, such as unplanned openings. In addition to this the effect of removing ceiling tiles and the size of ceiling void relative to the enclosure was investigated.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

RR988

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