HSE	**FIELD OPERATIONS DIRECTORATE** **OCCUPATIONAL HYGIENE SPECIALIST GROUP**	**REPORT**

ASBESTOS ENCLOSURE VENTILATION RESEARCH

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REPORT BACKGROUND AND SUMMARY

Background

1. HSL research work carried out in 2012/13 investigated the airflow characteristics of ventilated asbestos enclosures and the factors which affect their containment potential, in order to provide the information and data on which new ventilation guidance would be based. A revised ventilation rate for asbestos enclosures was subsequently introduced in December 2013 in the asbestos Approved Code of Practice (ACOP)(L143 Second Edition)(Reference 1).

2. Subsequently some concern was raised by industry regarding the implications of moving to a standard volume flow ventilation rate particularly regarding the stability of very small enclosures and the potential effect on airlock door flap displacement. The research and this report aim to clarify a number of issues raised by industry, regarding the impact of the new ventilation standard introduced in the ACOP. The report also aims to provide further information on the supply, management and measurement of airflow within asbestos enclosures in order to ensure a better understanding of the factors which influence airflow and containment.

Summary

3. This report summarises the results of the further research into the ventilation of asbestos enclosures. The study was carried out by Plant, Audits and Training (PAT), and overseen by HSE, in early 2014.

4. The conclusions of the report are as follows:

(i) For standard timber/polythene asbestos enclosures (see paragraph 3.2), negative pressure (NP) within the enclosure, and airlock door flap displacement are directly proportional to the air extraction rate. Door flap deflection can be used as a practical means to confirm the air extraction rate and the extent of NP within the enclosure.

(ii) An air extraction rate of 1000m^3/hr will produce a differential pressure of about -5Pa and a door flap deflection of between 200-250mm in the middle airlock sections. These conditions were created in all enclosures tested irrespective of enclosure size.

(iii) A door flap deflection of 200-250mm can be used as a key indicator of achieving the stated extraction volume for enclosures <120m^3.

(iv) The research has shown that standard enclosures and airlocks are sufficiently robust, strong and stable to withstand the air extraction rate (1000m^3/hr) stated in the new ACOP and significantly higher air flows. An air extraction rate of 1000m^3/hr has no adverse effects on the stability and integrity of very small enclosures (eg 6m^3).

(v) Sufficient airlock space is required to enable asbestos operatives to carry out transiting and decontamination procedures (ie cleaning footwear and RPE, and removing/donning transit coveralls and footwear). There should be sufficient working space with door flap deflection in a 3-stage airlock up to a volume flow of about 1500m^3/hr. Where larger volume flows are employed, then additional simple actions will be required to ensure sufficient space: the actions will include doubling the airlock door flap weight and opening up the second airlock (ie baglock) (more details are given in the report).

(vi) At very high flow rates eg about $4000m^3/hr$ or above, make-up air should be provided by the use of single stage airlocks ("cubes"). Further cubes will also be required for each additional $4000m^3/hr$ air extracted.

(vii) The desired minimum volume flow ($1000m^3/hr$) can be achieved by using a combination of negative pressure units (NPUs) eg 2 x "500s".

(viii) The research has shown that variable speed controls fitted on NPUs enable much greater control over airflow. The devices will allow adjustment of airflow to take account of airflow losses (eg through the use of roving heads or filter loading) and to reduce "excessive" door flap displacement. Many NPUs are already supplied with these devices fitted. Variable speed controls can also be fitted retrospectively to existing NPUs.

(ix) Airflow rates of NPUs should be measured at the start of each job to confirm that the required airflow is achieved.

1 INTRODUCTION

1.1. Many hazardous substances require effective containment to prevent their spread and release outside the controlled work area. Containment is achieved by physical enclosure and by ensuring that the work area is placed at an adequate lower atmospheric pressure compared with ambient air. This differential pressure (ΔP) (also referred to as negative pressure (NP)) will ensure that air movement will be into the containment area. The NP and inward airflow is achieved by mechanically extracting air from the containment zone. The extraction ventilation is also necessary to remove any process or activity generated contaminants effectively and efficiently.

1.2. A pressure differential of -5Pascals (Pa) relative to ambient air is employed for control and containment of hazardous agents in other industry sectors (eg microbiological agents). This NP is also specified in guidance (Reference 2) for the control and containment of airborne fibres in the work zone where high risk asbestos removal takes place (ie licensed asbestos removal). The asbestos work is conducted within an “enclosure” which is usually a purpose built temporary structure, but can also be part of an existing building.

1.3. The Licensed Contractor’s guidance on asbestos containment also indicates that an air extraction rate equivalent to at least 8 air changes per hour (acph) should be applied to the enclosure (Reference 2). This standard of ventilation has evolved from empirical work (custom and practice) and experience and was an increase over the previous minimum suggested rate of 7 acph in the guidance published in 1989 and updated in 1999 (Reference 3).

1.4. Until recently, no research work had been conducted to compare or correlate the air change rate per hour with NP in an asbestos enclosure context. The extent of NP within a particular confined area (eg an enclosure) depends on the conditions and circumstances prevailing at the time (ie the context). The NP will depend primarily on the air extraction rate from the enclosure. However, the exact NP for a given mechanical extraction rate will also be dependent on various other parameters and factors including the resistance or impedance to flow of the “make-up” or supply air which replaces the mechanically extracted air. Therefore, for a fixed air extraction rate (eg 1000m^3/hr), the NP in the enclosure for example would depend on the number of airlocks, the size of the openings of the airlocks and the weight of the airlock door flaps.

1.5. The HSL research conducted in 2012/13 demonstrated that the air extraction rate is directly proportional to the NP (other items being equal/fixed) (Reference 4). In an asbestos enclosure context, the HSL research has shown that an air extraction rate of approximately 1000m^3/hr would be needed to create a NP of -5Pa with one airlock open (Reference 4, Section 4.3). The HSL research has also shown that low volume flow rates (ie <500 m^3/hr) lead to poorly mixed atmospheres within the enclosure with, consequently, ineffective removal of airborne contaminants eg 50% of airborne contaminant still remained after 1 hour with an extraction rate of 8 acph (ie 384m^3/hr) and 10% remained after 3 hours (Reference 4, Section 4.2). The extraction rate of 1000m^3/hr will generate a NP of about -5Pa as well as achieving good air mixing in the enclosure and ensuring efficient and effective removal of airborne contaminants (Reference 4, Section 4.2). The HSL research further showed that the location of the negative pressure unit (NPU) had only had limited effect on mixing and that volume flow rate was more influential. However, the NPU location was more important in irregularly shaped enclosures.

1.6. On the basis of the HSL research, HSE has stated in the revised ACOP that asbestos enclosures less than $120m^3$ in volume should operate with a ventilation rate of $1000m^3$/hr (and be capable of achieving a NP of -5Pa)(Reference 1). For larger size enclosures (ie >$120m^3$), a volume flow of 8 acph is still specified. This latter extraction rate is unchanged from the previous requirements and will also achieve a minimum flow of about $1000m^3$/hr and a NP of around -5Pa. For these larger enclosures, the exact volume flow will be dependent on the size of the enclosure eg an enclosure size of $250m^3$ would require an air extraction rate of $2000m^3$/hr.

1.7 Some concerns have been raised by industry regarding the implications of moving to a standard volume flow ventilation rate, particularly regarding the stability of very small enclosures and the potential extent of airlock door flap displacement. There was concern that the relatively high air change rates per hour which occur with a volume flow of $1000m^3$/hr in small enclosures may generate turbulent air velocities with the theoretical potential to cause the enclosure to collapse or excessive door flap displacement. The research revealed that the concerns were unfounded and that enclosure stability is not affected and that door flap displacement is only modest.

1.8 However, it was recognised that further information on the supply, management and measurement of airflow within asbestos enclosures would be useful to provide the industry with an improved understanding of the factors which influence airflow and containment. Therefore, as well as providing clarity on the practical impact of the new ventilation requirement, the research provides the industry with information on management and monitoring of ventilation within asbestos enclosures.

1.9 The research was conducted by Plant, Audits and Training (PAT) and was overseen by HSE. The results of the research are reported in this document, and the objectives were to investigate:

(i) The link/correlation/relationship between airflow, NP and door flap deflection.
(ii) The effect of the new fixed ventilation rate on different sized enclosures including a very small unit.
(iii) The effect of the new fixed ventilation rate on the airlock and door flap displacement.
(iv) The integrity and stability of the enclosure at different air flow rates.
(v) The actions/solutions to reduce door flap deflection.
(vi) Sources of make-up air at higher ventilation rates.

2 METHODOLOGY

2.1 Three sizes of enclosures (with accompanying airlocks and baglocks) were investigated. A large enclosure measuring 9.6m x 5m x 2.5m (internal volume $120m^3$), a more typical enclosure measuring 2.4m x 5m x 2.5m (volume $30m^3$) and a very small enclosure measuring 1m x 2.4m x 2.5m (volume $6m^3$). The very small enclosure is the smallest enclosure that would be practical in most situations and is representative of a kitchen or other domestic cupboard with the necessary adjoining space to allow connection of the extraction unit (referred to as NPU). The enclosures were constructed in sequence with the smaller enclosures being prepared from the de-construction of the largest unit. The enclosures are shown diagrammatically in Figure 1.

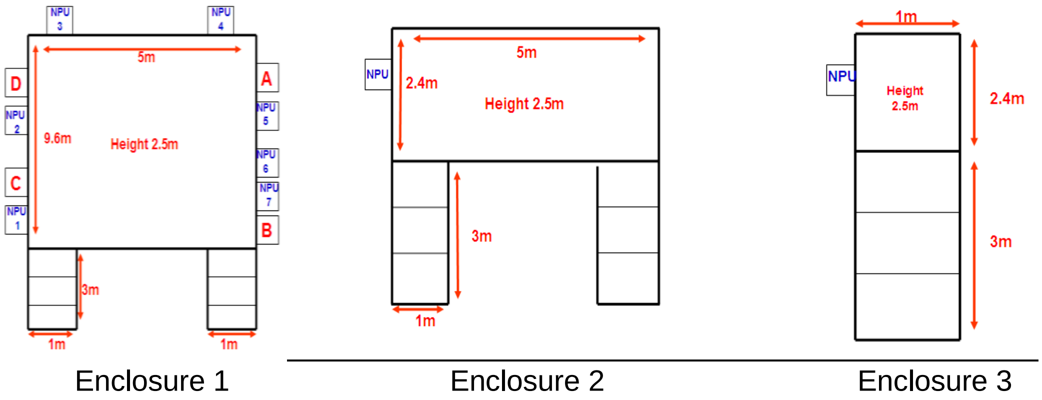

Figure 1: Plan view of the layout of the three enclosures showing the locations of the NPUs and "cubes" (A-D).

2.2 The units were constructed from normal materials as specified in HSE guidance (Reference 2) ie timber frames (63x37mm) for the enclosure, metal frame for the 3-stage airlock and baglock (referred to below as airlock 2) and 1000 gauge polythene sheeting for most of the walls and ceiling (plywood was used for one side of the airlocks). The polythene sheeting was attached to the inside of the frame using a combination of staples and 70mm fabric tape. Access through the airlocks was via standard size rectangular door openings in the polythene sheeting measuring 1.7m x 0.7m covered with weighted polythene door flaps extending 50mm on either side of the door opening. Flaps were weighted by attaching a rolled up section of the 1000-gauge polythene measuring approximately 2.2m x 1m (ie the remainder of the 4m x 1m sheeting after the door flap had been taken off). This length of polythene weighs around 380-400g. (For reference, door flap locations and labelling are shown in Photo 1).

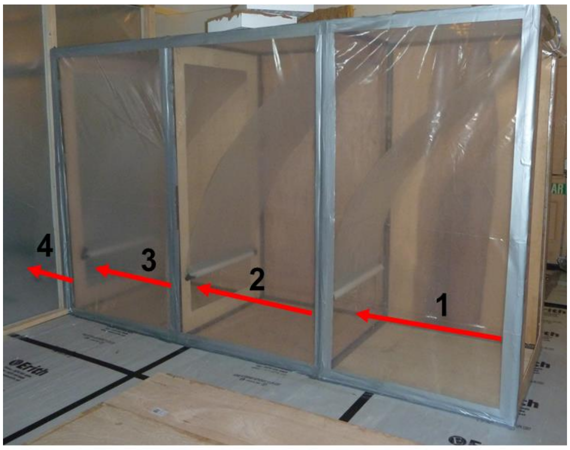

Photo 1: Photograph showing the locations and labelling of airlock door flaps. Flap 1 = airlock entrance section; Flap 2 = between outer and middle sections; Flap 3 = between middle and inner sections; and Flap 4 = entrance into main enclosure). (Photograph shows full scale deflection of Flaps 1-3).

2.3 Various series of tests were conducted to establish the effect of different levels of extraction on the stability of the enclosure and airlocks, the degree of NP obtained with different flow rates, the extent of door flap deflection and the actions which can be taken to reduce door flap displacement, and the sources and management of large volumes of make-up air.

2.4 Seven NPUs were used in the various ventilation tests to provide a range of ventilation rates and conditions. The locations of the NPUs are shown in Enclosure 1 in Figure 1. NPU 6, in the location shown, was used in all the tests involving Enclosures 2 and 3. Details of all the NPUs are summarised in Table 1. All NPUs were fitted with new HEPA and prefilters. Air velocity at the inlet of the NPUs was measured (twice) at five locations as shown in Photo 2 and the average value was calculated from the 10 results. Individual measurements were within 5% of the mean value in all cases. Air velocity was measured by a calibrated Kimo Instruments Vane probe thermo anemometer Type: LV120E (see Photo 3). Volume flow through the NPU was calculated by multiplying the face velocity (m/s) by the filter area ($0.137m^2$) (ie 0.37x0.37m) and by multiplying by 3600 to convert "seconds" into "hours".

NPU	Make	Date	Model	Serial No.	Design airflow (m^3/hr)	Measured airflow (m^3/hr)	% Measured /design
1	AMS	2013	AMS1500	15899	2217	2040	92
2	SI	2013	SI 5000	F1084	5200	5230	101
3	SI	2013	SI 5000	F1057	5200	5490	106
4	SI	2013	SI 5000	F1085	5200	5380	103
5	SI	2013	SI 5000	F1070	5200	5010	96
6	Beacon	2014	NPU2000/2/B	B-11113	2291	2220	97
7	AMS	2013	AMS1500	15900	2217	2060	93

Table 1: Details of NPUs used in the enclosure ventilation tests.

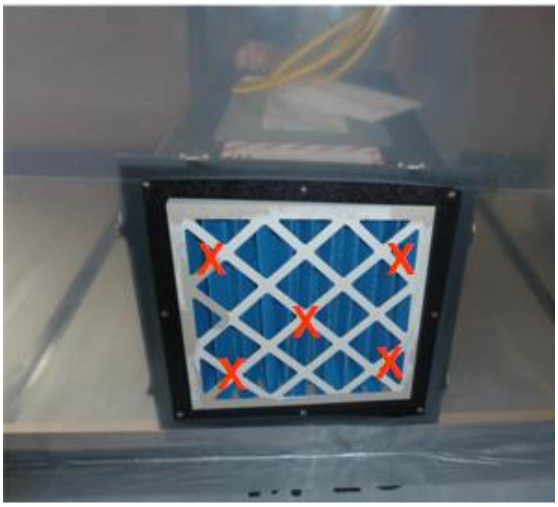

Photo 2: Approximate locations where air velocity was measured at the inlet of the NPU to establish average face velocity.

Photo 3 (Left): Kimo Instruments vane probe thermo anemometer Type LV120E used to measure NPU inlet face velocities. (Right): Kimo Instruments pressure monitor model MP120 used to measure negative pressure at various locations around the internal perimeter of the enclosures.

2.5 NP was measured at four internal locations during each test at a height of 1-1.5m at the perimeter of the enclosure. The NP was measured using a calibrated Kimo Instruments pressure monitor model MP120 (see Photo 3).

2.6 Four "cubes" were employed during the larger volume flow tests (see Paragraphs 4.15-4.16). The cubes were attached to the enclosure to allow supply of the necessary additional make-up air for the larger volume flows involved in these tests. A "cube" is essentially a single stage airlock measuring 1m x 1m x 2m (Volume 2 m^3) fitted with identical door openings and door flaps to the 3-stage airlocks. It has less resistance to flow compared with the 3-stage airlock and, therefore, proportionally more air will enter the enclosure via this unit rather than the 3-stage unit. The locations of the cubes in Enclosure 1 are shown in Figure 1 (marked A,B,C and D) . The door openings of the cubes were sealed until the respective tests were conducted. A photo of a "cube" is shown in Photo 4.

Photo 4 Photograph of a "cube" (a single stage airlock measuring 1m x 1m x 2m fitted with door openings and flaps identical to 3-stage airlock). Photo shows door flap with full scale deflection.

3 RESULTS

Test Series 1: Tests to establish relationship between air extraction volume, NP and airlock door flap deflection.

3.1 A series of tests were conducted in Enclosure 1 (volume 120m^3) at three extraction rates (530m^3/hr, 1070m^3/hr and 2220m^3/hr respectively) to establish the relationship between the extraction volume flow, the NP created and the extent of airlock door flap deflection. The tests were conducted with NPU 6 which has a variable volume flow ("speed") control, and with one airlock open. Air volume flow was established at each test by measuring the inward face velocity and calculating the volume flow (as described in Paragraph 2.4). The results are shown in Table 2.

3.2 The results show that NP was directly proportional to the air extraction rate (ie volume flow) with each 100m^3/hr, equivalent to approximately -0.5Pa. This is consistent with previous HSL research (Reference 4).The results also indicate that airlock door flap defection is directly related to volume flow (and therefore NP). Each extraction rate increment of 100m^3/hr (or NP increment of about -0.5Pa) creates a door flap deflection of 20-25mm in the middle airlock sections (ie door flaps 2 and 3) (see Photo 1). From these results, a door flap deflection (mm) to air volume flow (m^3/hr) ratio "value" can be derived. The "value" is usually between 0.20-0.25. A value of between 0.20-0.25 indicates that the correct door flap displacement has been achieved with the volume of air extracted (see Table 2). Therefore, NP and door flap deflection can be predicted from the air volume flow with a "standard" industry enclosure (ie fixed sized door openings and flap overlaps (openings 1.7x0.7m, overlap 0.05m), fixed weight door flap (~400g), one airlock open, 1000-gauge polythene sealed using tape and staples etc).

Air extracted (m^3/hr)	Airlock 1 Open	Airlock 1 Door flap deflection (mm) 1	2	3	4	NP	Flap deflection (mm) per m^3/hr
2220	✓	360	530	540	700	10	0.24
1070	✓	150	250	230	360	5	0.22
530	✓	90	130	120	110	3	0.24

Table 2: Relationship between air extraction volume, NP and airlock door flap deflection (Tests conducted on Enclosure 1 using NPU 6). The results show that as the air extraction volume flow is increased, the NP and the door flap deflection also increase proportionally (Numbers 1-4 in the "Airlock 1 Door flap deflection" column refer to door flaps 1-4 as shown in Photo 1). The door flap displacement/volume of air ratio "value" ranges from 0.22-0.24 (see Paragraph 3.2).

Test Series 2: Tests to establish effect of fixed air extraction volume on enclosures of various sizes.

3.3 A series of tests were conducted to establish the effect of the new ACOP ventilation rate (ie 1000m^3/hr) on enclosures of various sizes which are likely to be encountered in asbestos removal work. A small (6m^3), a medium (30m^3) and a large enclosure (120m^3) were assessed. The effect of this air extraction volume was evaluated in terms of door flap deflection and NP. All tests were conducted using NPU 6. Air volume flow was established at each test by measuring the inward face velocity of NPU 6 and calculating the volume flow (as described in Paragraph 2.4). The results are listed in Table 3.

Enclosure size (m^3)	Air extracted (m^3/hr)	Airlock 1 Open	Door flap deflection (mm) 1	2	3	4	NP	Flap deflection (mm) per m^3/hr
120	1050	✓	120	200	180	140	4	0.18
30	1045	✓	140	250	240	200	5	0.23
6	1070	✓	150	250	230	360	5	0.24

Table 3: Effect of a fixed air extraction rate (~1000m^3/hr) on door flap deflection and NP with different sized enclosures.

3.4 The results in Table 3 demonstrate that an extraction rate of 1000m^3/hr has a similar impact and effect on an enclosure's conditions/parameters irrespective of the enclosure size ie a similar size of door flap deflection is created and a similar NP is obtained in enclosures of varying size. The effects are independent of the enclosure size. Door flap deflection was consistent with other tests with a flap-to-volume ratio generally in the range 0.20-0.25 and a NP of about -5Pa.

3.5 The test also showed that the 1000m^3/hr ventilation rate had no adverse effects on the structure or stability of the very small enclosure, the most vulnerable in theory. The polythene was taut with no noticeable bellowing effect (see Photo 5). The ventilation rate is equivalent to over 80acph.

Test Series 3: Tests to show need for use of second airlock

3.6 The air extracted by the NPU is replenished by air entering the enclosure via the 3-stage airlock. However there are practical limitations on the extent that airlocks can supply "make-up" air as the airlocks serve to provide the facility for asbestos operatives to transit and decontaminate. In particular, airlock door deflection must not be excessive otherwise there would be insufficient space and it would be impractical for asbestos operatives to conduct changing and decontamination procedures. A practical working distance in the airlock is considered to be 700-750mm (ie equivalent to a door flap deflection of around 250-300mm).

Photo 5: Photograph showing visual effect of ventilation rate of 1070m^3/hr on the very small enclosure (Enclosure 3)

3.7 As already highlighted, the door flap deflection is primarily dependent on the extraction rate: a 1000m^3/hr volume flow will produce a door flap deflection of approximately 200-250mm. When the extraction rate needs to be higher than 1000m^3/hr (eg for enclosures >120m^3), then a single airlock will not be able to provide a practical working area. Therefore a series of tests was conducted to investigate the need to introduce (ie open) the second airlock to ensure sufficient practical working areas for asbestos operatives. The tests were conducted in Enclosure 2 using NPU 6. The results are summarised in Table 4.

Air extracted (m^3/hr)	Airlock open		Door flap deflection (mm)				NP	Flap deflection (mm) per m^3/hr
	1	2	1	2	3	4		
2116	✓		300	480	470	300	8	0.22
2116	✓		170	260	240	170	4-5	0.12
		✓	170	300	260			0.13

Table 4: The Table shows the effect of operating two airlocks simultaneously on NP and door flap deflection with an airflow of ~2100m^3/hr compared with operating only one airlock at the same volume airflow.

3.8 The results of these tests demonstrate that, with one 3-stage airlock operating, a volume flow of 2116m^3/hr will double the NP and door flap deflection in the middle two chambers respectively compared with 1000m^3/hr. The effects on NP and door flap deflection are consistent with the relationship with volume flow. At a flow rate 2116 m^3/hr, with one airlock open, door flap deflection measured 470-480mm for the middle two sections of the airlock which would provide insufficient space for transiting and decontamination procedures. The test results show that when a second airlock (of identical/similar size and other characteristics) is operated simultaneously with the original airlock (ie two airlocks operating), the supply air spreads evenly between both airlocks (see Table 4). Consequently the NP and door flap deflection is reduced by around 50% and there is now sufficient space for the operatives to carry out their procedures.

Test Series 4: Tests to investigate options to reduce door flap displacement
3.9 A series of tests were performed to examine other options to reduce door flap deflection. There will be various situations and circumstances where door flap deflection will need to be reduced to ensure there is sufficient working space for operatives. For larger volume flows the main options will be the second airlock or cubes. The effect of the second airlock was examined in Test Series 3 and the impact of "cubes" was investigated in Test Series 5. However, door flap deflection can be reduced by other actions particularly where small door flap reductions are required or where it may not be possible to have a second airlock due to restricted space. There are two further simple options to reduce door flap deflection: (i) increase door flap weight and (ii) introduce other controlled sources of make-up air eg through standard pre-filters. A further series of tests were carried out to investigate both options.

3.10 Flap weight was increased (ie doubled) in each door entrance of the 3-stage airlock by attaching a rolled up length of 1000-gauge polythene (4x1m) to the existing flap weight using fabric tape. In the other test, a controlled supply of make-up air was introduced into the enclosure by inserting two standard size (0.37x0.37m) pre-filters into the wall of the enclosure as shown in Photo 6. The filters were fitted with weighted polythene flaps (1000-gauge polythene) on the "inner" filter side and were also attached using fabric tape. The results of the tests are shown in Table 5.

Photo 6: Photograph showing two pre-filters (size 0.37x0.37m) inserted into Enclosure 3 to provide make-up air.

Air extracted (m³/hr)	Condition	Airlock 1 Open	Door flap deflection (mm) 1	2	3	4	NP	Flap deflection (mm) per m³/hr
2220	Normal Flap Wt (~400g)	✓	360	530	540	700	10	0.24
2220	Double Flap Wt (~800g)	✓	260	370	360	600	14	_
2220	1 Filter	✓	290	420	450	650	9-10	_
2220	2 Filters	✓	260	390	360	600	8	_

Table 5: Effect of doubling door flap weight and introducing filters to supply make-up air on NP and door flap deflection (- = Not applicable).

3.11 The results in Table 5 show that doubling the flap weight reduces flap deflection (in flaps 2 and 3) from 530/540mm to 360/370mm (~32% decrease). This is a significant reduction. Increasing the flap weight also created a higher NP within the enclosure (from -10 to -14Pa). The results also show that introducing the filters reduced door flap deflection and increased NP. Door flap deflection decreased from 530/540mm to 420/450mm (~19%) and from 530/540mm to 360/390mm (~30%) with one and two filters installed respectively.

Test Series 5: Tests to assess the stability of enclosures at high extraction rates

3.12 A series of tests were conducted to assess the stability and integrity of the asbestos enclosure at high extraction rates. The tests were designed to demonstrate the use of cubes in providing make-up air. Enclosure 1 was used for these tests. Various NPUs were operated in sequence to increase the volume of air being extracted from the enclosure. Details of the NPUs used for each test are listed in Table 1. Air extraction volumes ranged from 5490m^3/hr to 25390m^3/hr. These are volumes well in excess of those typically used for many enclosures but could be applied in some circumstances where large enclosures are deployed. The tests were conducted with both airlocks open and with various cubes opened progressively to allow the supply of make-up air. Full details of the test conditions and the results are presented in Table 6. NP was not measured.

NPUs used	Air extracted (m³/hr)	Airlock open 1	2	Door flap deflection (mm) 1	2	3	4	Cube flap deflection (mm) 1	2	3	4
3	5490	✓	✓		600			_	_	_	_
2, 3	10720	✓	✓	FD	FD	FD	FD	_	_	_	_
2,3,4	16100	✓	✓		450			FD	_	_	FD
2,3,4,5	21110	✓	✓		500			FD	FD	FD	FD
2,3,4,5,6,7	25390	✓	✓		600			FD	FD	FD	FD

Table 6: Tests demonstrating the effect of various volume flows on airlock door flap and cube door flap deflection (Enclosure 1, FD = Full deflection, - = Not open).

3.13 The results show that at higher extraction rates airlock door flap deflection becomes excessive and additional sources of make-up air are required to reduce the deflection. The empirical evidence suggests that each cube would be capable of providing around 4000-5000m^3/hr of make-up air. The tests also demonstrated that the integrity and stability of the enclosure and airlocks were not compromised even at ventilation rates of up to 25390m^3/hr.

4 DISCUSSION

4.1 The research was designed to explore several aspects of the relationship between air extraction rates and their impact on enclosures employed for asbestos removal work. In particular, the study investigated the stability of the enclosure and the associated airlock system and the effect of the new ACOP ventilation rate on door flap displacement. The study has also sought to provide more information on the management of air movement within enclosures.

4.2 The research has shown that standard asbestos enclosures and airlocks (ie consisting of timber and polythene) are sufficiently robust, strong and stable to withstand not just the new ACOP air extraction rate (1000m^3/hr) but also significantly higher air flows. The large enclosure (Enclosure 1 volume 120m^3) has been tested at airflows up to approximately 25000m^3/hr (using a combination of multiple NPUs with appropriate provision of make-up air). This volume flow is some 25 times the ACOP volume flow.

4.3 The research has confirmed that increased airflow extraction can be achieved by using multiple NPUs. Therefore it is practical to use two units (eg 2 x "500s") to obtain the desired minimum airflow of 1000m^3/hr.

4.4 The research sought to investigate the role of door flap displacement in monitoring and managing airflow and NP. The extent of door flap deflection varies depending on the location of the door flap in the airlock. "Perimeter external" flaps (ie flaps 1 and 4) are influenced by other positional factors and, therefore, the extent of their deflection differs from flaps 2 and 3. Flap 1 is usually more restricted/limited in movement (compared with flaps 2 and 3) due to turbulence and direction in airflow entering the airlock (ie air is drawn from around the side of the airlock as well as from the front). In contrast, flap 4 often has greater deflection (ie less resistance to flow) (compared with flaps 2 and 3) as the air passing around the side of this flap is entering a large and unrestricted air space (ie the enclosure) and is not restricted by the narrow walls of the airlock (locations of flaps are shown in Photo 1).

4.5 The research demonstrates that door flap deflection in the airlock is related to the extraction volume flow. The "middle two" door flaps in an airlock system will deflect approximately 20-25mm for every 100m3/hr. Therefore a volume flow of 1000m^3/hr will generate a door flap deflection of between 200-250mm. The standard relationship between volume flow and door flap deflection will allow door flap movement to be used as a simple and pragmatic clear method of indicating and indeed, monitoring and checking, air extraction performance.

4.6 The air extraction rate is also directly linked to NP. In the conditions encountered in a standard timber/polythene built asbestos enclosure, an extraction rate of 1000m^3/hr will create a NP of -5Pa. Therefore the door flap deflection of 200-250mm can also be used as a practical means to confirm the extent of NP within the enclosure. Door flap deflection in the middle two stages of the airlock is a key indicator of both sufficient airflow into the enclosure and of NP within the enclosure.

4.7 The new ACOP ventilation rate standard is 1000m^3/hr. This means in practice that NPU equipment which provides a slightly higher flow rate will be necessary to compensate for any losses in the system (eg due to roving heads/ducting, filter loading etc). Therefore higher capacity NPU equipment with variable speed control will be the best option. Air flow on this type of equipment can be adjusted to take account of air-flow losses and to ensure that the exact air flow rate is achieved.

4.8 However, some currently used NPUs have fixed extraction rates and therefore, in the short term at least, there will be limited flexibility in the actual air volumes extracted depending on the equipment available eg two "500s" each moving approximately 700m^3/hr will extract some 1400m^3/hr and a "1500" may extract some 2200m^3/hr. These "higher volume" flow rates have two implications: increased NP (which is desirable) and greater door flap deflection. Depending on the volume flows involved, there may be a need to reduce the extent of door flap displacement. The research has shown that door flap reduction can be achieved by various actions eg doubling door flap weight, introducing controlled airflow through the second airlock or through filters in the enclosure wall.

4.9 Door flap deflection needs to be managed to ensure that workers will have sufficient space to be able to carry out the necessary actions and activities within the airlock (ie cleaning footwear and RPE, and removing/donning transit coveralls and footwear). Door flap deflection up to around 250mm should allow adequate space for these activities to be undertaken. Air extraction volumes up to around 1500m^3/hr are unlikely to require door flap adjustment. However, higher air extraction volumes will lead to greater deflection which will require restriction and adjustment.

4.10 Door flap adjustment for situations involving the common sizes of NPUs (ie "500s" and "1500s" or other equipment which will produce airflow up to about 4000m^3/hr) can be achieved by carrying out some very simple measures. The options and recommendations for ensuring suitable working space in the airlock(s) (ie by reducing door flap movement) depending on airflow are as follows: at airflows up to 1500m^3/hr, single airlock operating: at airflows between 1500-2000m^3/hr, door flap weight should be doubled; at an airflow of ~2000m^3/hr, the second airlock should be opened (weighted flaps not required) and at airflows between 3000-4000m^3/hr, the second airlock with weighted flaps in both airlocks should be used. The details are summarised in Table 7.

Air extracted (m^3/hr)	Action to ensure sufficient airlock space (ie reduced door flap displacement)	Expected door flap deflection (mm)
1000-1500	Single airlock	200-300
1500-2000	Single airlock and double airlock flap weight	250-300
2000-3000	Two airlocks	200-300
3000-4000	Two airlocks and both airlocks double flap weight	250-300

Table 7: Impact of actions to reduce door flap displacement to ensure sufficient workable space in airlock at various air extraction rates.

4.11 Any "extra" ventilation capacity significantly over 1000m^3/hr is not required for control of spread in enclosures <120m^3. Therefore asbestos removal contractors should seek to achieve a measured extraction rate of 1000m^3/hr. This figure should be the airflow achieved taking account of other factors such as roving heads or discharge ducting. Many types of NPU are fitted with variable speed controls which will allow greater regulation of airflow movement and such a feature will also eliminate the need for other measures to reduce “excessive” door flap deflection. Where these speed controls are fitted, the air extraction rate should be reduced to the required rate (ie 1000m^3/hr). It is also possible and relatively easy to retrospectively fit these variable speed controls to existing equipment. The cost of fitting this feature is estimated to be significantly less than £100. Fitting such devices will make achievement of the exact air flow rate much easier.

Provision of Make-up Air

4.12 Enclosures over 120m^3 have a ventilation standard in the ACOP (Reference 1) of 8 acph. Therefore the volume of air extracted will depend on the size of the enclosure. As the enclosure size increases, then extraction of greater volumes of air will be required. For example: a 200m^3 enclosure will require an extraction volume of 1600m^3/hr while a 500m^3 enclosure will require 4000m^3/hr. In these situations, air volumes much greater than 1000m^3/hr will be required and the provision of make-up air will be necessary.

4.13 The volume of air extracted can be increased by simply increasing the extraction provision ie by increasing the number or the capacity (or both) of the NPUs. Table 6 provides examples of the combination of NPUs that can be used to provide required extraction volumes. As the NP and door flap deflection are directly related to the extraction rate, then there needs to be adequate make-up air to ensure that the door flap deflection is maintained within the manageable/workable dimensions. The approaches to providing make-up air up to 4000m^3/hr is described in paragraph 4.10 and in Table 7.

4.14 Where the volume flow exceeds 4000m^3/hr then make-up air should be provided by using a “cube”. Supplementary cubes will be required for each additional ~4000m^3/hr volume flow. Where such large air volumes are involved, the enclosure and air management will be complex and will require competent advice. The exact combination of airlocks, door flap adjustment and cubes will need to fully considered in the planning and preparation of the work and through testing and checking during the construction of the enclosure.

Cube Flap Deflection

4.15 Where cubes are employed to supplement the provision for make-up air, air will preferentially pass through these units rather than the 3-stage airlocks ie a greater proportion of the supply air will pass through the cube. The number of cubes required will be dependent on the volume of air extracted. Each cube will allow some 4000m^3/hr of air until they reach full scale deflection. Cubes can be added progressively as the air volume increases. Cubes will only be necessary where larger enclosures are involved. The “first” cube is likely to be required where volume flow of around 4000m^3/hr is required.

4.16 The cube’s sole purpose is to provide controlled make-up air. Cubes should not be used for access or movement of personnel or equipment. Cubes should be “protected” by barrier tape or warning signs to prevent unauthorised use. Cubes should be located in similar locations to the airlock (where space allows) and remote from the NPUs.

4.17 It is essential that the NPU volume flow rates are clearly understood by the industry to ensure correct extraction airflow rates are applied. The current use of two sets of units of measurement (CFM and m^3/hr) can lead to confusion and miscalculation of flow rates. Therefore it is recommended that manufacturers clearly rate their NPUs in m^3/hr so appropriately sized equipment can be easily identified.

4.18 The use of variable speed controls will be important in the selection of suitable volume flow. Therefore the variable speed controls must be reliable and accurate. Manufacturers should seek to ensure variable speed control switches are precise and accurately reflect volume flows.

4.19 The accuracy and reliability of the NPUs should be established before use. The airflow rate of NPUs should be measured at the start of each job using an anemometer (details on measuring given in Paragraph 2.4) to confirm the required airflow is achieved and the extent of any door flap deflection modification. Persons measuring airflow should be trained and competent and the equipment should be calibrated and serviced in accordance with the manufacturer's instructions.

5. CONCLUSIONS

5.1 For standard timber/polythene asbestos enclosures, NP within the enclosure and airlock door flap displacement are directly proportional to the air extraction rate. Door flap deflection can be used as a practical means to confirm the air extraction rate and the extent of NP within the enclosure.

5.2 An air extraction rate of $1000m^3$/hr will produce a differential pressure of about -5Pa and a door flap deflection of between 200-250mm in the middle airlock sections. These conditions were created in all enclosures tested irrespective of enclosure size.

5.3 A door flap deflection of 200-250mm can be used as a key indicator of achieving the stated extraction volume for enclosures $<120m^3$.

5.4 The research has shown that standard enclosures and airlocks are sufficiently robust, strong and stable to withstand the new ACOP air extraction rate ($1000m^3$/hr) and significantly higher air flows. An air extraction rate of $1000m^3$/hr has no adverse effects on the stability and integrity of very small enclosures (eg 6 m^3).

5.5 Sufficient airlock space is required to enable asbestos operatives to carry out transiting and decontamination procedures. There should be sufficient working space with door flap deflection in a 3-stage airlock up to a volume flow of about $1500m^3$/hr. Where larger volume flows are employed, then additional simple actions will be required to ensure sufficient space: the actions will include doubling the airlock door flap weight and opening up the second airlock (ie baglock).

5.6 At very high flow rates eg about $4000m^3$/hr or above, make-up air should be provided by the use of cubes (ie single stage airlocks). Further cubes will also be required for each additional $4000m^3$/hr air extracted.

5.7 The desired minimum volume flow ($1000m^3$/hr) can be achieved by using a combination of NPUs eg 2 x "500s".

5.8 The research has shown that variable speed controls fitted on NPUs enable much greater control over airflow. The devices will allow adjustment of airflow to take account of airflow losses (eg through the use of roving heads or filter loading) and to reduce "excessive" door flap displacement. Many NPUs are already supplied with these devices fitted. Variable speed controls can also be fitted retrospectively to existing NPUs.

5.9 Airflow rates of NPUs should be measured at the start of each job to confirm that the required airflow is achieved.

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