FRDG Publication 5/2000 The Use of Positive Pressure Ventilation for Smoke Clearance in Large Buildings

FIRE RESEARCH & DEVELOPMENT GROUP

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BUILDING A SAFE, JUST AND TOLERANT SOCIETY

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The Use of Positive Pressure Ventilation For Smoke Clearance in Large Buildings

by

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ABSTRACT

This report describes a series of trials designed to assess the effectiveness of Positive Pressure Ventilation (PPV) when used to clear smoke and gases from large buildings. Cold smoke was used to smoke-log variously sized compartments – from 91 to 7,000 cubic metres in volume – to 100% obscuration. The times taken to increase visibility to a working level using natural ventilation, and PPV, were measured and compared.

It is concluded that PPV can make a useful reduction in clearance times, particularly when the natural wind is light. The improvements due to PPV were greater in the smaller compartments – reducing the clearance time to about 25% of the natural ventilation time in the smallest compartment, and to about 50% in the 1,000 cubic metre compartment. A single PPV fan had no discernible effect, overall, in the 7,000 cubic metre compartment although two fans, properly used, could roughly halve the clearance time when the wind was very light.

MANAGEMENT SUMMARY

INTRODUCTION

In 1995 the Fire Experimental Unit (FEU) of the Home Office Fire Research and Development Group (FRDG) was asked to conduct a research project into the likely effects of Positive Pressure Ventilation (PPV) when used in firefighting. The first major part of this work dealt with the use of PPV in a domestic property, which was reported in FRDG Publication 17/96. Subsequently, the effects of PPV in the unpressurised stairwell of a four storey industrial building were examined and reported in FRDG Publication 11/97. An international survey of the use of PPV has also been undertaken (FRDG publication 6/94), and practical guidance is given in the recently published Fire Service Manual - Volume 2. A further report (FRDG Publication 8/98) describes trials undertaken by a brigade in collaboration with FEU, examining the effects of using PPV in a fire compartment, as they affect firefighters, and a casualty lying between the seat of the fire and the outlet vent.

This present report deals with the final major part of this work: the effectiveness of PPV in smoke clearance from large buildings.

BACKGROUND

The most usual reason for a brigade to deploy PPV in a fire, or post fire, situation in a building is to improve visibility inside the building, or fire compartment. The rapid removal of smoke and hot (and, possibly, potentially explosive) gas, and their replacement by, cooler, clean air assists firefighters and salvage workers alike in a number of ways, but the improvement in visibility is probably the most immediate and, possibly, vital factor.

There are currently a number of self-contained fan units on the market in the UK designed specifically for this purpose. These can be water powered, electrically powered or powered by an internal combustion engine. This latter group is by far the largest, and the brigades which have equipped themselves with PPV fans have opted, almost unanimously, for petrol engines.

The maximum size, and hence maximum power, of these PPV units is ultimately limited by stowage considerations: they need to be carried, adequately constrained, on fire appliances, where size, shape and weight are invariably of great importance. Also, they need to be able to be removed from the appliance by one firefighter, or at most two, and quickly positioned and deployed.

The petrol powered PPV fans available are all similar in principle, and broadly similar in size, weight and capacity (Figures 7 and 8 show typical examples). The claimed output ratings of these fans vary from some 10,000 cubic metres per hour (cu.m/h), 5,884 cubic feet per minute (cu.f/m), to some 30,000 cu.m/h (17,650 cu.f/m); increased capacity being achieved by more powerful motors and larger diameter fans. The most common sizes,

and those most popular with brigades, give some 13,600 - 17,000 cu.m/h (8,000 - 10,000 cu.f/m) and have, typically, 5.0 or 5.5 horsepower engines.

Although PPV has been shown to be very effective in domestic and other relatively small buildings, little was known about the effects the fans carried by brigades could have in larger buildings. It was this question that the present work was intended to address.

THE TRIALS

It was agreed at the outset that buildings significantly larger than the 'domestic' room used in the previous work should be sought. Ideally, a range of compartments should be examined ranging in volume from about twice that of the domestic room (which was approx. 53m^3) to some 6,000 - 8,000 m^3, which would represent a fairly large industrial building or warehouse.

It was realised that there would be virtually no such building available in which trial fires could be repeatedly lit except, possibly, at the Fire Service College. Several of the College's fire buildings were surveyed and considered, but were rejected for various reasons. It was therefore accepted that cold smoke, only, could be used for trials. Further, it was recognised that only buildings close to the FEU site could be used due to restrictions on staff availability, funding, etc.

In the event, cold smoke trials were undertaken in five different sized compartments. These were:-

a. The Fire Service College's 'green' garage – 39.3m. x 33.1m. x 5.4m. high – some 7,000m^3.

b. FEU garage – 16.0m. x 12.5m. x 5.0m. average height – some 1,000m^3.

c. Temporary building; 12.2m. x 7.5m. x 3.0m. high – 274m^3.

d. Temporary building; 12.2m. x 5.0m. x 3.0m. high – 183m^3.

e. Temporary building; 12.2m. x 2.5m. x 3.0m. high – 91m^3.

In each of these compartments, except the 'green' garage, a combination of three doorways of typical size and shape were used as inlet and outlet vents: these were:-

a.	single personnel access door:	1.98m. x 0.76m.	(6'-6" x 2'-6")
b	double personnel access door:	1.98m. x 1.52m.	(6'-6? x 5'-0")
c	domestic type garage door:	1.98m. x 2.44m.	(6'-6" x 8'-0").

The doorways in the 'green' garage were some 4.0m. wide, and 4.0m. high, when fully open.

Cold smoke trials were performed in pairs, as previously, one using PPV and the other using natural ventilation only. In this way the effect of PPV could be determined,

provided that the natural wind conditions were similar during each of a pair of trials, and that the trials were carried out in an identical manner. In each trial the compartments were smoke logged to 100% obscuration (or close as possible to this value), the smoke generators were stopped, the vents opened and the rate of smoke clearance monitored by three smoke obscuration meters which fed the data into FEU's datalogger. In the majority of trials in which PPV was used, the fan was set back from the inlet vent in order to effect a seal, as far as possible: 2.5 metres back for both personnel access doorways, and 3.0 metres back for the garage doorway. A limited number of trials were also undertaken using two PPV fans, in the 'green' garage, the FEU garage and the 2.5m. wide compartment. Also, some trials were undertaken using a fan positioned right in the vent, so that all of the fan's output entered the compartment instead of making a seal.

During all cold smoke trials the natural wind (speed and direction) was monitored and recorded, and an average value, over the duration of the trial, calculated.

In order to help us understand the effects of PPV within a compartment, and assess the predictability of the swirl patterns set up, a series of air movement surveys were undertaken in each compartment except the 'green' garage. To do this, an ultrasonic anemometer was purchased and built into a supporting and positioning rig which could accurately position and orientate the sensing head of the anemometer anywhere in the compartment, to enable 'weather chart' type plots to be produced. It was found during the early surveys that the air velocities measured in the vertical plane were small compared to those in the two mutually perpendicular horizontal planes, and so, in the later surveys, only plan view plots were produced.

RESULTS

The results of the cold smoke trials were tabulated separately for each compartment size. These tables give the scenario (sizes and positions of vents, and the tactics used) and all measured data, including the natural wind speed and direction, for each trial. The trials were tabulated in chronological order so that pairs of trials appear one above the other.

A general impression of the improvements in clearance times when using PPV, outlined above, and their relationship to the natural wind speed, can be obtained from Figures 94-101.

The airflow survey charts obtained in each sized compartment up to, and including, the FEU garage are given. Overall, what these charts show is that the air movement in a compartment is virtually impossible to predict, in all but the narrowest compartments with large vents at each end, and that these charts, if they had been available, would not have helped to predict smoke clearance times in any given situation (of natural wind, positions and sizes of vents, etc.). On the whole, they seem to indicate that the smoke clearance process is one of dilution, involving much mixing and re-circulation within the compartment, particularly in the larger compartments with relatively smaller vents.

CONCLUSIONS

(i) General

It was found that when using natural ventilation the time taken for smoke to clear from a building was related, albeit loosely, to the speed of the natural wind, independent of its direction relative to the inlet vent. When PPV was used in the same situation, the time taken to clear the smoke from the building was generally reduced, particularly when the natural wind speed was low. In other words, the dependence of the clearance time upon the natural wind speed was removed, or at least reduced, by the use of PPV. A single fan would not be effective in a very large building so the use of multiple fans would be necessary.

Also, it was found that the time taken to clear a building of smoke using PPV was more predictable than when using natural ventilation, only. However, firefighters would, in practice, only be able to predict such times based upon their previously gained experience in similar buildings.

(ii) Effect of Compartment Size

The overall effect of PPV was beneficial in all of the buildings:

- in the 2.5 metre wide compartment (91.5 cubic metres) a single PPV fan reduced the overall average clearance time (to 40% obscuration) to roughly one quarter of the natural ventilation time.
- In the 5.0 metre wide compartment (183 cubic metres), a single PPV fan reduced the overall average clearance time to roughly one third of the natural ventilation time.
- In the 7.5 metre wide compartment (264.5 cubic metres), a single PPV fan reduced the overall average clearance time to roughly one third of the natural ventilation time.
- In the FEU garage (1,000 cubic metres), PPV reduced the overall average clearance time to roughly one half of the natural ventilation time (considering the single fan trials, only).
- In the 'green' garage (7,000 cubic metres) a single PPV fan had no discernible effect. Two fans properly used reduced clearance times to roughly half of the natural ventilation time when the wind speed was low.

(iii) Use of Multiple Fans

As the volume of a smoke logged compartment increases so the effect that a single PPV fan can have decreases. A very large compartment would require a very large fan, or a number of 'small' fans to quickly reduce the level of smoke obscuration.

In these trials, when two fans were used in a very large inlet vent (so large that no 'seal' was possible) they appeared to work best, in terms of rate of smoke clearance, when they were positioned far enough apart for their outputs not to interact until well inside the

compartment. When sealing a personnel access door with two fans, the best result was achieved with one fan sealing the top half of the doorway and the other sealing the lower half.

In general, in these trials, when two fans were used they cleared the smoke somewhat faster than a single fan when used in identical circumstances and with a similar natural wind. It is considered most probable that, as a general rule: the greater the number of fans brought to bear, the faster will be the smoke clearance, in any given situation.

(iv) Effect of Vent Size

In this work, it has not been possible to identify any significant effects due to the different vent sizes, particularly in the larger compartments. This is probably because the compartments were too large and leaky.

In practice, firefighters may have little or no choice in the sizes of the vents available. It would seem sensible to open up the largest inlet and outlet vents available if the aim is simply to clear smoke from the building as fast as possible, and there is a reasonable natural wind (say, 1.5 metres per second, or more), whether using PPV or not. Also, if it is important to maintain control over the direction of airflow through the building, then the inlet vent must be kept to a size, and shape, which the fan or fans available at the scene can seal.

It would seem reasonable to assume that, provided the natural wind does not change direction markedly (the 'outlet vent' does not become the inlet), faster smoke clearance will be achieved with the largest possible vents, particularly the outlet vent. However, the results from the trials neither confirm nor deny this.

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THE USE OF POSITIVE PRESSURE VENTILATION FOR SMOKE CLEARANCE IN LARGE BUILDINGS

1. INTRODUCTION

In February 1995 the Fire Experimental Unit (FEU) of the Home Office Fire Research and Development Group, based at Moreton in Marsh, were asked to conduct a research project into the likely effects of Positive Pressure Ventilation (PPV) when used in firefighting. Several different scenarios have been investigated.

A brief look at the use of PPV in a cellar fire was included in FRDG Report 6/95[1].* A second package of work examined the use of PPV in a simple one room fire in a domestic building (FRDG 17/96)[2], and a third examined its use in an unpressurised stairwell (FRDG 11/97) [3].

An international survey of fire ventilation has also been undertaken (FRDG publication no. 6/94)[4], and practical guidance is given in the recently published Fire Service Manual - Volume 2[5].

A further report (FRDG 8/98)[6] describes trials undertaken by a brigade in collaboration with FEU. This work examined the effects of using PPV, in the fire compartment, as they affect firefighters, and a casualty lying between the seat of the fire and the outlet vent.

This present report covers the fourth package of work to be undertaken: the effect of PPV upon smoke clearance in larger single compartment buildings.

*References in square brackets are listed on page 50.

2. BACKGROUND

2.1 General

For many years fire brigades have used large fans to assist in clearing smoke and hot gases from buildings which have been involved in fires. Traditionally, fans have only been deployed for this purpose after the fire has been extinguished. It is a usual procedure to ventilate the building after extinguishing and any necessary damping down, in order to both make it possible to see throughout the building, and to gain a more tenable atmosphere for salvage crews, etc., to work in. This ventilation can be achieved by the strategic opening of doors and windows, to let the natural wind blow through the building. However, it has been found over the years that the use of a fan, or fans, can greatly increase the speed of this smoke clearing process.

Fans used in this way can be positioned to blow air into the building (Positive pressure ventilation), or to draw air out of the building (Negative pressure ventilation). In either case the fan, or fans, are best positioned to assist any natural airflow through the building. Of these two possibilities, positive pressure ventilation is preferred because it is, in general, rather more efficient. Also, a fan in an inlet opening stays cleaner and is unaffected by the smoke and gases being extracted from the building, and it can produce a very slight increase in static pressure within the building which also assists the smoke clearance.

In relatively recent years it has been suggested that fans could be used in some circumstances as an offensive firefighting tool, as well as for the purpose outlined above. This relatively new concept, termed 'Positive Pressure Ventilation' (PPV) was pioneered in the USA, where it is now employed widely, but not universally.

There are two distinct ways in which a fan can be used to blow air into a building: the fan can be positioned right in an open doorway, or it can be positioned at some distance outside the doorway so that its output forms a 'seal' around the doorway. In the former case, the whole of the output of the fan can enter the building, causing a slight positive pressure inside the building, but it is likely that much of the air forced into the building will come straight back out again, over and around the fan, because of the pressurisation (depending upon what other vents or leak paths are open). In other words, there is no control over the direction of air movement. In the latter case, where the fan is sited some distance outside the doorway, hence forming a 'seal' around the doorway, it is much less likely that air will leak back out past the fan. This is particularly so if a suitable outlet vent can be opened at the far side of the building. Hence control of the direction of air flow through the building can be established (although in this case only a proportion of the fan's output enters the building, resulting in slightly less pressurisation).

In recent years, in United Kingdom brigades, the term 'PPV' has come to mean almost solely this latter technique.

The advocates of this relatively new technique, of using PPV as an aggressive firefighting technique, claim that it offers a number of advantages, which may be briefly summarised in general, as follows.

(a) Airflow through a fire building can be accelerated by assisting the natural wind, or created where there is little or no natural wind.

(b) It may be possible to dictate, within limits, the direction of the airflow through a fire building by the strategic opening or closing of windows and external and internal doors and by the positioning of fans, so controlling the route the smoke will take to the outlet opening.

(c) By pressurising part of a building, (remote from the room directly involved in the fire), it may be possible to prevent smoke permeating into that part, as well as reducing the chance of the fire spreading towards that part.

(d) The use of a PPV fan can enable firefighters, entering the building with the fan at their backs, to locate the seat of the fire quicker by improving visibility. Also, the airflow from the fan will reduce the chance of the fire spreading towards them, and make the flames 'lean away' from them.

(e) The rapid removal of combustion products and their replacement by cooler air will enhance the chances of survival for persons trapped in the fire building, as well as improving conditions for firefighters.

However, one major potential disadvantage has to be set against all of this: the obvious one, that increasing the supply of oxygen to the fire will accelerate the fire.

Also, it is clear that, together with adequate training in the use of PPV, good, effective fireground communications would be essential if PPV is to be used effectively and safely. The use of a PPV fan in a fire situation would need to be carefully co-ordinated with all other fireground operations. The fan would need to be manned continually during its deployment, and decisions affecting its used based on information from the crews inside the fire building.

Whilst the technique of pressurising escape routes and stairwells has been employed when possible for some time, the current situation with PPV as far as the UK brigades are concerned can be summarised thus. All of the brigades have heard of PPV, most have studied the technique to some extent, and some are equipping themselves with purpose-built fans, and training their firefighters in its deployment. A number have purchased PPV fans, mostly for appraisal, and several brigades are known to have used the technique 'in anger'. Other brigades appear to be waiting for others to amass some long-term experience before deciding whether to commit themselves to promoting the technique.

It appears that the brigades who are promoting the technique are in broad agreement that the use of PPV can be of great value in domestic or similar properties when rapid searching, or location of the fire, is the prime objective. It is generally accepted by these brigades that a typical room in a domestic property can be cleared of smoke, starting from zero visibility, in 'a minute or two'.

However, less is known about the effects of PPV in larger compartments. It seems likely that there is a size of compartment beyond which a PPV fan could have no significant effect. (It would appear that this 'threshold' size will depend to a large extent upon the natural wind conditions and the size and location of any vents which could be opened.)

It was this latter situation that the present work was intended to address.

3 TRIALS PLANNING AND PROCUREMENT OF EQUIPMENT

3.1 General

It was agreed at the outset that buildings significantly larger than the 'domestic' room used in the previous work [2] should be sought. Ideally, a range of compartments should be examined ranging in volume from about twice that of the domestic room (which was approx. 53m^3) to some 6,000-8,000 m^3, which would represent a fairly large industrial building or warehouse.

It was realised that there would be virtually no such building available in which trial fires could be repeatedly lit except, possibly, at the Fire Service College. Several of the College's fire buildings were surveyed and considered, but were rejected for various reasons. It was therefore accepted that cold smoke, only, could be used for trials. Further, it was recognised that only buildings close to the FEU site could be used due to restrictions on staff availability, funding, etc.

It was decided that trials could be undertaken in compartments of five different sizes by:

(a) building a temporary modular structure within the FEU garage to give enclosed volumes of approximately 90m^3, 180m^3 and 270m^3.

(b) using the FEU garage (approx. 1,000m^3).

(c) using the Fire Service College's 'green' garage (approx. 7,025m^3).

It was considered that all of these compartment sizes were worth investigating. In this report, these compartments are considered in the chronological order in which they were examined in Section 5, and in order of decreasing size in Section 6.

The intention was that the trials would be performed in pairs, as previously [2], one using PPV and the other using natural ventilation only. In this way the effect of PPV could be determined, provided that the natural wind conditions were similar during each of a pair of trials, and that the trials were carried out in an identical manner. In each trial the compartment would be smoke logged to 100% obscuration (or as close as possible to this value), the smoke generators would be stopped, the vents opened and the rate of smoke clearance monitored.

It was decided that as well as conducting purely comparative smoke clearance trials, with and without the use of PPV, the effects of varying the relative sizes and positions of the vents should be examined. Also, a way of measuring and recording airflows in a compartment should be developed. These elements of the work would be carried out in the FEU garage.

FEU's three smoke obscuration meters (1, 2, 3)* would be used in all cold smoke trials to measure and record the rate of smoke clearance. A simple visual system would also be

*References in round brackets refer to the Notes on page 51.

developed and tried. This would consist of a number of lights fixed in known positions in the smoke logged compartment and a video camera placed just inside the inlet vent and a little to one side, so as not to obstruct the airflow, in a position that a firefighter might well take up.

For airflow measurements, an anemometer would be sought which could be built into an in-house built traversing rig, so that it could readily be positioned anywhere in the FEU garage and its position be accurately known in three mutually perpendicular planes. The anemometer should be capable of measuring airspeeds down to 0.1 metres per second, and the direction of the air movement in all three planes. This would allow a plot to be made at any position, in any two of the three planes, in the manner of a 'weather chart'.

During all trials it would be necessary to measure and record the natural wind velocity, i.e. speed and direction, to enable any effects of PPV to be assessed. The FEU's wind station [4] would be used for this purpose.

3.2 FEU Garage

The FEU garage is an integral part of the FEU buildings, internal access to it being through the heavy equipment laboratory. It is a steel portal frame building with concrete block walls, 4.2m. high, along both sides and wooden 'concertina' type folding doors across both ends, also 4.2m. high. These doors are hinged together in four sections (each section comprising four hinged panels) and can be moved along a rail across the end of the garage, so that the entire end 'walls' can be virtually removed. (This meant that by wedging the doors in the required position a vent of any chosen width could be made in almost any chosen position at each end of the garage, making it ideal for FEU's purpose). Above the level of the doors is a pitched asbestos roof, of shallow angle, with a central longitudinal ridge (Figures 1 and 2).

Internally, the garage measures 16.0m. long by 12.5m. wide, and the effective height (used to calculate the volume) is some 5.0m. The floor is of smoothly finished concrete, and reasonably flat and level.

It was decided that in all trials the vents used should be of typical size and shape, i.e. those most commonly encountered by brigades. Three sizes would be used in the trials for inlet and/or outlet vents. These would be:

(a) single personnel access door: 1.98m. x 0.76m.
(6'-6" x 2'-6")

(b) double personnel access door: 1.98m. x 1.52m.
(6'-6" x 5'-0")

(c) domestic type garage door: 1.98m. x 2.44m.
(6'-6" x 8'-0")

This meant that wooden frames, which could be clamped in position, would have to be made to blank off the upper part of the door openings, above the 1.98m. level.

3.3 Fire Service College's Large ('Green') Garage

The Fire Service College very kindly agreed to allow FEU to use their 'green' garage for a period of one week in November 1998, in which to carry out cold smoke trials. This is a very large rectangular building (some 7,000m^3), being 39.3m. long by 33.1m. wide, with a flat roof 5.4m. high, internally. Of pre-fabricated concrete construction, the garage has four large doors, two in each long side (Figures, 3, 4 and 5). These doors, three of the 'concertina type' and one roller shutter (near the S.W. corner) are all approximately 4m. high by 4m. wide, when fully open.

It was estimated that six Le Maitre 'G-300' smoke generators[5] would be needed to smoke log this large building to any worthwhile extent, and so it would be necessary for FEU to borrow or hire generators for these trials. It was agreed that if 100% obscuration proved unobtainable, the degree of smoke logging could be expected to be the same each time if the generators were run for the same period, at the same setting, so that valid results could still be obtained. It was further agreed that only the N.W. and S.E. doors would be used as vents during the trials, to avoid inconvenience to the adjacent workshops as far as possible.

3.4 Temporary Building inside FEU Garage

It was decided to construct a temporary building inside the FEU garage, the width (and also the length, if necessary) of which could be varied. This decision was taken while the trials in the FEU garage were in progress. The reason for this was that the garage trials had shown that swirling airflow patterns were set up in the garage both with and without PPV, which cleared smoke from the building by a process of dilution. It was considered that something more may be learned about how PPV works by using it in narrower compartments, tending more towards a corridor situation.

This temporary structure should be capable of being assembled from pre-fabricated panels to give compartments of three different widths; 2.5m., 5.0m. and 7.5m. It should initially be as long as reasonably practicable, with a ceiling height of 3.0m. It should be capable of having a vent in each end of any of the three previously mentioned sizes and, in the wider compartments, the vent positions should be variable. Also, it should be possible for two of the FEU vehicles to be parked inside it overnight with the minimum of dismantling.

It was agreed that FEU would design and develop such a structure at the same time that the FEU garage trials were being carried out. Once the design was proved, local building firms would be invited to tender for the construction of the pre-fabricated sections, roof etc., either to FEU manufacturing drawings or prototype components.

4. EQUIPMENT USED IN TRIALS

4.1 General

FEU already possessed some of the items of equipment needed for the trials while others had to be located and purchased, designed and built or otherwise procured. The main items of equipment and instrumentation are listed, and very briefly described below.

4.2 PPV Fans

Two PPV fans were used during the trials. These were:

(a) 24" Tempest petrol driven fan[6)] (Figure 7).

(b) 21" Tempest petrol driven fan[6] (Figure 8).

Both fans had seven blades and each was powered by a 5h.p. Tecumseh 4 stroke petrol engine. The cylindrical casing of the 24" fan was 0.63m. in diameter and 0.2m. long, while that of the 21" fan was 0.55m. diameter by 0.17m. long. The 24" fan was rated at 9,130 c.f.m. (258m^3/min.) and the 21" fan at 8,000 c.f.m. (226m^3/min.).

Both fans had five pre-set elevation, or tilt, positions. In each of these positions a spring-loaded pin located in a hole, at each side of the supporting structure. These holes were numbered 1 to 5, by FEU, to make setting and noting the position simple during trials. These five positions gave the following tilt angles:

Hole 1 = 21° fan axis above horizontal
" 2 = 15° "
" 3 = 9° "
" 4 = 3° "
" 5 = -3° fan axis below horizontal.

4.3 Cold Smoke Generators

FEU purchased two identical cold smoke generators[5] for this work (Figure 6). Essentially, these were electrically operated (110V) self-contained units, in which a specially formulated fluid was dripped onto a heated steel block to produce an opaque white smoke at a constant pre-determined rate. The control box of each generator could be detached from the main unit and connected via a single flexible cable, making remote operation and control possible.

4.4 Smoke Obscuration Meters

All three of FEU's smoke obscuration meters were used in the trials. Essentially, each meter consisted of two components; a light emitter, and a corresponding light receiver. The receiver would respond only to the emitted light, independent of the level of visible light or radiation from any other source. These two components could be set up facing each other, at any distance (up to 8m.) apart, and could be calibrated over the range 0% to 100% obscuration, by introducing a series of filters between them.(1)

Since these instruments could be operated only at around ambient temperatures, FEU had designed and procured water-cooled jackets to protect them from the hostile environment experienced in the previous trials.(2)

Three complete assemblies were constructed. In each, the emitter and receiver, mounted in their separate cooling jackets, were set up on a pair of Unistrut(3) rails, the effective distance between them being 1.0m. After being aligned, each component was bolted solidly to the rails to form a complete unit. A steel structure was then built for each obscuration meter assembly to support the unit horizontally at an effective height of 1.5m. from the floor (Figure 9), ie. at about eye level.

4.5 Video and Red Lamps

In an attempt to find a second, independent, method of assessing the rate of smoke clearance, a set of ten red lamps was made. These each consisted of a light emitting diode marketed as an auxiliary cycle rear light, modified by FEU by having wires soldered on so that they could be connected in parallel into the mains supply via a stabilised supply transformer/rectifier. The lights were mounted each on a simple, light, stand at a height of 1.0m. above the ground.

These red lamps would be used in conjunction with a video camera, set up on a tripod near the inlet vent. They would be carefully positioned in the compartment, at known distances from the camera lens, and the times when each first became visible to the camera would be recorded.

4.6 Wind Velocity Meter

The FEU wind station(4), used in the previous trials[1,2,3], was set up on a vertical pole at a height of 7.0m. from the ground, some 40.0 m. from the north east corner of the FEU garage. (Except for the green garage trials when it was mounted from the local control room pod, at a height of 6.0m.)

This device continuously monitored the wind speed and direction during all trials. Its output was continuously logged during all trials.

4.7 Ultrasonic Anemometer Rig

4.7.1 General

An ultrasonic anemometer rig (Figure 10) was constructed to enable airflow surveys to be carried out in the FEU garage. This consisted, basically, of a sensing head mounted on a traversing rig so that it could be set to measure air movements at any height between 0.5m. and 3.5m. from the floor. The rig was built on wheels, two of which were castors, so that it could readily be placed in any chosen position. The sensing head could thus be positioned anywhere, in all three mutually perpendicular planes, within the limiting space frame. The instrument's control and data read-out elements were housed on a separate mobile trolley, connected to the sensing head via a single flexible multi-core cable.

4.7.2 Ultrasonic Anemometer

The ultrasonic anemometer[7] (Figure 11) was purchased for this work. The instrument could be used, indoors or out, to measure wind velocities (speed and direction) over the range 0m./sec.-60m./sec., with a maximum error of 1.5% between 0 and 20m./sec.

The sensing head, some 0.75m. long overall, continuously measured the wind speed simultaneously in three mutually perpendicular planes. These three measured values could be displayed directly, or could be vectorially combined to give an overall resultant velocity in any selected plane. (Note, data for two mutually perpendicular planes would be needed to completely describe the airflow in three dimensions, in this latter case). The control and data readout elements of the instrument were housed separately on a trolley, connected to the sensing head only by a single flexible multi-core cable.

4.7.3 Traversing Rig

The traversing rig (Figures 10, 12 and 21) was designed and constructed by FEU. The basic elements of this – slides, linear bearings, end plates etc. - were adapted from an old traversing table owned by FEU. These were dismantled, refurbished and re-assembled, and mounted with the slideways vertical on wheels and castors. A system using steel roller chain and sprockets was devised to support and position the sensing head, at any height between 0.5m. and 3.5m. The chain was calibrated so that the head could readily be set to heights of 0.5m., 1.0m., 1.5m., 2.0m., 2.5m., 3.0m. and 3.5m.

The sensing head could be mounted with its axis either vertical or horizontal (both had their particular advantages, in practice). In either case, a pointer was positioned directly below the head, just above floor level, so that the position of the head could be easily determined, or pre-selected, by reference to a grid drawn on the floor.

4.7.4 Processing and Display Elements

All of the equipment concerned with powering the anemometer and with processing and displaying its output was mounted on a steel trolley, rather like a heavy duty tea trolley, along with the read-out box of the external windstation. (See Section 4.6) (Figure 13). Initially, this consisted of a 'power and communications interface' box, which was part of the anemometer, and a laptop computer[8], to process and display the data.

It was found in practice, that the display was difficult to read over long periods in the conditions prevailing during a survey, and so an analogue readout[9] was procured and tried. This gave the windspeed in each of the three mutually perpendicular planes, displayed on three dials each of 70mm. diameter. These displays needed to be switched to one of three available ranges, for each reading, in order to cover the range of 0-10 m./sec. (It would still be necessary to further process the data to obtain vector quantities which could be plotted on a 'weather chart' type drawing.)

However, during the later surveys when the instrument read-out was in polar co-ordinate mode (speed and angle in a single, selected, plane) it was found that using a larger, and somewhat clearer, VDU monitor[10] made the display acceptably easy to read.

4.8 Data Logger

During all of the cold smoke trials, the outputs from the three smoke obscuration meters and that from the wind velocity meter were continuously recorded by the FEU's data logger[11]. The logger was connected to a computer which was programmed, using commercially available software[12], to display essential monitoring data in the local trials control centre. (Housed in the FEU heavy equipment laboratory during the trials in the FEU garage, and in an adjacent pod during the trials in the green garage.)

4.9 Temporary Building

The temporary building, consisted, essentially, of ten free standing side panels each 1.22m. (4'0") wide by 3.0m. high, and six end frames – three at each end – each 2.5m. wide by 3.0m. high. The ten side panels formed one wall of the compartment, the other side being formed by the north wall of the FEU garage, (Figures 14, 15, 16 and 17).

The end walls needed diagonal legs, one per frame, bolted to the floor since, with the garage doors fully open, they would experience the full force of the natural wind, plus a component from the PPV fans.

The end walls were each made in three 2.5m. wide sections so that a compartment width of 2.5m., 5.0m and 7.5m. could be obtained. Also, the 12.19m. (40'0") length could, if required, be reduced in increments of 1.22m. (4'0"). All of the end frames were left open below the level of 1.98m. (6'6") in order to make it possible to position any sized vent anywhere, within certain limits, in either end of the compartment. Blanks were then made to fit these frames, so that each could have either:

(a) no vent;

(b) a single personnel access doorway, 1.98m. x 0.76m. (6'6" x 2'6");

(c) a double personnel access doorway, 1.98m. x 1.52m. (6'6" x 5'0");

(d) a garage doorway, 1.98m. x 2.44m. (6'6" x 8'0").

These blanking panels were made to be removable, as readily as possible, so that trials scenarios could be quickly changed, and vehicles could be parked inside the structure overnight, if necessary.

The wall partitions, end frames and blanks were made essentially from 102mm x 51mm (4" x 2"), 76mm x 51mm (3" x 2"), 51mm. x 51mm (2" x 2") and 38mm x 38mm (1.5" x 1.5") sawn timber, clad with 6mm. plywood, with 12mm. ply shear plates where necessary. Some mild steel components were incorporated where necessary for local strengthening, location or fixing.

The bulk of the frames necessary to construct this adjustable compartment were made by a local building firm[13] to FEU's specification. FEU made one of each main item to test the feasibility of the idea and prove the design, and these were then used by the builders as prototypes in lieu of drawings.

With the temporary side wall in its maximum width position, a very light untrussed roof was constructed. This consisted of eleven 102mm. x 51mm. (4" x 2") horizontal timber beams, 8.0m. long, each supported at one end by the side panels and at the other by beam hangers fixed to the wall of the garage. Longitudinal stringers (38mm. x 19mm. roof laths) were fixed at 600mm. (2'0") centres to the undersides of the beams, to cover the whole of the roof area. Slabs of expanded polystyrene, 2.44m. x 1.22m. x 50mm. (8'0" x 4'0" x 2") were fixed to the undersides of the stringers by means of fast helix woodscrews and aluminium repair washers at 600mm. nominal centres. The slabs were cut, where necessary, to fit closely against each other and to the walls to render the compartment as leaktight as practicable.

4.10 Doorway Defining Blanks for Garage

It was found that the width of a vent, representing a typical doorway of one sort or another, could be fixed by carefully wedging and propping the garage 'concertina type' doors. However, since the garage doors were 4.27m. (14'-0") high, and the required height of the vents was 1.98m. (6'-6"), the top part of the gap needed to be blanked off.

To achieve this wooden frames were constructed of 38mm. (1.5") square sawn timber, and their upper parts were covered with heavy duty polythene 'damp proof membrane', as used by the building industry in solid floors. These frames were freestanding and could, by fixing suitable clamping strips where necessary, be clamped to the edges of the garage doors. The inside dimensions of these frames thus defined the size and shape of the vent (Figure 18). Two such frames for each size of vent; single personnel door, double personnel door and garage door, were constructed.

Also, blanking frames were made, using the same materials, with which to seal the vents while the compartment was being smoke logged. These were designed to be propped in position from outside, so that they could be quickly removed at the start of a trial.

Triangular plywood blanks were also made to seal the voids formed at the top edges of the garage doors when wedged open. A system of improvised clamps and wedges was devised to ensure that these high level blanks were securely, and safely, fixed in position.

4.11 Garage Door Sealing Strips and Blanks

The FEU garage doors were found to be very 'leaky' when the building was first smoke logged. These doors consisted, at each end of the garage, of sixteen wooden sections, each 4.27m. (14'-0") high by 0.82m. (2'-8¼") wide and 0.068m. (2.6") thick. These were hinged together in four groups of four, with four large steel hinges equally spaced vertically from each other at each hinged joint. It was therefore inevitable that there should be gaps (of up to 10mm. in width) between the sections, and where the end sections hinged to the walls at the corners of the building.

To overcome this problem, a large number of strips of foam rubber were made, each some 40mm. (1.6") square and 0.56m. (1'-10") long. These were sawn from cushion sized pieces, and were ideal for sealing the gaps around the doors. They could be squeezed into quite small gaps where they expanded to form an efficient seal.

By these means the 'leakiness' of the garage could be greatly reduced, and was brought more into line with that of a conventional building of comparable size.

5 TRIALS METHOD

5.1 General

The underlying purpose of the trials was simple: to assess the effect of PPV in 'large' compartments. In order to do this cold smoke trials were performed in five different compartments ranging in volume from 90m.^{3} to some 7,000m^3. (The domestic room[2] was 53m.^{3} in volume.)

In this Section, the sets of trials performed are described in chronological order. This is because of the learning curve involved; various methods and techniques were tried during the earlier trials, some were adopted throughout all subsequent trials, some needed to be modified somewhat, and still others were subsequently abandoned. The first series of trials to be undertaken was that in the FEU garage, the second largest building used. The 'green' garage trials (by far the largest building) were next undertaken, followed by the three sets of trials in the temporary compartment in descending order of size. (In Section 6, this order is modified in order to deal with the largest building first, and the smallest last.)

The cold smoke trials were performed in pairs throughout. In each pair of trials PPV was used in one and natural ventilation, only, in the other. Everything else was kept identical: the same vents were used, nothing was moved within the compartment, the compartment was smoke logged by the same smoke generator/s identically set up, for the same period of time before the vents were opened. The second trial of a pair followed the first as quickly as possible so that the natural wind conditions would (probably) be, at least, similar.

The bulk of the trials were performed in the FEU garage, although some were performed in smaller compartments (within the FEU garage), and a limited number were performed in a much larger building; the Fire Service College's 'green' garage. The reason for this was that, as well as being convenient geographically, the FEU garage lent itself to the work since:

(a) Its size and shape made it fairly typical of a very large number of buildings (some 1,000m.^{3}).

(b) It had, in effect, removable ends, making it possible to site vents of any selected shape and size almost anywhere in the ends of the building.

(c) It has a smooth, flat floor, which made accurate positioning of an anemometer, at any height, possible.

(d) It could be made virtually leaktight, typical of many similarly sized buildings.

(e) It could be cleared of vehicles and other equipment for all trials, hence ensuring identical conditions within the building.

During all cold smoke trials in the uncompartmented garage, the three smoke obscuration meters were placed in the compartment, as were the red lamps and video camera and recorder. The position of each piece of equipment was recorded on a plan view drawing of the compartment for each trial, along with the sizes and positions of the vents.

In all trials a single inlet vent and single outlet vent were used. The vents were one of three different sizes, these being:

(a) single personnel access door – 1.98m., x 0.76m. (6'6" x 2'6");

(b) double personnel access door - 1.98m. x 1.52m. (6'6" x 5'0");

(c) garage door - 1.98m. x 2.4m. (6'6" x 8'0").

For convenience, the positions and sizes of the vents used in the trials were recorded by referring, initially at least, to that particular orientation as a 'scenario'. Hence, the first trials carried out were 'scenario A', then when the positions and/or sizes of the vents were changed (to represent a different building) this new set up became 'scenario B'. However, the positioning of the smoke obscuration meters could be (and was) changed between pairs of trials, within a single scenario. The 'scenario' designation simply identified the geometry of the compartment and its vents, and this held true whichever vent turned out to be the inlet vent, on the day. (This was decided by the direction of the natural wind immediately before the trials commenced, the PPV fan being positioned to assist the natural wind. This apparent natural inlet vent was designated the 'inlet vent' for that pair of trials, irrespective of any subsequent changes in the natural wind.)

When a single PPV fan was used, it was the 24" Tempest[6]. It was positioned outside the (natural) inlet vent in a position intended to 'seal' the vent: ie. to prevent any airflow out of the vent, unless stated otherwise. This sealing distance proved, in general, to be 2.5m. for both the single and double personnel access doors, and 3.0m. for the garage door. These distances from the vent were fixed upon, and were used throughout all trials, marks being painted on the ground to enable the fan to be quickly and consistently positioned.

In some trials two PPV fans were used simultaneously. These were the 24" Tempest[6] and the 21" Tempest[6] during such trials in the FEU garage and the 'green' garage, but a later set of trials used two 24" Tempest fans in the 2.5m. wide compartment in several different orientations, at the request of a brigade. (See Section 6.6.2.) Fans were employed both in tandem (one behind the other) and side by side. When used in tandem, the aim was that the fan furthest from the vent should form a seal around the vent while the whole of the output of the closer fan should enter the compartment. When the fans were used side by side the aim was to get as much of their combined output into the compartment as possible while also maintaining a seal. When the fans were used in tandem, the larger (24") was placed further from the vent. In all cases where two fans were used, their positions relative to the vent were recorded on the trial record sheet, and this was filed with the relevant data.

The smoke obscuration readings were logged at five-second intervals during all trials except those conducted in the 5.0m. wide, and 2.5m. wide, compartments when the interval was reduced to 1.0 second. The data, from the three meters was subsequently plotted against time (zero time, in all cases, being the moment when the vent blanks were simultaneously removed). Also, in the FEU garage trials, a videotape was produced for each trial, from a camera positioned just inside the inlet vent and a little to one side. The data from these videos was subsequently processed manually, thus. Elapsed times were noted when each red lamp, each a known distance from the camera lens, first became visible, and also the time after which it remained visible. These 'visibility distances' were then plotted against elapsed time. Finally, as a check, the results given by these two different methods of assessing the changing visibility were compared with each other. A graph of 'visibility distance' (from the video evidence) was plotted against obscuration (the average value from the three meters), the values being taken off the previously plotted graphs at one-minute intervals. (If the results obtained from these two methods were in perfect agreement a straight-line graph would result.) Typical examples of these graphs are given in Figures 40 and 41).

During all trials the speed and direction of the natural wind were recorded over the entire duration of the trial. Both speed and direction were plotted against time, and an average value for each was calculated. These average values were subsequently recorded on the trial record sheet.

During the trials period in each different sized compartment (other than the 'Green' garage) a series of air movement surveys were undertaken, using the ultrasonic anemometer. The results of these surveys were plotted in the manner of a weather chart, in all cases.

Unless otherwise stated:

(a) the 24" fan was used in all cases where a single PPV fan was employed;

(b) the fan was positioned on the centreline of the inlet vent, and set 2.5m. back from the vent for 0.76m. (2'-6") and 1.52m. (5'-0") wide vents, and 3.0m. back from the 2.44m. (8'-0") wide vent;

(c) the fan was tilted back, using the built-in adjustment, so that it appeared to best effect a seal around the doorway. (A line of sight along the fan's axis bisected the vent at about half its height from the ground.);

(d) when two fans were employed simultaneously, they were a 24" and a 21" fan. In these cases the fan positions are described for each separate trial.

5.2 FEU Garage – Trials Procedure

5.2.1 General

The garage was initially cleared of all equipment, as far as possible. The only items to remain in the building not directly concerned with the trials were an open fronted cupboard, full of garage equipment and supplies, and two sets of steel steps, of light tubular construction. These latter, were necessary for blanking off and sealing the gaps around and above the doors at the start of each day of trials, and removing blanks etc. at the finish, so that the garage could be closed and secured. The cupboard remained in the same position throughout all trials, while the steps were stored in the same positions during the trials of each scenario, and always close to a corner away from all vents.

A grid was accurately drawn on the floor with a 'magic marker' pen, symmetrically positioned, to divide the area into 1m. squares. The lines running north-south, across the garage, were numbered 1 to 15, while those running east-west, along the garage, were given a letter: 'A' to 'L' (Figure 19).

In order to outline the procedures adopted during the trials, and the air movement surveys, a typical day of trials, and an airflow survey, will now be described.

5.2.2 Cold Smoke Trials

The first task was to drive all vehicles out of the garage and park them well away from the anticipated vent positions. The wind station readout was switched on and studied, and a decision made concerning which end of the garage was most likely to be upwind and therefore the inlet end. (Although it took at least two hours of preparation before the first trial of the day could commence, this early assessment was usually, but not always, correct.)

The scenario, or positions and sizes of the vents, to be examined was decided; the garage doors were wedged and propped in position and the vent defining frames erected and clamped into position at each end of the compartment. The gaps around and above the doors were then sealed, using plywood blanks clamped above the opened door sections and strips of foam rubber in all vertical gaps between the door sections, and under the doors.

The smoke generators were fuelled, overhauled, positioned and switched on to warm up. Also, the PPV fan/s to be used was overhauled, fuelled and run, outside the building, to warm up. The smoke obscuration meters were positioned, connected, and switched on. All instrumentation was switched on to warm up, and be checked through. The red lamps were positioned, connected into the mains via a DC laboratory power supply (stabilised transformer/rectifier)[14] and switched on.

The video camera, recorder, etc. was brought from the FEU video room, on a trolley and positioned just inside and to one side of the inlet vent, connected, and set up. The smoke obscuration meters' windows were cleaned, and the calibration of each meter checked. All physical measurements, and the position and orientation of all equipment was checked and recorded.

The vents were next blanked off, the blanks being propped in position with wooden props and bricks in such a way that they could be readily removed, from outside the building, at a given signal. Foam rubber strips were again used to render these blanks as leaktight as practicable and the PPV fan/s was set in position.

A final check of all systems was made. The trials officer then entered the garage, donned the lapel microphone connected into the video recorder, checked its operation, then started the video recorder. He then came out of the garage, ensuring that all ceiling lights were turned off, into the adjoining heavy equipment laboratory, closing the interjoining door, and started the smoke generators. At the same instant the second operator started two stopwatches.

The smoke logging was monitored from the trials instrumentation pod. After 11 minutes of smoke logging, the data logger was switched on, to record all obscuration readings and the natural wind speed and direction. After 14 minutes of smoke logging (two Le Maitre 'G.300s' 'flat out') the smoke generation was stopped, and the operators walked briskly to their pre-determined vents. After a short countdown, both vents were removed simultaneously, the trials operator pressing an 'event' button to put a mark signifying 't=0' onto all of the data being recorded. (The audible countdown being recorded on the video record.)

In the trials where PPV was used, the pre-positioned fan was run up to maximum power as quickly as practicable after the blanks were removed. The fan having been pre-warmed, this was generally achieved within 10 seconds of 't=0'. (During later trials in smaller compartments - where any variations in timing would be more critical - the fan was run up first, and then the vents removed at a pre-determined signal, while the fan was running at full power.)

The trial was monitored from the instrumentation pod, while the trials officer walked around outside the building, giving a commentary upon what appeared to be happening, this being recorded by the video. The trial was terminated when all of the smoke obscuration values had reduced to about 5%, which meant that the garage was to all intents and purposes, clear of smoke. The video tape and computer disk were labelled and filed.

For each trial a plan view sketch was made of the garage to record the sizes and positions of the vents, the positions of the PPV fans, when used, etc. This sketch was filed with the data obtained from the trial, and a vector representing the natural wind (average speed and direction over the duration of the trial) was subsequently superimposed onto it. Examples, scaled down, are given in Figures 84-90 inclusive.

After the last trial of the day all instruments were switched off, and disconnected and moved, where necessary. The sealing strips, blanks and vent-defining frames were removed, and the vehicles returned to the garage; which was secured overnight.

5.2.3 Air Movement Surveys

Air movement surveys were carried out in the FEU garage using the ultrasonic anemometer rig (Figures 10, 11 and 12). The anemometer's sensing head was accurately positioned at each required point in the plan view by reference to the grid marked on the garage floor, and its height was fixed by means of the calibrated roller chain support system built into the rig. In all surveys the 24" Tempest PPV fan was set up 2.5m. outside the vent to assist the natural wind. The fan was refuelled at approximately 40-minute intervals, to avoid running dry, which could possibly have caused subsequent running problems.

It initially required two operators to undertake a survey, basically, one controlling the anemometer rig, and the other controlling the read-out trolley, which was connected to the anemometer by some 10m. of cable, and recorded all data. (Figure 13) (The rig was later simplified so that a single operator could complete a survey, at a single height of 1.5metres, in the smaller temporary compartments within the FEU garage - see Figure 20)

After setting up the required scenario, as outlined in Section 5.2.2, one operator moved the anemometer rig from point to point on the floor grid, locked its position and orientation by applying the brakes, set the anemometer to the required height, and then retired to a distance of at least 5m. from the anemometer. Once the anemometer was in position the second operator positioned the trolley as far from the anemometer as was reasonably practicable, waited until the first operator was clear, and air movements due to his movements had subsided, then watched the anemometer read-out for a period of some 10-15 seconds and manually recorded the average of the data displayed over this period, as well as the data from the outside wind station. This procedure was repeated until data for every required point in space had been obtained.

During the early surveys the anemometer was mounted with its axis horizontal (Figure 21). It was programmed to give a read-out of air speed in three mutually perpendicular planes, designated 'U', 'V' and 'W'. The anemometer rig was therefore always (as far as possible - see below) orientated with the anemometer pointing towards the east end of the building, aligned with the floor grid lines, so that +ive 'U' was north, +ive 'W' was east and +ive 'V' was vertically upwards. With the anemometer in this mode, the data obtained could be manually processed (a trigonometrical calculation) to give vector quantities, both in plan view and in vertical cross section which could subsequently be plotted onto 'weather chart' type drawings. The vector quantities resulting from these surveys were finally plotted onto a plan view of the building, using the grid, which also showed the vents, and fan position. Longitudinal vertical cross sections were also produced, in the same way. Subsequently a vector representing the average natural wind over the duration of the survey, drawn to the same vector scale, was superimposed upon the plan view charts, where practicable. (Figure 47, for example).

Subsequent study of the vertical cross section charts suggested that the vertical components of the airflows were, in general, small in comparison with the horizontal components. The decision was therefore taken to ignore the vertical components in any further surveys, in order to simplify and speed up the procedure. This meant that the anemometer rig could now be modified to mount the anemometer vertically and it could then be programmed to add the two horizontal components vectorially and read out the data in the form of a resultant air speed and an angle (relative to north). These modifications were carried out, and this greatly simplified the data recording and processing part of the exercise in subsequent surveys.

One slight difficulty with the use of the anemometer rig in the FEU garage was that, for the data to be simply recorded direct from the instrument, the orientation of the rig had to be known and kept constant throughout the survey. While this was easy to achieve over most of the survey, it was not always possible due to the geometry of the rig, and the closeness of the outer grid lines to the walls the doors of the garage. Prior to the modification the rig needed to be turned through 180°, about a vertical axis in order to reach the 'No.1' grid line while, after the modification it needed to be turned similarly to reach the 'A' grid line. This meant that the data taken anywhere on this grid line needed to be reversed, for this single line, only. This was done in all surveys.

During the early surveys, plan view charts were produced at heights of 0.5 metre, 1.0 metre, 1.5 metres and 2.0 metres, using the same scenario. Also, vertical cross sections were produced on a grid line close to the centreline of both the inlet and outlet vents, using data taken at heights of 0.5 metres, 1.0 metres and 2.0 metres, this latter being just above the level of the tops of the vents. Subsequently, plan view charts were only made for a single height; 1.5 metres from the floor, this representing approximately the level of a firefighter's eyes.

5.3 Green Garage Trials

Since the 'green' garage was available to FEU for a period of one working week, only, and all equipment needed to be transported to and from the site and set up within this period, the trials were, of necessity, rather simpler than had previously been undertaken in the FEU garage. Again, pairs of trials were performed, each pair consisting of one in which PPV was used, and one using natural ventilation, only. The only instruments used in these trials were the three smoke obscuration meters, and the (natural) wind station.

In order to be able to smoke log this large building (some 7,000m.^{3}) in a reasonable time (in the event 14 minutes were allowed), six smoke generators were required. Le Maitre Ltd., the manufacturers of FEU's generators, very kindly loaned FEU four 'G.300' generators and all necessary cabling for the duration of the trials. On the first morning of the building being available, their representative brought the equipment to the site and connected it up so that all six generators could be operated from a single control panel sited just outside the building, near the control pod. (Figure 22)

The wind station was mounted atop the control pod, some 2m. above the highest parts of the adjacent roof.

In conducting the trials, the procedure was identical to that used in the FEU garage trials (Section 5.2.2), except that when PPV was employed the fan/s was started and run up just before the vents were opened. Radio communications were used to synchronise the vents opening, and while testing the instruments. At the start of each day of trials, all vehicles were removed from the building and parked well away from the intended vents. The garage was thus virtually empty except for some equipment stored semi-permanently; this was positioned close to the walls and was not moved during the trials period.

In all, 14 trials were completed. Essentially, the trials were designed to examine whether the use of one, or two PPV fans (24" and 21") could make any significant different to the time taken to clear smoke from this large building (the vents were also large; some 4 metres high by 4 metres wide when fully open).

The complete detailed list of trials completed in the green garage is given below in chronological order. Reference is made to sketches (Figures 23 to 26 inc.) to explain the positioning of the fan/s relative to the inlet vent, where necessary rather than give lengthy descriptions.

The inlet vent was fully open unless stated and the outlet vent was always fully open.

Green 1. Single 24" fan on centre line of vent, 2.5 metres outside.

" 2. As 1. above, no PPV.

" 3. Two fans side by side - see Figure 23.

" 4. As 2 above, no PPV.

" 5. Two fans, one above the other, vent only opened to 1.82m. (6'-6") – see Figure 24.

" 6. As 5 above, vent fully open, no PPV.

" 7. Two fans <u>in</u> vent - see Figure 25.

" 8. Similar to 3. above, but different fan positioning - see Figure 26.

" 9. Two fans, one behind the other – both on vent centreline, 21" <u>in</u> vent, 24" - 2.5m. outside – vent only opened to 2.13m. (7'-0").

" 10. Immediately after 9. above, no PPV.

" 11. No PPV (rather different natural wind).

" 12. Single 21" fan in vent, on centreline.

" 13. Single 24" fan in vent, on centreline, vent only opened to 2.13m. (7'-0").

" 14. No PPV, vent fully open.

5.4 Temporary Compartment Trials

5.4.1 Cold Smoke Trials

Three series of cold smoke trials were carried out with three different widths of compartment: 7.5m., 5.0m. and 2.5m. Both the length of the compartment – 12.19m. (40'-0"), and the height – 3.0m. (9'-10") remained the same throughout all trials. The volumes of these compartments were therefore: 274.3 cubic metres, 182.8 cubic metres and 91.4 cubic metres, respectively. In each series (at each compartment width) a number of scenarios, or combinations of vent sizes was tried. The vent sizes used were those previously used in the FEU garage trials:

(a) single personnel access door - 1.98m. x 0.76m. (6'-6" x 2-'6")

(b) double personnel access door - 1.98m. x 1.52m. (6'-6" x 5'-0")

(c) garage door - 1.98m. x 2.44m. (6'-6" x 8'-0").

In all trials, at all three compartment widths, the vents were positioned on the centreline of the compartment.

With each of three compartment widths used, a pair of trials – with and without PPV – was performed with every possible combination of inlet/outlet vents; eighteen trials (at least) in each compartment.

During all trials the garage doors were fully open so that the temporary building would represent a separate free standing building, as far as possible. However, it was not possible to achieve this fully, as the vents were shielded from the natural wind by the garage doors and/or the 'simlab' building in many cases (Figure 27). (In the case of the 2.5 metre wide compartment, the end section of the garage doors had to be unhinged completely and moved to the other side of the garage, at each end.)

The underlying trials method employed was that previously described for the FEU garage trials (Section 5.2.2), except that no video was used. Again, trials were conducted in pairs; one using PPV, the other using natural ventilation, only. The second trial of a pair followed as soon as practicable after the first so that the natural wind would, hopefully, remain similar during both trials.

In the trials during which PPV was employed, the fan was started and run up to full power just before the vents were simultaneously opened; it was in position and had been idling during the 'smoking up' process, unlike the previous FEU garage trials. This was because it was considered that when ventilating smaller compartments the effects would be more immediate and, since the time taken to start and run the fan up could vary by up to some 10 seconds, fairer comparisons could be made between the effects of PPV and natural ventilation.

The three smoke obscuration meters were pre-positioned in the trial compartment for each trial, always at a height of 1.5m., the existing floor grid being used to record their positions, in all but the 2.5 metre wide compartment in which a new grid was used. These positions, referring to the floor grid (Figure 19), were:

in the 7.5m. wide compartment; No.1 at G12, No. 2 at I18, No.3 at K14

in the 5.0m. wide compartment; No.1 at H/I12, No.2 at J8, No.3 at K/L4
('H/I' here means midway between the 'H' and 'I' lines)

and in the 2.5m. wide compartment; No.1 at Z12, No.2 at Y8, No.3 at X4.

Two 'G.300' cold smoke generators were used throughout to smoke log the compartments. These were positioned relative to each other so that their tendencies to initiate a swirl in the compartment would, largely, cancel each other out. For each size of compartment, the same time was allowed in each trial for smoke logging, the generators being pre-set to deliver their maximum output. The times used were those sufficient to give 100% obscuration throughout the compartment plus one minute. The times were:

2.5 minutes in the 7.5m. wide compartment

1.5 " 5.0m. "

1.5 " 2.5m. "

A limited series of trials was subsequently performed in the 2.5 metre wide compartment, using two 24" Tempest fans, to compare various possible tactics.

5.4.2 Air Movement Surveys

Air movement surveys were carried out in the temporary compartment in a similar way to those in the FEU garage. However, the decision having been made to carry out surveys at a height of 1.5 metres only, a simplified rig was designed to support and locate the ultrasonic anemometer. This modification made it more suitable for single handed use, and made it possible to position and orientate closer to the walls.

The same floor grid was used to position the instrument while making measurements, and for plotting results, while working in the 7.5 metre and 5.0 metre wide compartments, but a new grid was drawn for the 2.5 metre wide compartment to allow a more symmetrical positioning of the longitudinal lines.

As with the corresponding cold smoke trials, all surveys were performed with a vent at each end of the compartment. These vents were on the longitudinal centreline of the compartment in all cases, and again, the same three vent sizes were employed, these being:

(a) single personnel access door: 1.98m. x 0.76m.
(6'-6" x 2'-6")

(b) double personnel access door: 1.98m. x 1.52m.
(6'-6" x 5'-0")

(c) garage door: 1.98m. x 2.44m.
(6'-6" x 8'-0").

With the 7.5 metre wide compartment, surveys were undertaken with the following vent arrangements:

2'-6" inlet - 2'-6" outlet

2'-6" inlet – 8'-0" outlet

5'-0" inlet – 5'-0" outlet (twice – different natural wind conditions)

8'-0" inlet – 2'-6" outlet (twice – different natural wind conditions).

In both the 5.0 metre and 2.5 metre wide compartments a total of nine surveys were completed, every possible combination of inlet and outlet vent sizes being included. All of the data was recorded in the form of a weather chart and the average natural wind was subsequently superimposed onto these charts, to the same vector scale. (Figures 55, 62 and 72 are examples.)

6 TRIALS RESULTS, PROCESSING AND INTERPRETATION

6.1 General

The results of the trials performed in the five different compartments are treated separately in Sections 6.2 to 6.6 inclusive. In each case the scenarios being examined and the data obtained from each are given in tabular form. The trials are dealt with and tabulated in order of decreasing compartment size.

6.2 'Green' Garage Trials

The results of the cold smoke trials conducted in the green garage are brought together and summarised in Table 1. This table was constructed from the data obtained during the trials by the data logger, and other information derived from this.

A sample package of the raw data (that for trial no. 7) is given in Figures 28 to 33 inclusive. This data consisted of:

(i) Plot of obscuration Vs. time - meter no. 1 (Figure 28)

(ii) " " - meter no. 2 (Figure 29)

(iii) " " - meter no. 3 (Figure 30)

(iv) " " - the above three superimposed upon each other, (colour coded) with the calculated times for the average of the three meter readings to reduce to 40%, 20% and 10%. (Figure 31)

(v) Plot of natural wind speed Vs. time, with calculated average. (Figure 32)

(vi) Plot of natural wind direction Vs. time, with calculated average. (Figure 33)

It should be noted that in (i), (ii) and (iii) above, the curves were smoothed by taking an eleven point moving average. This was done in order to make it easier to see the underlying trends and make the curves easier to compare, since the raw data was rather 'spiky'. (See Figure 31)

In (iv), (v) and (vi) above, the averages were calculated over the duration of the trial; ie. From 'time=zero' until the logger was stopped.

In Table 1, the first column gives the trial number, showing the chronological order in which the trials were performed. The second column indicates when PPV was used and how many fans were deployed. The third column outlines the tactic used (making reference to further Figures in some cases), and the fourth and fifth columns give the natural wind data as recorded by the wind station some 2.0 metres above the flat roof. The sixth column indicates which vent was designated the 'inlet vent' (a question mark in this column indicates that there is some doubt about whether the said vent, in fact, acted as the inlet throughout the entire trial). The seventh column gives the value of the component of the natural wind along the vent axis – that is blowing directly into the inlet vent – averaged over the duration of the trial. The eighth column gives the elapsed times from when the vents were opened, in minutes and seconds, for the average obscuration to reduce to 40%, 20%, 10% and 5% respectively.

No airflow surveys were attempted in the 'green' garage.

6.3 FEU Garage Trials

6.3.1 General

Both cold smoke trials and airflow surveys were undertaken in the FEU garage. The results of both are introduced below.

6.3.2 Cold Smoke Trials

The results of the cold smoke trials conducted in the FEU garage are brought together and summarised in Table 2. This Table was constructed from the data obtained during the trials by the data logger and other information derived from this.

A sample package of data recorded during a trial (no. 15/4/98: No.1 in this case) is given in Figures 34 to 41 inclusive. This is typical of the data packages collated for each trial, and is listed here in the order in which it is filed in the trials results folders.

(i) A scale plan view sketch of the building showing the positions and sizes of the vents, the location of the PPV fan, the positioning grid – 1.0 metre squares – and the positions of all smoke obscuration meters, light emitting diodes (red lamps), and the video camera. The average velocity of the natural wind during the trial was subsequently superimposed onto this sketch to assist with the results analysis.

(ii) Plot of obscurationVs. time - meter no. 1 (Figure 34)

(iii) " " - meter no. 2 (Figure 35)

(iv) " " - meter no. 3 (Figure 36)

(Note that in (ii), (iii) and (iv) above, the curves were smoothed by taking an eleven point moving average of the raw data used to produce the overall, three curves superimposed, plot (v) below.)

(v) Plot of overall average obscuration; the above three superimposed upon each other (colour coded). Subsequently, the times for the average reading of the three meters to reduce to 40%, 20% and 10% were calculated and printed upon this sheet. (Figure 37)

(vi) Plot of natural wind speed Vs. time; with calculated average superimposed. (Figure 38)

(vii) Plot of natural wind direction Vs. time, with calculated average superimposed (Figure 39). (In v, vi and vii above, the averages were taken over the duration of the trial, ie. From 'time=zero' until the logger was stopped.)

(viii) Video viewing log. This pre-printed form was filled in while subsequently watching the video of the trial, and simultaneously listening to the observer's commentary recorded on the same tape. The primary objective was to record the time when each red lamp: a) first became visible, and b) remained visible. Some quotes from the commentary were also noted, at the right hand side of the form. All of this was later taken into account when assessing the overall results.

(ix) Smoke obscuration meters/positions comparison sheet. These comparisons were done for each trial : a) to decide, initially, whether there appeared to be a preferred position in which to site the meters in subsequent trials, and b) to assess the swirl effects and find out if one area cleared significantly faster than another.

(x) Plot of 'visibility distance' (video camera lens to red lamps) Vs. time graph by constructing another (distance) scale at the right hand side. (Figure 40). Two lines were plotted; a green one showing when each lamp in the main diagonal line first became visible, and a red one showing when they last became, and remained, visible. It was agreed that it was this latter time which should be used in subsequent comparisons.

(xi) Finally the "visibility distances, found from (viii) and (x) above, and the average smoke obscuration were plotted against each other. (Figure 41) (If the agreement between the results of the two different methods of assessing the level of visibility had been perfect, the result would have been a straight line on this graph.) Since it was not known which of these two quite different methods would yield the most useful information for firefighters, this procedure was continued throughout the trials to determine by how much the results of the two methods varied, within the same trial, and whether there was a consistent difference in the overall results yielded by the two methods.

Most of the data contained in these packages - that most relevant to firefighters - was incorporated into Table 2. In this table, the first column gives the trial number, showing the chronological order in which the trials were performed. The second column shows whether PPV was used, and indicates the trials in which two fans were used. (The notes below the table elaborate on this.) The third column states the sizes of the vents used and also gives an indication of the relative positions of the vents. Only the three "standard" sizes of vent were used: 2'-6" x 6'-6", 5'-0" x 6'-6" and 8'-0" x 6'-6". In this column, '2'-6"→8'-0"' means that the inlet vent was 2'-6" wide and the outlet vent was 8'-0" wide, the arrow indicating the (intended) direction of flow. The word 'diagonal' in this column means that the vents were fairly close to the diagonally opposite corners of the building. The fourth column gives the inlet/outlet area ratio of the vents; being simply the cross-sectional area of the inlet vent divided by that of the outlet vent, rounded off to a single place of decimals. The fifth and sixth columns, together, give the natural wind data - average values - recorded by the wind station over the duration of the trial. The seventh column gives the average value of the component of the natural wind along the vent axis ie. blowing directly into the vent.

The eighth column in Table 2 gives the elapsed times, from when the vents were opened, in minutes and seconds, for the average obscuration to reduce to 40%, 20% and 10%. In this column, certain of the trials have been marked by a number superimposed on the '10%' column, thus '(1)'. This is to readily identify them, to make it easy for comparisons to be made in the next column. The ninth column gives the percentage of the time taken by natural ventilation for the average obscuration to fall to 40%, 20% and 10%

respectively. The pair of trials being compared is indicated by a pair of numbers superimposed onto the '40%' column, thus '(½)'. This means that the stated values are those obtained when the times for trial '(1)' (previous column) are divided by the times for trial '(2)' and multiplied by 100%. This is simply an attempt to readily show by how much the use of PPV speeded up the smoke clearance although, obviously, care has to be taken in deciding which pairs of trials can be reasonably fairly compared. (Same set-up, similar natural wind conditions, etc.) Again, notes are appended below the Table to explain its meaning.

6.3.3 Airflow Surveys

During the early surveys the data was read out as air speed, only, in three mutually perpendicular planes, so that a calculation was necessary to convert the data into vector form, for each point, to facilitate plotting. The rig was later modified to give a read-out in polar co-ordinates in the plan view, which could be plotted directly.

Data was subsequently plotted onto a plan view of the garage, and onto longitudinal vertical cross-sections in line with the vents, in the manner of a weather chart. On these charts (see below), the arrows represent vector quantities: they show the direction of the local air movement and their length gives an indication of the local air speed. (The scales stated on these charts should be ignored in the following Figures, since the charts have been reduced significantly for publication in report form.)

Figures 42, 43 and 44 show the charts produced from data taken at heights of 0.5 metres, 1.0 metres and 2.0 metres respectively, with the same arrangement of vents, diagonally offset from each other, in all cases, while Figure 45 shows a chart for 1.5 metres height made with a different arrangement of vents. It should be noted that the surveys were carried out on three different days, and hence with different natural wind conditions. Nevertheless, the swirl patterns established in the building, when the vents are diagonally opposite each other, can be clearly seen in these charts. Furthermore, it can be seen that these swirl patterns are broadly similar to each other.

Figure 46 shows a chart plotted on a longitudinal vertical cross section of the building, in line with the inlet vent. This chart, and a small number of others, show that vertical components of the airflow were generally small in comparison with the horizontal components, and that there was little overall difference between the airflows at the various levels surveyed. Vertical surveys were therefore discontinued, in this and subsequently examined compartments.

Figures 47 and 48 show two plan view charts plotted from data taken at a height of 1.5 metres, with identical vent arrangements, but on different days and hence in different natural wind conditions. (The average natural wind vector is superimposed upon both of these Figures.) These Figures show that, in both cases, when the vents were on the building centreline there was a flow along the centre of the building, virtually direct from vent to vent, and a more or less symmetrical swirl outwards at the outlet end, to each side of centre, with a tendency for the flow to be reversed locally near the walls and to be, generally, relatively slower. This basic pattern was evident in both charts; with the natural wind both blowing directly into the inlet vent (on average) and at roughly 45° to the inlet vent, although it is clearly more symmetrical in the former case. Also, interestingly, in neither case did any velocity measured within the building exceed, or even closely approach, that of the average natural wind measured outside.

6.4 Temporary Compartment Trials: 7.5 metres Wide

6.4.1 General

Both cold smoke trials and airflow surveys were undertaken in the 7.5 metre wide compartment, all with vents positioned on the longitudinal centreline. The results of both are introduced below.

6.4.2 Cold Smoke Trials

The results of the cold smoke trials conducted in the 7.5 metre wide compartment are brought together and summarised in Table 3. This table was constructed from the data obtained during the trials by the data logger, and other information derived from this.

A sample package of the data recorded - for trial no. 13/1/99: No.8 in this case - is given in Figures 49 to 54 inclusive. This package is typical of those collated for each trial, and consists of:

(i) Plot of obscuration Vs time - meter No.1 (Figure 49)

(ii) " " - meter no. 2 (Figure 50)

(iii) " " - meter no. 3 (Figure 51)

(iv) " " - the above three plots superimposed upon each other (colour coded on the original). The times for the average of the three readings to reduce to 40%, 20% and 10% were calculated and printed upon this sheet. (Figure 52)

(v) Plot of natural wind speed Vs time, with the calculated average printed on (Figure 53)

(vi) Plot of natural wind direction Vs time, with the calculated average printed on. (Figure 54)

In all of the above data, average values were taken over the duration of the trial, from when the vents were simultaneously opened (t=0) until the end of the trial, when the logger was stopped.

In Table 3, the first column gives the trial number and the second indicates whether PPV was used. The third column shows the arrangement of the vents: here, '5'0" → 8'0"' means the inlet vent was 5'0" wide and the outlet vent was 8'0" wide (all were on the compartment centreline). The fourth column gives the inlet/outlet area ratio. The fifth and sixth columns, together, give the natural wind data; the first of these being the wind speed and the second its direction, these are average values recorded over the duration of the trial. The seventh column gives the average value of the natural wind component blowing directly into the vent, that is along the axis of the compartment. The eighth column gives the elapsed time, from when the vents were opened, for the average value of the obscuration to reduce to 40%, 20% and 10%. The ninth column compares the time taken when using PPV for the average obscuration to reduce to 40%, 20% and 10% with that taken when using natural ventilation, only,in the same situation. The pairs of trials being compared are bracketed together in this column. (These pairs of trials were performed one after the other as quickly as possible to ensure that the natural wind conditions would be similar for each.)

6.4.3 Airflow Surveys

Seven separate airflow surveys were undertaken in the 7.5 metre wide compartment, all at a height of 1.5 metres from the floor. All were undertaken single handed, using the new simplified anemometer rig to support and position the ultrasonic anemometer so that it gave a read-out in polar co-ordinates. The natural wind speed and direction, was recorded, manually, throughout the duration of all surveys.

The data from each survey was subsequently plotted onto a plan view of the compartment, using the positioning grid marked on the floor (the same grid used for the FEU garage survey, dividing the building into 1.0 metre squares). These plots are shown in Figures 55 to 61 inclusive, and comprise:

(i) 2'-6" inlet - 8'-0" outlet, with PPV. (Figure 55)

(ii) 8'-0" inlet - 2'-6" outlet, with PPV. (Figure 56)

(iii) 2'-6" inlet, and outlet, with PPV. (Figure 57)

(iv) two separate plots, each with two 5'-0" vents, in similar wind conditions, one using PPV (Figure 58), the other using natural ventilation, only (Figure 59).

(v) Two separate plots with different natural wind conditions, with 8'0 inlet and outlet. (Figures 60 and 61)

The average natural wind was calculated for each survey and a vector representing this was subsequently drawn onto each plot, to the same vector scale as the internal data. A scale of 1.0"≡ 1.0 metre per second was used on the original charts, but this must be ignored in the Figures since they have been significantly reduced for presentation in report form.

6.5 Temporary Compartment Trials: 5.0 metres Wide

6.5.1 General

Both cold smoke trials and airflow surveys were conducted in the 5.0 metre wide compartment. The data was collated and treated as previously described for the 7.5metre compartment (Section 6.4), but some additional trials and surveys were also undertaken.

6.5.2 Cold Smoke Trials

The results of the cold smoke trials conducted in the 5.0 metre wide compartment are brought together and summarised in Table 4. The table was constructed in an identical way to that outlined in Section 6.4.2 (for the 7.5 metre wide compartment), from data obtained from identical sources.

A total of thirty cold smoke trials were conducted. The first eighteen were nine pairs of trials using every possible combination of the three vent sizes, both with and without PPV. There then followed three pairs of trials using a 'non-standard' inlet vent; 3'-9" wide and 6'-6" high. This was done to test a possibility that there was some significance in the size of the inlet vent relative to the PPV fan's performance. (No significanct difference was found). Finally, three pairs of trials were repeated; those with the 2'-6" wide inlet. It was hoped that very different natural wind conditions from those previously experienced would prevail during these 'repeat' trials but, in fact, they turned out to be fairly similar in all cases. All of the results are given in Table 4.

6.5.3 Airflow Surveys

Nine separate airflow surveys were undertaken in the 5.0 metre wide compartment, all at a height of 1.5 metres from the floor. The nine surveys, all using PPV, represent every possible combination of the three vent sizes. The natural wind, speed and direction, was again recorded throughout the duration of each survey.

The data was, again, collated and plotted onto plan view charts, onto which the corresponding average natural wind velocities were subsequently superimposed to the same vector scale. These charts are given, for completeness, in Figures 62 to 70 inclusive. Note that the vector scale stated on these charts must be ignored in the Figures since they have been significantly reduced for presentation in report form.

6.6 Temporary Compartment Trials: 2.5 metres Wide

6.6.1 General

Both cold smoke trials and airflow surveys were undertaken in the 2.5 metre wide compartment. The data was collated and treated as previously described (Section 6.4). Some additional cold smoke trials, using two PPV fans were also undertaken.

6.6.2 Cold Smoke Trials

The results of the bulk of the cold smoke trials conducted in the 2.5 metre wide compartment are brought together and summarised in Table 5, while Table 6 gives the results of some limited trials, performed later, using two 24" Tempest fans simultaneously. The eighteen trials comprising Table 5 were nine pairs of trials, using every possible combination of the three vent sizes, both with and without PPV.

There subsequently followed a further five trials, undertaken at the suggestion of brigades' personnel who had recently returned from studying PPV tactics in the USA. These trials used two PPV fans simultaneously (except for one using a single fan and one using natural ventilation only, for comparisons). All were undertaken with a 2'-6" wide vent at each end of the compartment, and were completed in a single morning so that the natural wind conditions would, hopefully, be similar throughout. The tactics used and results obtained are given in Table 6. A new tactic, previously untried, was to seal the top half of the single personnel access doorway with one fan and the lower half with another. This meant that the fans had to be separated in plan view - see Figure 71. It should be noted that the airflow data given in Table 6 was obtained in a completely different way from that previously described, and therefore the results cannot be directly compared with any previous results (see Section 6.6.3).

6.6.3 Airflow Surveys

Nine separate airflow surveys were undertaken in the 2.5 metre wide compartment, all at a height of 1.5 metres from the floor. The nine surveys, all using PPV, represent every possible combination of the three vent sizes. The natural wind, speed and direction, was again recorded throughout the duration of each survey.

The data was, again, collated and plotted onto plan view charts, onto which the corresponding average natural wind velocities were subsequently superimposed to the same vector scale. These charts are all given, for completeness, in Figures 72 to 80 inclusive. Note that a different positioning grid (to that used previously) was used in the 2.5 metre wide compartment, to give three longitudinal rows of readings, one on the compartment centreline and one at 0.85 metres to either side of this, (0.4 metres from either wall). Note, also, that the vector scale stated on these charts must be ignored in the Figures since they have been significantly reduced for presentation in report form.

In the subsequent 'two fan' trials (Table 6), a different method was used to measure the airflow through the compartment. Here, a grid was formed across the outlet vent, using nails and string, to give thirty five sampling points; five rows across and seven rows down (see Figure 81). A fan type anemometer[15], 0.1 metres in diameter on a long, thin, handle was used to take a reading at each intersection of the strings. The value given in Table 6 is the average of these readings, in each case. Each set of airflow data was taken immediately after the corresponding cold smoke trial. The corresponding natural wind velocities were not recorded, but all trials were completed in a single morning, in broadly similar wind conditions.

6.7 Further Data Processing

For each building size used, the trials data obtained was examined to see if any broad underlying trends were evident. If any such trends could have been identified they may have formed the basis for a useful 'rule of thumb' for firefighters.

When considering the results of the 'green' garage trials it was evident that in some instances the use of one or two PPV fans had a fairly marked beneficial effect, in others the effect was less marked and in others again, natural ventilation cleared the building faster than either one or two fans. It appeared that the PPV fans had relatively more effect when the natural wind was very light. Graphs were plotted of both the natural wind speed, and the component of the natural wind acting along the axis of the inlet vent, against the time to reduce the obscuration to 20% (and 40%, 10% and 5%). The latter plot revealed no trends of any sort but the former, reproduced as Figure 82, showed a slight tendency for the clearance time to be related to the natural wind speed (and this applied at whatever obscuration level the data was plotted).

In Figure 82 the result of each trial is plotted as a data point. On this plot, three kinds of trial were identified, by using differently shaped data points in Figure 82. These three kinds of trial were: natural ventilation, using a single PPV fan, and using two fans simultaneously.

The data obtained from the FEU garage trials was arranged in several different ways to see if any underlying trends were evident. The plots of the three smoke obscuration meters Vs time, with the recorded visibility distance times superimposed, for all trials, were reduced in size and assembled onto one large sheet of paper for examination. No consistent trends were evident. Also, the plots of visibility distance Vs average smoke obscuration all tended to produce a straight, or nearly straight, line. This indicated that there was no real, or significant, difference in the story being told by the smoke obscuration meters and the red lamps and video technique, and that the variability and spread in both sets of data were due to swirl effects. (With the red lamps and video, the time difference between any given lamp first becoming momentarily visible, and remaining visible could be in excess of half a minute). The lamps and video were not used in subsequent trials for this reason.

The overall average spread of the three smoke obscuration meter readings, during each of the FEU garage trials was calculated using, firstly, the raw 'spiky' data (Figure 37) and, secondly, using the smoothed data (11 point moving average, Figures, 34, 35 and 36). The former gave an overall average spread of 19.2%, while the latter gave 13.9%. The difference in these figures gives some indication of the 'spikiness' of the raw data; the amount by which the visibility at a localised spot in the building increases and decreases alternately over a short timescale (readings were taken at 5 second intervals). Also, in the raw, 'spiky' data (Figure 37), the curve might have gone up and down through the 40% level several times. The overall spread was used in this calculation (from the leading meter first recording 40% to the trailing meter last recording it), whereas the smoothed graphs used only the times when the curve passed through 40% for the last time. This only occurred once, in general, in the smoothed graphs. There was no discernible pattern in the way the readings of the obscuration meters reduced relative to each other. In some cases the meter furthest 'upstream' reduced marginally faster than the others,in others that furthest downstream did. The 'spikiness' of the raw data plots is, in itself, an indication of the swirling taking place in the building.

A graph was plotted of the average smoke clearance time (to 40% obscuration) against the average natural wind speed, independent of its direction, for all trials except those in which both vents were in the same end of the building. In this plot (Figure 83), the result of each trial is represented by a single data point. The trials are segregated into three types, in this plot, by the use of different shaped data points, the three types being: natural ventilation, single PPV fan and two PPV fans. A regression analysis was then carried out [16, 17] for each of these three sets of data and the best straight line drawn through the sets of points. The slight, broad, trends shown are discussed in Section 7.

A similar graph was also constructed using the component of the average natural wind blowing directly into the inlet vent, instead of the average natural wind, but this showed no trends at all.

The data obtained from the temporary compartment trials: 7.5 metres, 5.0 metres and 2.5 metres wide, was treated in the same way as described above for the FEU garage trials, except that there was no 'red lamps and video' data. The spreads in the time to reach 40% obscuration, calculated as above, were:

7.5 metre wide compartment

overall raw 'spiky' data -	16.4%
smoothed data -	12.1%

5.0 metre wide compartment

overall raw 'spiky' data -	28.6%
smoothed data -	22.0%

2.5 metre wide compartment

overall raw 'spiky' data	-	54%
smoothed data	-	43%

In the 7.5 metre wide compartment there was a tendency for the reading of the downstream obscuration meter to reduce to 40% rather faster than that of the upstream one. Considering all trials, both with and without PPV, the upstream meter was marginally faster to reach 40% on three occasions, and the downstream meter was fastest on seventeen occasions. There was no such tendency in the results of the trials in the 5.0 metre wide compartment. Here, the upstream meter was marginally faster on fourteen occasions, and the downstream meter was marginally faster on fourteen occasions, there being no discernible pattern.

However, in the trials in the 2.5 metre wide compartment, the readings of the upstream meter reduced to 40% marginally faster than those of the downstream meter in all trials, both with PPV and natural ventilation. (The positions of the smoke obscuration meters within each compartment are given in Figures 91,92 and 93.)

Further comparisons were subsequently made to determine whether there was any link between which obscuration meter positions reached 40% first and the average natural wind direction, in the trials done in the 5.0 metre wide and 7.5 metre wide compartments, and in the FEU garage trials after no. 15/4/98: No.1 (when the meter positions remained unchanged). There was no pattern evident in any of these comparisons. The spread in the meter readings can therefore only be explained by fluctuating swirl effects.

The data obtained from the temporary compartment trials, 7.5 metres, 5.0 metres and 2.5 metres wide, were summarised in still further ways to see if any relationships, however tentative, were evident between the improvement in smoke clearance time when using PPV and the relative vent sizes; this improvement and the natural wind speed; and this improvement and the component of the natural wind blowing directly along the centreline of the compartment.

Graphs were constructed, one for each compartment width, plotting the percentage of the natural ventilation time taken by PPV to reduce the average obscuration to 40% against the inlet/outlet area ratio for each inlet size giving three points for each, and for each outlet side giving three points again. Hence, three curves could be drawn onto each graph, one for each inlet and outlet size. However, no significance was evident in any of these plots.

Graphs were also plotted, one for each compartment width, of the percentage of the natural ventilation time taken by PPV to reduce the average obscuration to 40% against the natural wind speed (independent of its direction) and a further, overall, graph plotted all of this data on a single sheet. This latter plot was colour coded, and the compartment widths were also identified by the shape of the points (Figures 94-98 inc.). (The 'natural wind speeds' used in these plots were the average of the averages for each pair of trials - each pair conducted in as nearly identical conditions as possible.) In order to ascertain whether there was any statistical significance in the data presented in these graphs, a statistical software package[16, 17] was employed to determine, firstly, the best straight line that could be drawn through the data (regression analysis), and then the degree of significance[7] was calculated and printed onto each plot (in Figures 94-98 inc.). The 'R^2' value would have been 1.0 if all of the points had been on a perfectly straight line, and the line was not too close to either the horizontal or the vertical. The results confirmed what the eye perceives: that there was little significance in the data, the scatter of the points being too great.

Graphs were also plotted of this relative improvement when using PPV versus the component of the natural wind blowing directly into the inlet vent, for all three compartment widths, and an overall plot showing the results for all three widths. These plots were subsequently treated in the same way as outlined above, to see if any trends were evident. The statistical analysis confirmed what the eye perceived: no significance.

Graphs were also plotted of the average clearance time, to 40% obscuration, against the average natural wind speed, independent of its direction, for each of the three temporary compartment widths: 7.5 metres, 5.0 metres and 2.5 metres (Figures 99, 100 and 101). On each of these three graphs the points were segregated into two separate groups: those representing PPV trials and those representing natural ventilation trials, by drawing the points different shapes. Again, the best possible straight line [16, 17] was calculated and drawn through each of the two families of data points on each of these graphs. The underlying natural ventilation data showed there was a tendency for the clearance times to be longer when the natural wind speed was lower. This tendency was much less marked when PPV was used, the clearance times being shorter but also far less dependent upon the natural wind speed. (See Section 7)

7 DISCUSSION ON TRIALS

7.1 General

Cold smoke trials were undertaken in five different sized compartments ranging in volume from some 7,000 cubic metres (green garage), through 1,000 cubic metres (FEU garage), 275 cubic metres (7.5 metres wide compartment), 183 cubic metres (5.0 metres wide compartment), to 91.5 cubic metres (2.5 metres wide compartment).

Throughout the trials (except those in the 'green' garage) three different sizes of vent were used. The size and shape of these vents represented types of doorways commonly encountered by brigades, these being: a single personnel access door, a double personnel access door and a domestic garage door. (A fourth vent size, midway between a single and a double personnel access doorway was used in a small number of additional trials in the 5.0 metre wide compartment in order to examine a possible trend.)

The positions of the vents were chosen to be as typical as possible for a range of types of building, where this was possible. In the FEU garage, which approximates in size to a small/medium warehouse, industrial workshop, or garage for 8-12 vehicles, the vents were usually sited one in each end of the building either on the building centreline or near diagonally opposite corners. Some trials were also carried out with two vents at the same end of the building and none at the other (with the vents both upwind and downwind). In the smaller compartments, 7.5 metres wide or less, the vents were always on the compartment centreline, one at each end.

Before considering the sets of trials in each of the different sized compartments separately, it is possible to state the single overriding conclusion which emerges from these trials. This is that PPV can improve the rate of smoke clearance from heavily smoke logged buildings of sizes up to, and including, that of the 'green' garage. In these trials, this improvement was most marked in the smaller buildings (in the FEU garage the clearance times were roughly halved, on average, when compared to the corresponding natural ventilation times) and was least apparent in the largest - 'green' garage - building. However, even in this very large building some improvement was evident when two fans were deployed and natural windspeeds were low (below 2.0 metres/second).

A general impression of the improvements in clerance times when using PPV, outlied above, and their relationship to the natural wind speed, can be obtained from Figures 94-101.

The airflow survey charts obtained in each sized compartment up to, and including, the FEU garage are given (reduced in size for reproduction as Figures). Overall, what these charts show is that the air movement in a compartment is virtually impossible to predict, in all but the narrowest compartments with large vents at each end, and that these charts, if they had been available, would not have helped to predict smoke clearance times in any given situation (of natural wind, positions and sizes of vents, etc.). On the whole, they seem to indicate that the smoke clearance process is one of dilution, involving much mixing and recirculation within the compartment, particularly in the larger compartments with, relatively, smaller vents.

7.2 'Green' garage trials

In considering the results of the 'green' garage trials (Table 1) it has to be borne in mind that, unless stated otherwise, the vents were very large; roughly 4 metres square.

There would be no possibility of forming a 'seal' in such a doorway when fully open, with a PPV fan, or even with two fans. A brigade attempting to clear smoke from a building with such large vents would be much more at the mercy of the natural wind than in a building with smaller vents.

The graph of smoke clearance time versus average natural wind speed (Figure 82) shows the results of all of the 'green' garage trials, and differentiates between those using natural ventilation, a single fan, and two fans. A perusal of this graph, and the data given in Table 1, suggest that it is the average natural wind speed which is the dominant factor in determining the rate of smoke clearance, irrespective of the wind's angle relative to the vents.

It can be seen (Figure 82) that four of the trials in which natural ventilation was used lie on an almost perfectly straight line. These are the trials nos. 6, 4, 10 and 14: all carried out with an average natural wind speed of less than 2.0 metres per second. The line upon which these four trials lie is relatively steep, indicating that there is a correlation between average natural wind speed and the corresponding smoke clearance time, over this range of average natural wind speeds. The remaining two natural ventilation trials, nos. 2 and 11, were conducted when the average natural wind speed was somewhat higher; 3.3 and 3.0 metres per second, respectively. If a straight line was drawn onto the graph (Figure 82) through these two points it would be horizontal, the smoke clearance times being virtually identical. Further, if this line through trials 2 and 11 were extended to pass through no. 14, also, it would still be fairly close to horizontal. This suggests that there is no correlation between the average natural wind speed and the smoke clearance time when the average wind speed is above some 2.0 metres per second. This curve (virtually two straight lines, according to this limited evidence) can be thought of as the underlying relationship between the two plotted variables when natural ventilation, only, is used: that is, that if further similar trials were to be undertaken we could reasonably expect their results to lie on, or close to, this curve.

The question we can now ask is "What difference did PPV, one fan or two, make to this underlying relationship ? ". Figure 82 shows that of the three trials conducted in which a single PPV fan was used, nos. 1, 12 and 13, two fall a little above the natural ventilation correlation line (longer smoke clearance times than would have been expected using natural ventilation) and one was a little below. It is clear, therefore, that overall no significant improvement, ie. no reduction in smoke clearance time, was achieved using a single fan, the clearance times being rather worse than 'expected' in two cases and rather better in one. However, it is interesting to note that the one trial in which some improvement may have been achieved was that which experienced the lowest average natural wind speed of the three. It was unfortunate that no 'single fan' trial experienced a natural wind of less than 1.8 metres per second (when greater improvements may have been achieved).

Figure 82 also shows that of the five trials conducted with two PPV fans acting simultaneously, nos.3, 5, 7, 8 and 9, four resulted in faster smoke clearance than would have been predicted for natural ventilation (from the correlation curve) and one took longer. Again, the greatest improvement occurred at the lowest average natural wind speeds: the four trials in which the apparent improvements were made experienced average natural wind speeds of between 1.0 and 1.6 metres per second, whereas in the trial in which the result was worse than would have been expected, the average natural wind speed was 2.8 metres per second. Again, the greatest improvement occurred at the lowest wind speeds.

If the best possible straight line was drawn through the 'single fan' trials, and another through the 'double fan' trials in Figure 82, both lines would be nearly horizontal. This indicates that there is no longer any correlation between the average natural wind speed and the smoke clearance time. The use of PPV has clearly altered things: in very general terms, there appears to be some improvement, whether using one fan or two, when the average natural wind speed is below some 2.0 metres per second, but when the wind speed is above this value the use of PPV may actually make smoke clearance take longer.

It is clear from Figure 82 that the use of two fans produced greater improvements in smoke clearance times than a single fan, at the lower natural wind speeds. It is, however, probable that the various tactics employed with two fans were, at least to some extent, responsible for the differences in their relative performances. The best improvement (trial no. 5) was achieved with the inlet vent opened to be only 1.8 metres wide, and with the fans mounted one above the other, the higher one being some 2.5 metres from the ground. It is possible that, in this mode, the fans achieved a seal in the inlet vent. The next best (no. 8) used two fans side by side with the vent fully open. Here the fans could not make a seal. They were placed far enough apart for their outputs not to interact with each other until well inside the vent. In each of these two trials good 'improvements' were made in smoke clearance times (relative to the 'expected' times for natural ventilation at similar natural wind speeds). In the next best two trials, nos. 7 and 9, some, more marginal, improvement was made. In no. 7 the fans were positioned right in the fully open vent, while in no. 9 the fans were placed one behind the other on the centreline of the 2.1 metre wide vent.

It appears, from Figure 82, that the introduction of a PPV fan, or even two fans, made little difference to smoke clearance times when the natural wind speed was in excess of some 1.75 metres per second. A significant reduction in the clearance time, from what would be expected with natural ventilation, was made in two trials, both using two fans set back from the inlet doorway side by side (or one above the other). In both of these cases the natural wind speed was below 1.5 metres per second.

Overall, it does appear that a PPV fan, or fans, can make little improvement upon natural ventilation times in a building of this size, or larger, and particularly with these very large vents, unless the natural wind is light. A PPV fan, or fans, can make a relatively larger improvement to smoke clearance times when the natural wind speed is low. In a building like the 'green' garage, PPV could be expected to reduce the smoke clearance time when a natural wind speed is below some 1.0-1.5 metres per second. On a completely windless day, or night, PPV could make a significant difference. However, in a building of this size and type it would probably be more beneficial to fully open all possible vents, if they are large, and not deploy PPV, if the natural wind speed was in excess of some 1.5 metres per second, irrespective of its direction relative to the major vents. Again, it could be reasonably argued that deploying PPV can do no harm, (and may do a little good) however strong the wind and however large the vents, provided one can be certain that the fan is not opposing the natural wind. If PPV is to be used in such a building, then 'the more fans, the better' would appear to be a valid maxim.

7.3 FEU Garage Trials

The first cold smoke trials to be conducted were carried out in the FEU garage since this building was, and would continue to be, continuously available to the researchers. It was, therefore, worthwhile making equipment to suit the building, and to render it as leaktight as reasonably possible. The first preliminary trials were performed to develop the trials techniques and to determine such things as the optimum positions for the PPV fans in the various doorway vents used, the positions and settings for the smoke generators, and the period to allow for 'smoking-up',using either one or two cold smoke generators.

It was found during the main trials that the average smoke obscuration usually attained 100% some two minutes or so before the generators were switched off, but not always. Subsequent analysis of the trials results showed that the initial average obscuration was only about 90% on two occasions and about 95% on six occasions. The reason for this is unclear. Care was taken to ensure that the smoke generators were always programmed in the same way, in the same positions, and run for the same length of time on each occasion. Also, the time elapsing between the generators being switched off and the trial commencing was very similar in all cases. For these reasons, it is believed that the quantity of smoke generated in the building was very similar at the start of each trial, and that the differences, from 100% obscuration, at the start of some trials were due to the varying strength and direction of the natural wind causing different degrees of leaking from the building (particularly from the roof) during, and immediately after, the 'smoking-up' process, when the vents were nominally sealed by removable blanks, in a very similar way each time. Certainly, some leak was perceptible from the roof, from outside the building, during 'smoking-up' on some days but not on others.

The use of video and red lamps during the FEU garage trials was an attempt to have a second, independent, method of assessing visibility in the smoke logged building. Also, the video evidence could be used to relate the smoke obscuration values to what the human eye might perceive. This technique may have given a rather different perception of the rate of improvement in visibility but, in the event, it was found that the results from the two methods told very much the same story. The subsequent viewing of the videotapes confirmed the swirl effects which caused the 'spikiness' of the obscuration versus time graphs. For this reason the video and lamps method was not used in the subsequent trials, it being far more time consuming and labour intensive than reliance upon the smoke obscuration meters and data logger.

Relating the measured obscuration values to what the human eye could detect in a partially smoke-logged building is not a simple matter. The smoke obscuration meters measured smoke density, only; i.e. the presence of solid particles between emitter and receiver. They could not tell the difference between bright daylight and pitch darkness. On the other hand, what the human eye could perceive (particularly through a BA facemask visor) would depend very much upon the level of daylight, or artificial light, in the compartment. Also, the ability to pick out details within the compartment would depend upon colour and tonal contrasts between objects and their surroundings. (There is, of course, a tendency for everything in a fire compartment to appear matt black to a greater or lesser degree, although this did not apply in these cold smoke trials.)

However, some broad comparison could be made by comparing the notes made on the video viewing records, of the commentator's observations as the trial progressed, with the simultaenous readings of the smoke obscuration meters. These commentaries were made by a researcher, not in BA, standing just inside the inlet vent and a little to one side, so as not to impede the airflow, in a position which may well be taken up by a firefighter. These comparisons showed that, in the FEU garage, the loom of the daylight from the far vent, some 18 metres away, could be just detected from this position when the average obscuration was about 40% on a bright, sunny day and at about 34% on a dull, overcast, day. On a dull day, the shape and size of the far doorway became clear at about 28% obscuration and equipment near the line from vent to vent was visible in silhouette at about the same time, all of the far end of the building (the 'join' between the floor and the end 'wall') was visible at about 20%, and fairly small details (for example, a football) would have been visible, in the furthest corner, at 15% obscuration.

The cold smoke trials undertaken in the FEU garage can be divided, broadly, into three categories, thus:

(1) both vents on the longitudinal centreline of the building;

(2) vents near diagonally opposite corners of the building; and

(3) both vents in the same end of the building.

If the smoke clearance times, to 40%, are averaged separately (considering only those PPV trials in which a single fan was used, and irrespective of vent sizes and natural winds) for these categories of trials, firstly using PPV and secondly using natural ventilation, these average times are:

(1) PPV trials (single fan)

Both vents on centreline	-	5 mins.-30 secs.
Diagonally opposite	-	5 mins.- 20 secs.

(2) Natural ventilation trials

Both vents on centreline	-	13 mins.-0 secs.
Diagonally opposite	-	10 mins.-34 secs.

It is seen that, according to these overall average values, PPV significantly reduces the clearance time when the vents are on the building centreline, while if the vents are diagonally opposed, the reduction in clearance time due to PPV is less marked (though still 'useful').

This may be explained by reference to the airflow survey charts (Figures 45 and 47). When the vents are central in the ends of the compartment, and PPV is used to move air along the centreline, the major swirl patterns set up in the building are broadly symmetrical; one side is a mirror image of the other. These swirls will converge on the building centreline, cancelling each other out, and air will move along the centreline of the building towards the outlet vent. However, when the vents are diagonally opposite each other a 'circular' overall swirl is set up in the building, tending to cause the air to flow across the outlet vent, rather than directly towards it.

Also, it appears from these trials that if vents are only available at one end of a building, PPV will be rather more effective when the vents are in the downwind end of the building. However, when natural ventilation was used, the clearance times were shorter when the vents were at the upstream end. In both cases PPV reduced the clearance times significantly.

Direct comparisons between pairs of similar trials, with and without PPV, conducted in the FEU garage, can be made from Table 2. In this Table, the pairs of trials which have been compared with each other to produce the '% age of natural time taken by PPV...' column are bracketed together, where possible (in the '40%' sub-column). Also, other comparisons that can be fairly made are indicated by numbers in parenthesis inserted into the '10%' sub-column of the 'obscuration reduction time ...' column. When studying Table 2, it may be helpful to consult the sketches which show the sizes and orientation of the vents, the fan position where applicable and the speed and direction of the natural wind. (Figures 84-90 inc.)

Direct comparisons from the results of the trials (Table 2) show that, in general, the use of PPV reduced the smoke obscuration markedly faster than natural ventilation, alone, with the same vents open and a similar natural wind blowing.

The graph in which clearance times (to 40% obscuration) are plotted against the natural wind speed (Figure 83) shows the result of each trial as a single data point. All trials are show on this plot except those in which both vents were at the same end of the building. They are segregated into three different types of trial by using different shapes for the data points, the types being: natural ventilation, PPV using a single fan, and PPV using two fans. This plot is, clearly, a very broad overall summary of results, ignoring, as it does, vent sizes and the direction of the natural wind, but it does show a very broad trend.

The natural ventilation trials cover a very wide range of clearance times in this graph and there is little discernible relationship between this clearance time and the natural wind speed, or any other measured variable. The line shows a gradient but the points are widely scattered about it, so there can be little confidence in the accuracy of the line. It would appear that the smoke clearance time in any given building and situation, in which natural ventilation is used, will be unpredictable, and will be influenced by a combination of a number of local factors.

There appears to be some relationship between wind speed and clerance time, when the PPV trials using a single fan are considered and the clearance times are certainly reduced somewhat, overall, across the range of natural wind speeds experienced. The slope of the regression line through these points suggests that the clearance times are still rather lower at higher natural wind speeds. Also, as well as being lower, indicating faster clearance times overall, its slope is less marked i.e. it is more nearly horizontal, which suggests that the clearance times are less dependent upon the natural wind speed when a PPV fan is introduced. However, it can be seen that the ranges of data points for natural ventilation and a single PPV fan overlap each other. This suggests that the introduction of a PPV fan in a given situation may have a significant beneficial effect, or may make virtually no difference. The regression line through the PPV trials in which two fans were used shows that, again, the clearance times are rather lower, and the line is still more nearly horizontal, indicating that the clearance times are even less dependent upon the natural wind speed, and therefore still more predictable, there being less spread between the data points.

7.4 To Seal or Not to Seal?

In all but four of the trials in which a single PPV fan was used, the fan was positioned 2.5 (or 3.0) metres outside the inlet vent, to affect a 'seal' around the doorway, as far as possible. However, it was perceived that, if it was not deemed necessary to 'seal' the inlet vent, faster smoke clearance might, possibly, be achieved by moving the fan forward into the vent so that all of its output would enter the building (instead of perhaps some 60% in the case of a 2'6" wide doorway). If a fan were used in this way, no control could be exercised over the way in which the smoke leaves the building, and much would inevitably be forced out above and around the fan – some of which would be re-circulated back into the building.

To test this hypothesis, four trials were carried out in which the fan was positioned on the centreline of the vent and 0.3 metres out, to allow access. In all cases, all of the fan's output entered the building. In one of these trials the inlet vent was 2'-6" wide with an 8'-0" wide outlet, and in the remaining three, the inlet was 8'-0" wide with a 2'-6" wide outlet.

Table 2 shows that the trial using the 2'-6" wide inlet vent (no. 22/7/98:2) gave similar clearance times to the similar trial (no. 22/7/98:1) in which the fan was set back from the vent, and the average natural winds were similar during these two trials. Both were faster than the broadly equivalent natural ventilation trial (no. 22/7/98:4).

The three trials using the 8'-0" wide inlet vent were also inconclusive, overall. One (no. 21/7/98:2) gave very similar clearance times to the equivalent trial (no. 21/7/98:1) in which the fan was set back from the vent where, again the average natural winds were broadly similar, though slightly in favour of the former (fan in vent) trial; both were faster than the equivalent natural ventilation trial (no. 21/7/98:3). Another (no. 28/5/98:2) gave longer clearance times than the equivalent trial (no. 28/5/98:1) in which the fan was set back from the vent, although with this pair of trials the average natural winds were rather different, being quite different in direction. The third trial (no. 21/5/98:2) gave clearance times, roughly three times longer than the equivalent trial (no. 21/5/98:1) in which the fan was set back from the vent but again, the average natural winds were different (and the average wind direction during the former trial was estimated, anyway, due to instrument failure).

Certainly, no benefit in terms of smoke clearance times was evident as a result of moving the fan up into the inlet vent. In fact it appears that the clearance times may be rather worse. Also, as has been said, any control of smoke movement is lost when the fan is deployed in this way. This disappointing result may possibly be due to the partial re-circulation of the smoke which escapes above and around the fan (due both to the effect of the fan itself and to the fact that this inlet vent will be at the upwind end of the building).

When an inlet vent is so large, or of such a shape, that it is unlikely that a single PPV fan can form an effective seal, a second fan (if available) may be deployed to achieve this end. In such cases, it appears that, as well as making a 'seal' possible, more rapid smoke clearance can be achieved if the outputs from the two fans are directed at separate parts of the vent (ie. parallel side by side, or one directed at the lower half of a doorway and the other at the top half). The fans would be pointed at the centre of their appointed part of the vent and then moved bodily outwards until a seal is affected (see Section 7.5).

7.5 The Simultaneous Use of Two PPV Fans

A limited number of trials were performed using two fans simultaneously, and their results compared with those of similar trials using both natural ventilation and a single fan. Six such trials were undertaken in the FEU garage, in a range of vent configurations, a further three were subsequently performed in the 2.5 metre wide compartment with a 2'-6" wide vent at each end, and five were performed in the 'green' garage.

To deal with the trials in the FEU garage first, the trials are considered in chronological order, as far as possible, referring to Table 2.

The results of the trial using two fans in tandem (one behind the other with one at 'sealing' distance and the other virtually in the vent) with a 5'-0" wide inlet vent and 2'-6" wide outlet vent (no. 16/4/98:3), can be compared with those of the equivalent natural ventilation trial (16/4/98:2) and the equivalent single fan trial (no. 16/4/98:1). The natural wind conditions during these trials were fairly similar except for the wind direction during the single fan trial, which was some 90° different from the others. The smoke clearance times were reduced by the single fan by approximately 30%, while the two fans in tandem reduced these times by 40%. The subsequent trial (no. 16/4/98:4) used two fans positioned side by side, in the same situation, and again with similar natural wind conditions, so that its result could be compared with the same natural ventilation and single fan trials as above. This also reduced the clearance times by approximately 40%. It is seen that there was very little difference between the results of the two trials, each using two fans. Both arrangements reduced the clearance times significantly when compared with both natural ventilation and the use of a single fan.

Another group of four trials can be considered, all with an 8'-0" wide inlet vent and a 2'-6" wide outlet vent. This group, also, consists of a natural ventilation trial (no. 28/5/98:5), one using a single fan (no. 28/5/98:1), one using two fans in tandem (no. 28/5/98:4) and the other using two fans side by side (no. 28/5/98:3). The natural wind conditions remained broadly similar during all of these trials, allowing reasonable comparisons to be made. The smoke clearance times were reduced in the single fan trial by approximately 40%. The use of the two fans in tandem reduced these times by approximately 50%. However, the use of two fans side by side reduced the clearance times by 60%, a further improvement. It is seen that, in this group of trials, the smoke clearance times were shorter when the two fans were used side by side than when used in tandem. This may be because the two fans positioned side by side effectively 'sealed' the 8'-0" wide doorway, whereas they could not achieve this when positioned in tandem, although they almost certainly propelled more air into the building when in this latter mode.

A further two trials (nos. 7/5/98:2 and 22/7/98:3) were undertaken, on different days and hence in rather different natural wind conditions, both using two fans in tandem with a 2'-6" wide inlet vent and an 8'-0" wide outlet vent. The result of these two trials were broadly comparable, one with the other, indicating that this was a reasonably repeatable result in spite of the rather different wind conditions. In each case the smoke clearance times were shorter than were achieved during their respective equivalent single fan, and natural ventilation trials.

Subsequently, a group of 'two fan' trials were carried out in the 2.5 metre wide compartment with a single 2'-6" wide vent at each end. The results are given in Table 6. This group consisted of a natural ventilation trial, one using a single fan to 'seal' the inlet vent and three trials each using two fans, but in different ways. The natural wind was not monitored during these trials but, since the trials were performed quickly, one after the other, it is considered that the natural wind conditions remained essentially similar throughout all trials. It is seen (Table 6) that the single fan reduced the natural ventilation times (by some 70%). All of the trials using two fans reduced the times still further, though only relatively slightly, by a few percent, in all cases. The difference in clearance times between the three different 'two fan' methods were fairly slight, the fastest clearance being achieved by the two fans set up so that one would 'seal' the top half of the doorway while the other sealed the lower half. (Figure 71)

While the results of the 'two fan' trials conducted in the 'green' garage were somewhat inconclusive, a glance at Figure 82 does show that the clearance times obtained with two fans were, generally, shorter than would have been expected with natural ventilation, particularly at the lower average natural wind speeds, and probably better than would have been achieved with a single fan at similar natural wind speeds (although this, latter, was not in fact tested). It appears that the positioning of the fans in the 'green' garage trials may have been significant. The fastest clearance, trial no. 5, was achieved with the fans one above the other with the inlet vent only 1.8 metres wide. It is possible that a seal was achieved in the inlet vent in this case. The second fastest clearance, no. 8, was achieved with the fans side by side, but far enough apart for their outputs not to interact with each other until well inside the building, with the vent fully open. Unfortunately, there are no 'single fan' trial results with which these can be compared, since none of the 'single fan' trials experienced similar natural winds.

7.6 Temporary (smaller) Compartment Trials

The findings from the trials carried out in the temporary compartment bear out, in broad terms, what has been said about the results of the FEU garage trials. Firstly, comparing the results of pairs of similar trials, with and without PPV (Tables 3, 4 and 5) shows that, in the 7.5 metre wide compartment, PPV reduced the smoke clearance time in all cases; to between 62% and 29% of the natural ventilation time, to the same level of obscuration. (These percentages were generally similar in all cases whatever level of obscuration was considered.)

In the 5.0 metre wide compartment, PPV reduced the clearance times in all cases, except one; to between 65% and 17% of the natural ventilation time, to the same level of obscuration. In the case of the exception, the effect of the PPV fan appears to have disrupted the effect of a fairly strong and helpful natural wind blowing into the 2'-6" wide vent, producing very similar clearance times. (However, broadly similar conditions prevailed during the preceding pair of trials, with the same sized inlet vent, yet here PPV reduced the clearance time to 65% of the corresponding natural ventilation time.) This result is difficult to explain, except in terms of experimental errors (see 7.8 below).

In the 2.5 metre wide compartment, PPV reduced the clearance times in all cases, except two, to between 38% and 12% of the natural ventilation time, to the same, 40% obscuration, level. In the cases of both of the exceptions, in which PPV took 137% and 104% of the natural ventilation time (i.e. longer!) to reach 40% obscuration, the natural winds were fairly helpful and, in both cases, the inlet vent was 8'-0" wide (the outlet vents being 5'-0" wide in the former case and 8'-0" in the latter.) While it is possible that the effect of the PPV fan was to disrupt the beneficial effect of the natural wind by increasing the swirling within the compartment, it is also probable that experimental errors played some part in these results (see 7.8 below).

Overall, these comparisons show that the introduction of PPV did reduce the smoke clearance times in the vast majority of cases in all three compartments. Of the three cases where PPV apparently made things worse, two occurred in the 2.5 metre wide compartment, when an 8'-0" wide inlet vent had to be opened up. (This meant removing virtually the whole end of the compartment.) Since, with a helpful wind, the clearance times were so short anyway - between 19 seconds and 26 seconds - the errors caused by the difficulties of opening the vents simultaneously, on cue, were more significant than previously - see below. In the third such case, with a 5.0 metre wide compartment, and 2'-6" inlet vent and, again, a helpful wind, the clearance times were longer - 71-72 seconds - as would be expected with the smaller inlet vent. Here, it would have been expected that PPV may have reduced the clearance time, and this result can only be explained in terms of experimental errors (see Section 7.8).

With regard to the graphs which were plotted showing the percentage of natural clearance time taken by PPV (in similar conditions) versus the natural wind speed (Figures 94-98 inc.) The plot for each of the three compartment widths shows considerable spread between the points (where each data point represented a pair of trials). However, the regression analysis [16, 17] which superimposed the best possible straight line which could be drawn through the points onto each graph did produce a line sloping in the same general direction in every case. The slopes of these lines suggest that there is an overall tendency for PPV to produce greater reductions in smoke clearance times when the natural wind speed is low, and to offer relatively less improvement as the natural wind speed increases. However, it must be emphasised that this is a very broad trend only, and there is no guarantee that it will apply in every case.

Similarly, with the graphs showing average smoke clearance times versus average natural wind speed, both with and without PPV (Figures 99-101 inc.) The plot for each of the three compartment widths has two separate regression analysis lines superimposed upon it: one for the natural ventilation data, and one for the PPV data. It was noted that, for each compartment width, the natural ventilation line indicated that there was some slight correlation between the two variables, and the slope of these lines indicated that as the natural wind speed increased, the smoke clearance time decreased. When PPV was used the linearity of the data points was clearly better, the spread away from the regression line being less. This suggests that results may be more predictable with PPV than without. Also, the slope of the PPV lines was less in all cases, i.e. more nearly horizontal, indicating that the smoke clearance time was less dependant upon the natural wind speed. The relative positions of the two lines on each graph show that the PPV times were, in general, less than the natural ventilation times, and that this difference, or improvement, increased as the natural wind speed decreased.

7.7 Airflow Surveys

The airflow surveys were undertaken in order to find out if they could increase our understanding of the way in which PPV works, and also because they may have yielded some information which may have been of value to brigades. In the event, the data gained from the surveys was of rather limited value, except to confirm the view that, in a real situation, brigades would not be able to predict the airflow patterns that may be set up in a compartment in any detail, or with any reasonable degree of certainty. It has to be borne in mind that these surveys were carried out, at ambient temperatures, in a virtually empty and symmetrically shaped compartment, whereas any sub-divisions of the floor area, stacks of goods, cupboards, etc., would have made things more complicated. Also, the results of the surveys were consistent with the behaviour of the smoke observed during the cold smoke trials. An examination of the charts produced (Figures 42-45 inc., 47, 48, 55-70 inc., and 72-80 inc.) shows that, apart from some underlying trends, the actual airflows within the compartments were fairly unpredictable in all compartments except the narrowest, and even then only when it had large vents at each end (making it virtually a rectangular duct).

In very general terms, it is seen that, in the FEU garage, one of two basic kinds of flow pattern seem to be set up:

a) When the vents were on the compartment centreline there tended to be a flow straight along the axis of the compartment from vent to vent, with a roughly symmetrical swirl and back eddy to each side, each of which rejoined the flow along the axis in the vicinity of the inlet vent, when PPV was used. (This is what would be expected if there was no natural wind, or if the natural wind was blowing directly into the inlet vent.) This can be seen in Figures 47 and 48.

b) When the vents were diagonally opposed, ie. near the opposite corners of the compartment, a 'circular' underlying swirl pattern was set up, the flow from the inlet vent continuing roughly parallel to the nearest wall, then turning across the far end of the compartment and turning back along the other long wall (some found its way out through the outlet vent) to turn again near the end wall and rejoin the flow from the inlet vent. This can be seen in Figures 42-45 inclusive.

It is clear from the charts, however, that these underlying swirl patterns are only a very broad trend, and that within them there are what appear to be random air movements. Also, the effects of the natural wind may continually modify, or influence, them.

It was found during the early airflow surveys that the vertical components of the airflows in the compartment were invariably small compared to the horizontal components (Figure 46 is an example), and so these were ignored throughout the later surveys. (Although, of course, this may not be so in a real, hot, fire situation because of buoyancy effects in the smoke/gas/air mixture.)

In all of the smaller compartments, (7.5, 5.0 and 2.5 metre widths) the surveys were carried out with the vents central in the ends of the compartment, only. The charts produced from these surveys show just how unpredictable, and how different from each other, the airflow patterns can be in each compartment and, further, they seem to indicate that the flow patterns set up cannot be reliably predicted by studying the natural wind strength and direction.

For example, in the 7.5 metre wide compartment, Figure 55 displays an underlying circular flow pattern while Figure 56 does not, despite the natural wind being broadly similar. Again, Figure 58 shows random eddies, even air moving across the fan while quite close to it, but this is with a cross wind nearly at right angles to the fan axis, while Figure 57 shows an essentially circular flow pattern, also with a cross wind at about 90° to the fan's axis.

When the charts from the surveys in the 5.0 metre wide compartment are studied (Figures 62-70 inclusive) it is seen that there is a tendency to a single circular swirl in them all. In most of these cases this swirl is in the direction which one would predict from looking at the natural wind, but in several cases (notably Figures 64, 65 and 67) it is not: the direction of the swirl is reversed. This merely serves to underline the inherent uncertainty about how air will actually move in a pressurised compartment.

The flow patterns in the narrowest compartment, 2.5 metres wide, show less upredictability (Figures 72-80 inclusive). Generally, the relatively small cross and back eddies tended to occur in the upstream end of the compartment, only, in the parts shrouded from the direct effect of the fan. The flows, generally, appeared to be virtually 'straight through', and this tendency was most marked with the larger vents, which corresponds with the rapid smoke clearance observed in these situations.

Overall, the flow charts produced appear to be consistent with the smoke clearance results, and confirm that there is bound to be much swirling of the smoke (as observed in all but the narrowest, and large vented, compartments). They underline the view that smoke clearance is essentially a process of dilution, with much mixing and recirculation taking place.

There would appear to be little point in pursuing this kind of experimentation in the future (at least, for firefighting purposes) since the precise nature of air movements within a pressurised compartment are likely to remain largely unpredictable. Also, in a real fire situation, it is likely that there would be buoyancy effects due to temperature differences in the smoke/air mixture.

7.8 Limitations of the Trials

The whole process of producing the graphs to show the trends in smoke clearance attributable to the use of PPV was one of averaging and summarising the measured data, throughout. The resulting conclusions should therefore be treated as a very broad overall indication of the likelihood of improving smoke clearance rates by the use of PPV.

Throughout the duration of each trial both the natural wind speed and its direction were continually changing to some extent, and very markedly in some trials. Both of these variables were averaged over the duration of the trial. Also, the windstation which monitored these variables was positioned at a higher level, and some distance away from the trial building, or compartment. While this measured the prevailing wind conditions as well as could be done, there was no way in which the experimenters could know about the 'local' wind conditions in the vicinity of the inlet and outlet vents, and what effect other parts of the buildings, trees etc., might have upon the air movements in and around the building or compartment.

Also, the data used to construct the airflow charts took some considerable time to collect (between 30 minutes and 90 minutes). The data for each grid point had to be monitored separately, and the natural wind was noted at the same time, which meant that a period of about one minute elapsed between each reading. The natural wind was subsequently averaged over the duration of the survey, but the natural wind was fluctuating continually during the survey, and may have altered appreciably between the beginning and end of a survey. It follows, then, that these airflow charts can give only a broad indication of the pattern of air movement in a compartment. They are not a snapshot taken at a single instant in time.

For each size of compartment, the number of smoke generators, generator setting and time allowed for 'smoking up' were decided and adhered to for all trials. However, in all of the 'green' garage trials (the largest compartment by far) and in several of the FEU garage trials, the smoke obscuration at the start of a trial was rather less than 100%. In these cases the level was between 90% and 100%. In the case of the 'green' garage trials, in which six smoke generators were used, the 'smoke-up' time could not be increased because of doubts about how long the smoke particles would remain in suspension. In the FEU garage, the 100% level was usually, but not always, achieved and it was unclear why this was. It is considered that different wind conditions may have caused different degrees of leakage from the building during the short period between the generators being switched off and the vents being opened (the start of the trial). The suppliers of the generators confirmed that if the generators were set in the same way, and switched on for the same period of time, they would burn the same quantity of 'oil' and therefore produce the same amount of smoke.

Furthermore, it has to be accepted that all of the trials were conducted with cold, or artificial, smoke, which does not behave in the same way as the hot smoke that would probably be encountered in a firefighting situation, there being no buoyancy effects. Also, there may be optical differences between this, almost white, cold smoke and the, usually, black smoke encountered in a fire compartment. The level of daylight would also have some effect upon what the human eye might perceive, although neither of these things would have any effect upon the smoke obscuration meters used throughout the trials.

With regard to errors in the times recorded in the trials for the smoke obscuration to reduce to a given level: by far the main source of error was in the time which elapsed between the smoke generators being switched off and the vents being simultaneously opened. The maximum differences in these times are thought not to exceed 5 seconds in the 'green' garage trials, and 3 seconds in the FEU garage and temporary compartment trials. Care was taken to do everything in the same way in all trials, and it is believed that the errors were, in general, less than this. However, some difficulty was, on occasion, experienced in removing the vent sealing blanks at the start of a trial in the temporary building, particularly with the 2.5 metres wide compartment, when using the larger sizes of vent, due to the close proximity of the garage wall on one side and the diagonal bracing of the compartment on the other. The procedure was for the two experimenters to stand outside the compartment, on the centreline of its length, adjacent to the control box of the smoke generators during 'smoking-up', with a stopwatch. As the time for turning off the smoke generators approached, one ran the PPV fan up to full power (where applicable) and returned to his position. At the pre-determined time the smoke generators were switched off and the experimenters walked to their respective ends of the compartment. After a short, shouted, countdown, the vents were lowered as quickly as possible and laid flat on the ground, the event button was pressed simultaneously to mark 'time=zero' on the datalogger output, signifying the start of the trial. The difficulty occurred when pulling the vent blank down against the effect of the PPV fan, and a natural wind. This could cause the lowering of the blank to take possibly 3 seconds instead of the usual 1 second, or so. Usually, the sound of the blanks hitting the ground could be heard by the experimenter at the outlet end of the compartment, and if the delay appeared to be in excess of 3 seconds, the trial was declared void, and repeated.

However, as the compartment sizes became smaller, and the corresponding clearance times became less, these errors became more critical, causing a relatively larger error, overall and, as has been stated, the greatest difficulties were experienced in the narrowest compartment. For these reasons, the overall accuracy of the times recorded in the 2.5 metres wide compartment is liable to be less reliable than the others, particularly when the largest inlet vents are involved.

8 CONCLUSIONS

8.1 General

Guidance on ventilation is given, to brigades, in the Fire Service Manual – Vol.2 'Fire Service Operations' under the heading 'Compartment Fires and Tactical Ventilation'. The practical advice given therein has been supported by these trials.

Brigades should look upon the PPV fan as simply another tool in their armoury. It is a tool whose use needs to be carefully considered in any given situation. It has the capability of rapidly improving the situation in some instances, but it can also make things worse. Brigades have used natural ventilation to good effect for many years, and there is a vast pool of experience within the brigades in this field. The PPV fan provides, in effect, an extension to this basic technique, giving the firefighters some further options, and it can, of course, be instantly turned off, unlike natural ventilation.

Good fireground communications would be essential where a PPV fan was deployed, particularly between the firefighters inside the fire building and the fan operator. The continued use of the fan should depend upon the feedback from the firefighters inside the building.

It is clear that in a real situation where firefighters need to ventilate a building in order to search and/or fight the fire, the inlet and outlet openings should be carefully chosen. If natural ventilation, only, is to be used there is no choice about which side of the building will be the inlet – it will be the upwind side. When a PPV fan is available, the same basic rule will still apply. Any natural wind should be used to advantage if possible, and the PPV fan should be thought of as a means of assisting, or augmenting, the natural wind.

8.2 Findings from the Trials, Effect of Building Size

Previous research[2] had shown that PPV can be used to advantage in a typical domestic property. This present work was intended to explore its use in larger compartments. The trials assessed the effect of PPV on smoke clearance times, only.

It was found that when using natural ventilation the time taken for smoke to clear from a building was related, albeit loosely, to the speed of the natural wind, independent of its direction relative to the inlet vent. When PPV was used in the same situation, the time taken to clear the smoke from the building was generally reduced, particularly when the natural wind speed was low. In other words, the dependence of the clearance time upon the natural wind speed was removed, or at least reduced, by the use of PPV. A single fan would not be effective in a very large building so the use of multiple fans would be necessary.

Also, it was found that the time taken to clear a building of smoke using PPV was more predictable than when using natural ventilation, only. However, firefighters would, in practice, only be able to predict such times based upon their previously gained experience in similar buildings.

To summarise: the overall effect of PPV was beneficial in all of the buildings: the effect in the 2.5 metre wide compartment (91.5 cubic metres) was to reduce the overall average clearance time (to 40% obscuration) to roughly one quarter of the natural ventilation time.

In the 5.0 metre wide compartment (183 cubic metres), PPV reduced the overall average clearance time to roughly one third of the natural ventilation time.

In the 7.5 metre wide compartment (264.5 cubic metres), PPV reduced the overall average clearance time to roughly one third of the natural ventilation time.

In the FEU garage (1,000 cubic metres), PPV reduced the overall average clearance time to roughly one half of the natural ventilation time (considering the single fan trials, only).

In the 'green' garage (7,000 cubic metres) a single PPV fan had no discernible effect. Two fans properly used reduced clearance times to roughly half of the natural ventilation time when the wind speed was low.

8.3 Effect of Vent Positions

As a general rule, the natural wind will determine what vents can be used to advantage at an incident, whether or not PPV is to be used. In a fire situation all relevant circumstances will need to be taken into account by the firefighters.

Trials in the FEU garage suggested that, when natural ventilation was used in an open plan rectangular building, vents in line with each other on the centreline of the building were, in general, less conducive to rapid smoke clearance than the same sized vents displaced towards diagonally opposite corners of the building. (The overall average clearance time was some 23% longer in the former case.) However, when PPV was used, in the same situations, there was very little difference in the respective smoke clearance times, whichever vent positions were used. (And they were of shorter duration in both cases, than with natural ventilation.)

8.4 Effect of Vent Sizes

In this work, it has not been possible to identify any significant effects due to the different vent sizes, particularly in the larger compartments. This is probably because the compartments were too large and leaky.

In practice, firefighters may have little or no choice in the sizes of the vents available. It would seem sensible to open up the largest inlet and outlet vents available if the aim is simply to clear smoke from the building as fast as possible, and there is a reasonable natural wind (say, 1.5 metres per second, or more), whether using PPV or not. Also, if it is important to maintain control over the direction of airflow through the building, then the inlet vent must be kept to a size, and shape, which the fan or fans available at the scene can seal.

It would seem reasonable to assume that, provided the natural wind does not change direction markedly (the 'outlet vent' does not become the inlet), faster smoke clearance will be achieved with the largest possible vents, particularly the outlet vent. However, the results from the trials neither confirm nor deny this.

8.5 Probable Effect of Multiple Fans

As the volume of a smoke logged compartment increases so the effect that a single PPV fan can have decreases. A very large compartment would require a very large fan, or a number of 'small' fans to quickly reduce the level of smoke obscuration.

In these trials, when two fans were used in a very large inlet vent (so large that no 'seal' was possible) they appeared to work best, in terms of rate of smoke clearance, when they were positioned far enough apart for their outputs not to interact until well inside the compartment. When sealing a personnel access door with two fans, the best result was achieved with one fan sealing the top half of the doorway and the other sealing the lower half.

In general, in these trials, when two fans were used they cleared the smoke somewhat faster than a single fan when used in identical circumstances and with a similar natural wind. It is considered most probable that, as a general rule: the greater the number of fans brought to bear, the faster will be the smoke clearance, in any given situation.

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6. FRDG publication no. 8/98 "Measurements of the Firefighting Environment made during Tyne and Wear Metropolitan Fire Brigade's Positive Pressure Ventilation Trials at the Fire Service College". M D Thomas

7. Glenberg, Arthur M., "Learning from Data - an Introduction to Statistical Reasoning", pub. Harcourt Brace Jovanovich.

REFERENCES TO TEXT

1. "Visible Emissions Monitor" - model 250, supplied by Skil Controls Ltd., Greenhey Place, East Gillibrands, Skelmersdale, Lancs.

2. Manufactured by Aston Magana Engineering Ltd., Units 86-92, Northwick Park Business Centre, Blockley, Moreton in Marsh, Glos. GL56 9RF, to FEU drg. No. FEU-1-248 and associated drawings.

3. Unistrut 40 x 40, supplied by City Electrical Factors Ltd., Unit 5, Western Road Industrial Estate, Stratford-upon-Avon, Warks. CV37 0AH.

4. Wind speed and direction indicator, type D.600/120., supplied by Vector Instruments Ltd., Marsh Road, Rhyl, Clwyd.

5. "G-300" cold smoke generator, manufactured and supplied by Le Maitre Ltd., 6, Forval Close, Wandle Way, Mitcham, Surrey CR4 4NE.

6. "Tempest" PPV fans manufactured by Tempest Controlled Airstreams, 4645, N. Bendel Ave., Fresno, CA 93722, USA., and marketed in UK by Fire Safety Equipment Ltd., Wilford Industrial Estate, Wilford, Nottingham NG11 7EP.

7. Ultrasonic anemometer: 3 axis "Windmaster" model no. 1086.M/1189.PC. Manufactured by Gill Instruments Ltd., Solent House, Cannon St., Lymington, Hants. SO41 9BR and supplied by Bristol Industrial and Research Associates Ltd., PO Box 2, Portishead, Bristol BS20 9JB.

8. Laptop computer: Toshiba T.2000.Sxe, using "Anemcom" operating software supplied with the anemomenter (7).

9. Analogue read-out manufactured to FEU specification by St. Albans Meter Co. Ltd., Unit 4, The Enterprise Park, Cloggy Rd., Kimpton, Hants. SG4 8HP.

10. Dell "Ultrascan" model no. VC.5.EN.

11. Scorpio datalogger SI.3535D., supplied by Solartron Instruments, Victoria Rd., Farnborough., Hants. GU14 7PW.

12. Solatron Instruments, Victoria Rd., Farnborough, Hants. GU14 7PW. Scorpio Software.

13. E. E. Bennett & Sons, Holly Mount, Sheep St., Chipping Campden, Glos. GL55 6DR.

14. Weir '413'. Weir Instrumentation Ltd., Durham Rd., Bognor Regis, Sussex.

15. Battery powered (12V) anemometer, supplied by Airflow Developments Ltd., Lancaster Rd., High Wycombe, Bucks.

16. Scatter graphs, regression and correlation analysis were carried out using Microsoft Excel, the Microsoft Corporation, 1 Microsoft Way, Redmond, WA 98052-6399, USA.

17. The statistical techniques used in (16), above, are given in "Learning from Data" by A M Glenberg. (Ref. 7).

TABLES

TRIAL NO.	PPV USED	TACTIC USED	AVERAGE NATURAL WIND		INLET VENT POSITION	AVERAGE COMPONENT OF NATURAL WIND NORMAL TO VENT AXIS M/SEC.	OBSCURATION REDUCTION. TIME TO: (MIN + SEC.)			
			SPEED M/SEC.	DIRECTION (FROM °)			40%	20%	10%	5%
8	YES (X2)	Vent fully open: Two fans side by side	1.3	217	S.E.	0.2	12.30	16.50	20.45	N/A
9	YES (X2)	Fans one behind other: 21" IN vent, 24" at 2.5m., both on centreline of vent Inlet vent = 7'0" wide	1.5	234	S.E.	1.6	18.10	24.30	28.45	N/A
10	NO	Vents fully open. (Soon after (9) above)	1.8	241	S.E.(?)	0.9	16.20	22.10	25.35	27.05
11	NO	Vents fully open (Similar to (10) above, but different wind.)	3.0	342	N.W.	2.2	8.50	13.00	15.40	19.05
12	YES	Single (21") fan. IN vent on centreline, vent fully open.	2.3	323	N.W.	2.1	14.05	18.15	22.50	N/A
13	YES	Single (24") fan on vent centreline at 2.5m. out. Vent width = 7'0"	1.8	228	N.W.	0.6	15.15	19.30	23.20	26.05
14	NO	Vent fully open.	2.0	212	S.E.(?)	0.1	12.45	17.20	20.50	22.40

Notes:
1. Both vents used were of approximately equal size (≏ 4m. x 4m.).
2. In all trials the outlet vent was fully opened.
3. The fan was in position and running "flat out" before the inlet vent was opened, in all cases.
4. A question mark in the "inlet vent position" column, when no PPV was used indicates that some smoke escaped via both vents during the trial.

Table 1 Results of Cold Smoke Trials in the 'Green' Garage

TRIAL NO.	PPV USED	TACTIC USED	AVERAGE NATURAL WIND		INLET VENT POSITION	AVERAGE COMPONENT OF NATURAL WIND NORMAL TO VENT AXIS	OBSCURATION REDUCTION. TIME TO: (MIN + SEC.)			
			SPEED M/SEC.	DIRECTION (FROM °)		M/SEC.	40%	20%	10%	5%
1	YES	24" Fan on centreline of vent – 2.5m. out Vent fully open	2.4	175	S.E	1.4	11.50	15.35	19.10	21.10
2	NO	Vent fully open	3.3	182	S.E(?)	1.5	10.35	13.05	14.35	17.00
3	YES (X2)	Vent fully open: Two fans (24" and 21") Side by side Just "sealing" up to ≏ 7'0" high (Fans - 2.5m. out)	2.8	229	S.E	1.0	13.25	17.20	21.10	22.30
4	NO	As for (3) above	1.7	232	S.E.(?)	0.7	20.10	26.05	30.45	33.35
5	YES (X2)	Two fans one above other (24" top), at ≏ 7'0" high (Figure 24) Inlet vent opened to 6'0" wide only	1.0	289	N.W.	1.0	13.00	16.10	19.10	21.40
6	NO	Vent fully open (soon after (5) above)	0.9	328	N.W.(?)	0.8	38.50	50.10	55.05	58.50
7	YES (X2)	Two fans. IN vent (Figure 25), Vent fully open	1.6	323	N.W.	1.5	18.15	23.45	28.50	N/A

Table 1 Results of Cold Smoke Trials in the 'Green' Garage

TRIAL NO.	PPV USED	VENTS IN→OUT	INLET/OUTLET AREA RATIO	AVERAGE NATURAL WIND		COMPONENT OF NATURAL WIND NORMAL TO VENT AXIS (AVERAGE)	TIME TO —% OBSCURATION (AV. OF 3 5.0M.S.) MIN. + SEC.			% AGE OF 'NATURAL' TIME TAKEN BY P.P.V. TO		
				SPEED M/SEC.	DIRECTION —°	M/SEC.	40%	20%	10%	40%	20%	10%
21/1/98 No. 1	NO	5' 0"→ 5' 0" Diagonal	1.0	3.3	180	0	7.35	10.40	13.50	} 62	} 60	} 54
No. 2	YES	"	1.0	3.4	182	0.1	4.40	6.25	7.25			
No. 3	YES	"	1.0	4.2	187	0.5	4.20	5.30	6.45			
22/1/98 No. 1	YES	"	1.0	3.5	184	0.2	3.50	5.10	6.05	} 53	} 48	} 48
No. 2	NO	"	1.0	3.3	184	0.2	7.15	10.50	13.20			
28/1/98 No. 1	YES	"	1.0	1.1	N/A (≏ 0°)	(≏ 0)	6.00	7.40	8.50	} 40	} 33	} 31
No. 2	NO	"	1.0	1.3	N/A (≏ 0°)	(≏ 0)	15.00	23.50	28.40			
No. 3	YES	"	1.0	1.0	N/A (≏ 0°)	(≏ 0)	8.10	10.30	12.10			
30/1/98 No. 1	YES	"	1.0	1.0	354	0.1	9.10	11.25	13.20	} 28	} 28	} 28
No. 2	NO	"	1.0	1.1	001	0	32.45	41.10	48.20			
6/2/98 No. 1	TRIAL ABORTED - NO DATA											
No. 2	NO	"	1.0	6.4	202	2.4	13.25	16.20	19.35			
9/2/98 No. 1	YES	"	1.0	3.9	197	1.1	6.00	7.25	8.30	48	49	47
10/2/98 No. 1	YES	Both on centreline	1.0	4.6	208	2.2	6.25	8.00	9.10			
No. 2	NO	"	1.0	4.6	221	3.0	17.45	21.30	25.35	36	37	36
No. 3	YES	"	1.0	4.2	214	2.3	6.30	8.00	9.35	37	37	37
No. 4	YES	"	1.0	4.0	206	1.8	7.05	8.25	9.30			
19/2/98 No. 1	YES	"	1.0	3.4	206	1.5	7.15	9.30	11.20			
No. 2	YES	"	1.0	4.7	231	3.6	6.30	7.45	8.40			
No. 3	TRIAL ABORTED - NO DATA											
26/2/98 No. 1	YES	"	1.0	3.2	211	1.7	5.50	7.15	8.25			
No. 2	YES	"	1.0	4.0	213	2.2	6.05	7.35	9.30	} 41	} 38	} 40
No. 3	NO	"	1.0	4.0	215	2.3	14.40	19.30	23.30			
4/3/98 No. 1	YES	"	1.0	6.1	258	6.0	3.05	4.25	5.00			
No. 2	YES	"	1.0	6.4	250	6.0	3.10	4.20	4.55			
No. 3	YES	"	1.0	5.5	252	5.2	2.50	3.25	4.40	} 41	} 36	} 42
No. 4	NO	"	1.0	5.7	234	4.6	6.50	9.35	11.05			
12/3/98 No. 1	YES	5' 0" Vents same end (upstream)	1.0	3.3	266	3.3	4.25	5.25	6.35	} 53	} 47	} 43
No. 2	NO	"	1.0	3.1	260	3.0	8.20	11.30	15.15			
13/3/98 No. 1	YES	" Both downstream end	1.0	3.9	311	-2.7	6.05	7.35	8.45	} 30	} 28	} 29
No. 2	NO	5' 0" " "	1.0	3.7	307	-2.9	20.35	26.45	30.25			
No. 3	YES	5' 0" " "	1.0	3.6	305	-2.9	7.55	10.10	11.40			
15/4/98 No. 1	YES	2' 6"→ 5' 0"Diagonal	0.5	6.2	318	4.2	4.35	6.20	7.45	} 76	} 71	} 70
No. 2	NO	"	0.5	6.3	324	3.7	6.00	8.55	11.05			
16/4/98 No. 1	YES	5' 0"→2' 6"Diagonal	2.0	1.3	268	1.3	5.00	6.20	7.25[(1)]	[(1/2)]66	58	54
No. 2	NO	"	2.0	1.4	177	0.1	7.35	10.55	13.50[(2)]			
No. 3	YES Two in tandem	"	2.0	0.8	166	-0.2	4.35	5.50	6.45[(3)]	[(3/2)]60	53	49

Table 2 Results of Cold Smoke Trials in the FEU Garage.

Sheet 1 of 2 sheets

TRIAL NO.	PPV USED	VENTS IN→OUT	INLET/OUTLET AREA RATIO	AVERAGE NATURAL WIND		COMPONENT OF NATURAL WIND NORMAL TO VENT AXIS (AVERAGE)	TIME TO % OBSCURATION (AV. OF 3 5.0M.S.) MIN. + SEC			% AGE OF 'NATURAL' TIME TAKEN BY P.P.V. TO		
				SPEED M/SEC.	DIRECTION —°	M/SEC.	40%	20%	10%	40%	20%	10%
16/4/98 No. 4	YES Two side by side	5' 0"→2' 6"Diagonal	2.0	0.8	177	0.1	4.40	5.40	6.30			
7/5/98 No. 1	YES	2' 6"→8' 0"Diagonal	0.3	5.7	207	2.6	5.30	7.25	$9.05^{(4)}$	$^{(4/6)}66$	64	59
No. 2	YES Two in tandem	"	0.3	4.2	213	2.3	3.55	5.10	$6.25^{(5)}$			
No. 3	NO	"	0.3	4.4	214	2.5	8.20	11.40	$15.30^{(6)}$	$^{(5/6)}47$	44	41
21/5/98 No. 1	YES	8' 0"→2' 6"Diagonal	3.2	3.9	N/A (Ω 330?)	Ω 2.0	4.25	5.55	6.50			
No. 2	YES In doorway	"	3.2	2.1	N/A (Ω 330?)	Ω 1.1	12.10	16.30	21.20			
28/5/98 No. 1	YES	"	3.2	2.7	049	2.1	4.40	6.35	$8.05^{(7)}$	$^{(7/10)}60$	65	58
No. 2	YES In doorway	"	3.2	3.1	359	0.1	7.40	10.20	$12.40^{(8)}$	$^{(8/10)}99$	102	90
No. 3	YES Two side by side	"	3.2	2.4	050	1.9	3.20	4:15	$5.05^{(9)}$	$^{(9/10)}43$	43	36
No. 4	YES Two in tandem	"	3.2	2.0	051	1.6	4.05	5.20	6.25			
No. 5	NO	"	3.2	2.5	065	2.3	7.45	10.10	$14.00^{(10)}$			
21/7/98 No. 1	YES	"	3.2	4.8	221	3.1	3.00	4.35	$5.35^{(11)}$	$^{(11/12)}69$	65	64
No. 2	YES In doorway	"	3.2	5.2	234	4.2	3.00	4.15	5.50			
No. 3	NO	"	3.2	5.4	234	4.3	4.20	7.05	$8.45^{(12)}$		84	80
22/7/98 No. 1	YES	2' 6"→8' 0"Diagonal	0.3	5.2	191	1.0	5.10	7.00	$8.40^{(13)}$	$^{(13/16)}84$		
No. 2	YES In doorway	"	0.3	5.1	186	0.5	5.10	7.10	$9.20^{(14)}$	$^{(14/16)}84$	85	85
No. 3	YES Two in tandem	"	0.3	5.6	187	0.7	3.35	4.50	$6.15^{(15)}$	$^{(15/16)}58$	57	57
No. 4	NO	"	0.3	6.0	180	0	6.10	8.25	$11.00^{(16)}$			

Notes:

1. The orientation and sizes of the vents used and the position of any fan are shown, in relation to the average natural wind in Figures 84-90 inc.
2. In trials no. 12/3/98: No. 1 – 13/3/98: No. 3, both vents were at the same end of the building: windward end in 12/3/98 No.1, downwind end in the others.
3. Where two fans were used, their orientation relative to the vent is shown in the trial record sketches, listed below:

Trial no.	-	Figure No.	Trial no.	-	Figure No.
16/4/98: No 3	-	102.A.	28/5/98: No. 3	-	102.D.
" No. 4	-	102.C.	" No. 4	-	102.B.
7/5/98: No. 2	-	102.A.	22/7/98. No. 3	-	102.A.

4. In the column headed % age of natural time taken by PPV… "the stated figure for each level of obscuration is simply the value "with PPV "divided by the value for natural ventilation. In trial no. 16/4/98: No. 1, and some subsequent trials, where other comparisons are also being made, a number (thus (1) is given in the observed time column and the numbers of the two trials being compared are given in the "% of natural… "column. (Thus "$\frac{1}{3}$ "means value (1) divided by value (3), x 100%.)

Table 2 Results of Cold Smoke Trials in the FEU Garage.

Sheet 2 of 2 sheets

TRIAL NO.	PPV	VENTS IN→OUT	IN/OUT AREA RATIO	AVERAGE NATURAL WIND		COMPONENT OF NATURAL WIND NORMAL TO VENT AXIS (AVERAGE)	OBSCURATION REDUCTION TIME TO:...% MIN.+SEC.			% OF 'NATURAL' TIME TAKEN BY PPV TO:		
				SPEED M/SEC.	DIRECTION (FROM) ...°	M/SEC.	40%	20%	10%	40%	20%	10%
11/1/99 No. 1	YES	5'0"→5'0"	1	2.7	315	1.9	1-50	2-20	2-35	40	39	37
" No. 2	NO	"	1	2.8	312	2.0	4-35	5-55	7-00			
" No. 3	YES	5'0"→2'6"	2	2.6	307	2.1	3-05	3-50	4-30	52	53	55
" No. 4	NO	"	2	3.0	302	2.5	5-55	7-15	8-15			
" No. 5	YES	2'0"→2'6"	1	2.3	303	1.9	5-00	6-00	6-55	38	37	39
" No. 6	NO	"	1	1.9	311	1.4	13-15	16-15	18-15			
13/1/99 No. 1	YES	2'6"→8'0"	0.3	2.7	230	2.1	2-45	3-25	3-50	29	28	27
" No. 2	NO	"	0.3	2.0	217	1.2	9-30	12-20	14-10			
" No. 3	YES	2'6"→5'0"	0.5	2.5	190	0.4	3-40	4-25	4-55	32	31	30
" No. 4	NO	"	0.5	3.2	196	0.9	11-25	14-10	16-10			
" No. 5	YES	5'0"→8'0"	0.63	5.7	189	1.1	2-00	2-25	2-40	44	47	46
" No. 6	NO	"	0.63	6.4	185	0.5	4-30	5-25	5-45			
" No. 7	YES	8'0"→8'0"	1	4.9	185	0.4	1-55	2-40	3-40	37	42	51
" No. 8	NO	"	1	3.6	190	0.6	5-10	6-25	7-10			
15/1/99 No. 1	YES	8'0"→5'0"	1.6	7.3	192	1.5	1-45	2-05	2-15	55	60	61
" No. 2	NO	"	1.6	7.3	191	1.2	3-10	3-30	3-40			
" No. 3	YES	8'0"→2'6"	3.1	7.8	198	2.4	2-10	2-45	3-10	50	55	57
" No. 4	NO	"	3.1	7.3	194	1.8	4-20	5-00	5-35			
" No. 5	YES	5'0"→2'6"	2	8.8	194	2.1	2-05	2-40	2-55	62	63	59
" No. 6	NO	"	2	8.1	193	1.8	3-20	4-15	4-55			

Notes: 1. All vents positioned on the longitudinal centreline of the compartment.
2. The obscuration reduction values are the averages from the three smoke obscuration meters.

Table 3 Results of Cold Smoke Trials in the 7.5m. Wide Compartment.

TRIAL NO.	PPV USED	VENTS IN→OUT	IN/OUT AREA RATIO	AVERAGE NATURAL WIND		COMPONENT OF NATURAL WIND ALONG VENT AXIS (AVERAGE)	OBSCURATION REDUCTION TIME TO:...% MIN.+SEC.			% OF 'NATURAL' TIME TAKEN BY PPV TO:		
				SPEED M/SEC.	DIRECTION (FROM) ...°	M/SEC.	40%	20%	10%	40%	20%	10%
23/2/99 No. 1	YES	2'6"→2'6"	1	4.7	270	4.7	1-10	1-30	1-45	53	55	57
" No. 2	NO	"	1	4.9	284	4.8	2-15	2-45	3-05			
" No. 3	YES	2'6"→5'0"	0.5	5.2	275	5.1	1-00	1-15	1-25	43	45	44
" No. 4	NO	"	0.5	4.8	294	4.0	2-20	2-45	3-15			
" No. 5	YES	2'6"→8'0"	0.3	4.4	276	4.4	0-50	1-05	1-15	50	54	54
" No. 6	NO	"	0.3	3.6	269	3.6	1-40	2-00	2-20			
25/2/99 No. 1	YES	5'0"→8'0"	0.63	3.4	208	1.6	0-53	1-06	1-15	27	29	26
" No. 2	NO	"	0.63	2.8	205	1.2	3-13	3-44	4-44			
" No. 3	YES	5'0"→5'0"	1	2.0	215	1.1	0-57	1-08	1-15	32	35	36
" No. 4	NO	"	1	3.4	215	1.9	2-56	3-12	3-29			
" No. 5	YES	5'0"→2'6"	2	3.2	219	2.1	1-07	1-20	1-31	28	31	34
" No. 6	NO	"	2	3.5	214	1.9	3-58	4-15	4-31			
" No. 7	YES	8'0"→2'6"	3.2	2.6	218	1.6	0-56	1-31	1-39	30	38	40
" No. 8	NO	"	3.2	2.8	220	1.8	3-05	3-59	4-05			
" No. 9	YES	8'0"→5'0"	1.6	3.6	218	2.2	0-31	0-47	0-48	24	34	30
" No.10	NO	"	1.6	4.2	222	2.8	2-08	2-20	2-39			
" No.11	YES	8'0"→8'0"	1	4.9	212	2.6	0-25	0-32	0-40	23	25	30
" No.12	NO	"	1	3.9	219	2.5	1-48	2-07	2-15			
12/3/99 No. 1	YES	3'9"→8'0"	0.47	0.7	221	0.5	1-15	1-33	1-46	17	16	17
" No. 2	NO	"	0.47	1.1	199	0.3	7-20	9-32	10-34			
" No. 3	YES	3'9"→5'0"	0.75	1.9	162	0.6	1-48	2-16	2-28	32	36	36
" No. 4	NO	"	0.75	2.3	169	0.4	5-37	6-19	6-48			
" No. 5	YES	3'9"→2'6"	1.5	2.5	179	0	1-48	2-16	2-42	37	39	41
" No. 6	NO	"	1.5	3.0	177	0.2	4-52	5-45	6-35			
22/3/99 No. 1	YES	2'6"→2'6"	1	4.3	304	3.6	1-33	1-45	2-13	49	49	58
" No. 2	NO	"	1	3.5	292	3.2	3-10	3-36	3-51			
" No. 3	YES	2'6"→5'0"	0.5	4.7	292	4.4	1-12	1-29	1-49	65	67	74
" No. 4	NO	"	0.5	3.5	276	3.5	1-50	2-12	2-28			
" No. 5	YES	2'6"→8'0"	0.3	3.7	306	3.0	1-12	1-39	1-53	101	103	105
" No. 6	NO	"	0.3	3.5	279	3.4	1-11	1-36	1-48			

Notes:
1. All vents positioned on the longitudinal centreline of the compartment.
2. The obscuration reduction values are the averages from the three smoke obscuration meters.
3. The 12/3/99 trials used non-standard vent sizes (see Section 6.5.2.).

Table 4 Results of Cold Smoke Trials in the 5.0m. Wide Compartment.

TRIAL NO.	PPV USED	VENTS IN→OUT	IN/OUT AREA RATIO	AVERAGE NATURAL WIND		COMPONENT OF NATURAL WIND ALONG VENT AXIS (AVERAGE)	OBSCURATION REDUCTION TIME TO: (MIN. + SEC.)			% AGE OF 'NATURAL' VENT TIME TO:		
				SPEED M/SEC.	DIRECTION (FROM) —°	M/SEC.	40%	20%	10%	40%	20%	10%
28/4/99 No.1	YES	2'6"→2'6"	1.0	3.7	354	-0.4	0-39	0-48	0-51	12%	14%	14%
" No.2	NO	" "	1.0	2.7	39	1.7	5-35	5-50	6-12			
" No.3	YES	2'6"→5'0"	0.5	3.2	36	1.9	0-23	0-32	0-40	19%	20%	23%
" No.4	NO	" "	0.5	3.1	5	0.3	2-04	2-49	2-57			
" No.5	YES	2'6"→8'0"	0.3	2.9	38	1.8	0-29	0-37	0-38	27%	32%	32%
" No.6	NO	" "	0.3	3.2	12	0.6	1-46	1-56	1-57			
" No.7	YES	5'0"→8'0"	0.63	3.4	61	3.0	(4) 0-23	(4) 0-24	(4) 0-24	38%	33%	33%
" No.8	NO	" "	0.63	3.0	59	2.6	1-01	1-12	1-13			
" No.9	YES	8'0"→8'0"	1.0	3.1	61	2.7	0-26	0-27	0-28	104%	100%	100%
" No.10	NO	" "	1.0	4.3	76	4.2	0-25	0-27	0-28			
" No.11	YES	8'0"→5'0"	1.6	3.2	39	2.0	0-26	0-37	0-38	137%	185%	173%
" No.12	NO	" "	1.6	3.3	58	1.7	0-19	0-20	0-22			
" No.13	YES	8'0"→2'6"	3.2	3.7	53	2.9	0-28	0-31	0-38	24%	23%	28%
" No.14	NO	" "	3.2	2.9	74	2.8	1-57	2-14	2-16			
" No.15	YES	5'0"→2'6"	2.0	3.4	51	2.7	0-25	0-3-	0-31	22%	20%	17%
" No.16	NO	" "	2.0	3.2	47	2.3	1-55	2-28	2-58			
" No.17	YES	5'0"→5'0"	1.0	3.3	353	-0.4	0-23	0-24	0-26	29%	27%	40%
" No.18	NO	" "	1.0	3.1	84	3.0	1-18	1-28	1-29			

Notes:
1. All vents positioned on the longitudinal centreline of the compartment.
2. Smoke obscuration meters were positioned at 'X4', 'Y8', and 'Z12'. (See Figure 93).
3. The obscuration reduction values are the average from the three smoke obscuration meters.
4. Obscuration reduction values for trial no. 28/4/99: No.7 are estimated. (Event marker – t=o- did not function.)

Table 5 Results of Cold Smoke Trials in the 2.5m. Wide Compartment.

COLD SMOKE CLEARANCE															AIRFLOW MEASUREMENTS	
TRIAL NO.	METHOD	NATURAL WIND		COMPONENT OF NATURAL WIND NORMAL TO VENT AXIS (AVERAGE)	OBSCURATION REDUCTION. TIME TO REACH: (MIN. + SEC.)			% AGE OF 'NATURAL' CLEARANCE TIME TO			% AGE OF SINGLE FAN CLEARANCE TIME TO			AVERAGE OUTLET VELOCITY	CORRESPONDING AVERAGE FLOWRATE
		SPEED (M/SEC.)	DIRECTION (FROM) __°	M/SEC.	40%	20%	10%	40%	20%	10%	40%	20%	10%	M/SEC.	M^3/SEC.
17/5/99 No.1	Two fans: One sealing lower half of doorway, the other sealing top half (See Figure 71.)	2.7	41	1.4	0-31	0-34	0-41	20%	20%	24%	78	69	71	3.8	5.7
17/5/99 No.2	Single fan at 2.5m. Max. Tilt (≏20° upward) 'Sealing'	4.4	46	3.1	0-40	0-49	0-57	26%	29%	33%	-	-	-	2.9	4.4
17/5/99 No.3	Two fans in line on vent axis. One at 2.5m. 'Sealing' One at 0.3m. ('all in')	4.0	36	2.3	0-37	0-44	0-45	24%	26%	26%	93	90	79	4.4	6.6
17/5/99 No.4	Two fans side by side: 2.4m. from vent centreline, both aimed at centreline of vent (fans 1.6m. apart)	4.8	26	2.1	0-30	0-42	0-53	19%	25%	31%	75	86	93	3.5	5.3
17/5/99 No.5	Natural ventilation, only	4.5	8	0.6	2-35	2-48	2-51	-	-	-	-	-	-	1.0	1.5

Notes: 1. These trials were conducted using two 24" Tempest fans. All trials were conducted in the 2.5 metre wide compartment. A single vent 2'6" wide by 6'6" high was positioned on the longitudinal centreline at each end, throughout all trials.
2. The 'airflow measurements' given were obtained separately using a hand held anemometer in the outlet vent (see Section 6.6.2), no corresponding natural wind data is available.

Table 6 Results of Trials using Two PPV Fans in 2.5m. Wide Compartment with 2'6" Vents.

FIGURES

Figure 1. F E U garage from the south east.

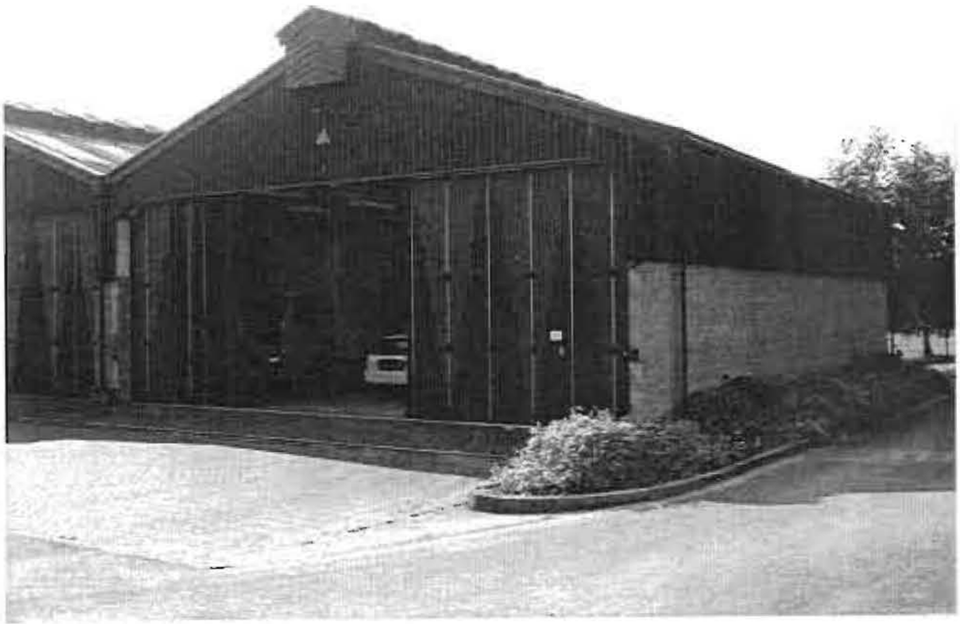


Figure 2. F E U garage from the north east.

Figure 3.The 'green' garage: general view.

Figure 4. The 'green' garage: one of the four doors.

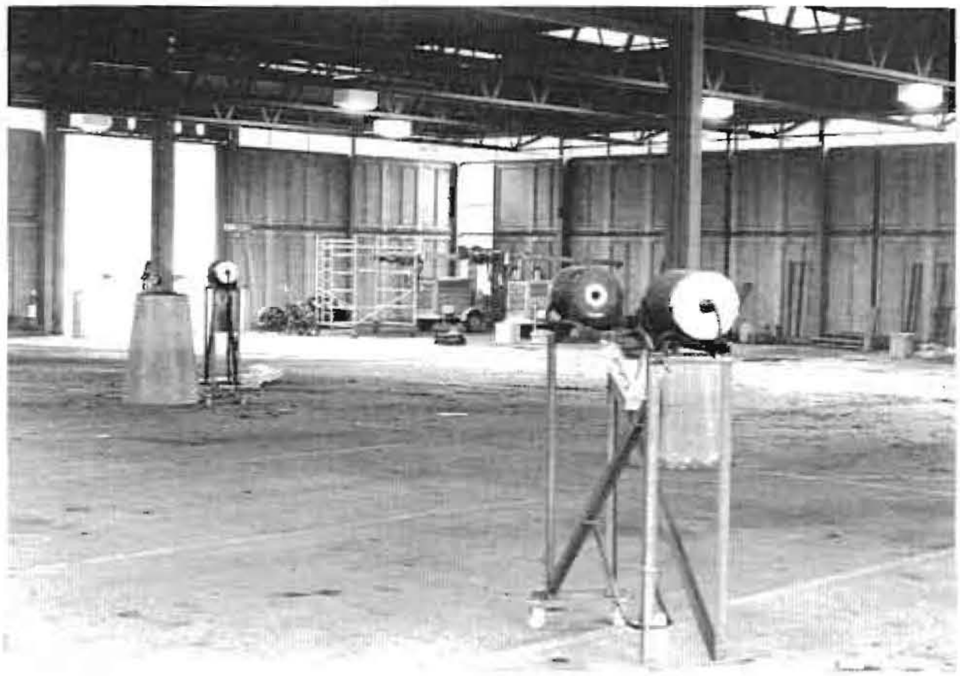


Figure 5. The 'green' garage; internal view, with door open at left.

Figure 6. LeMaitre 'G-300' cold smoke generator.

Figure 7. 24" 'Tempest' P P V fan.

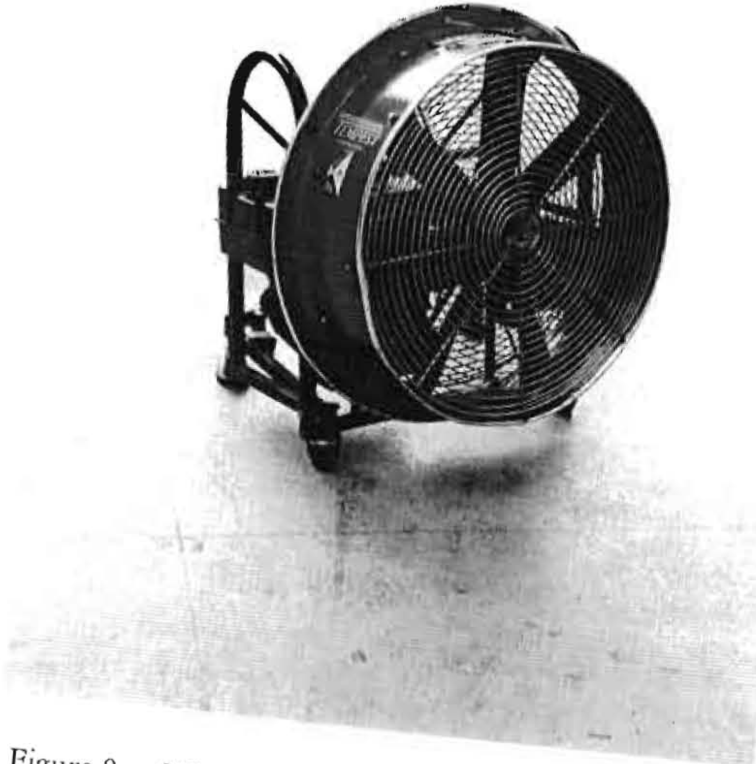


Figure 8. 21"" 'Tempest' P P V fan.

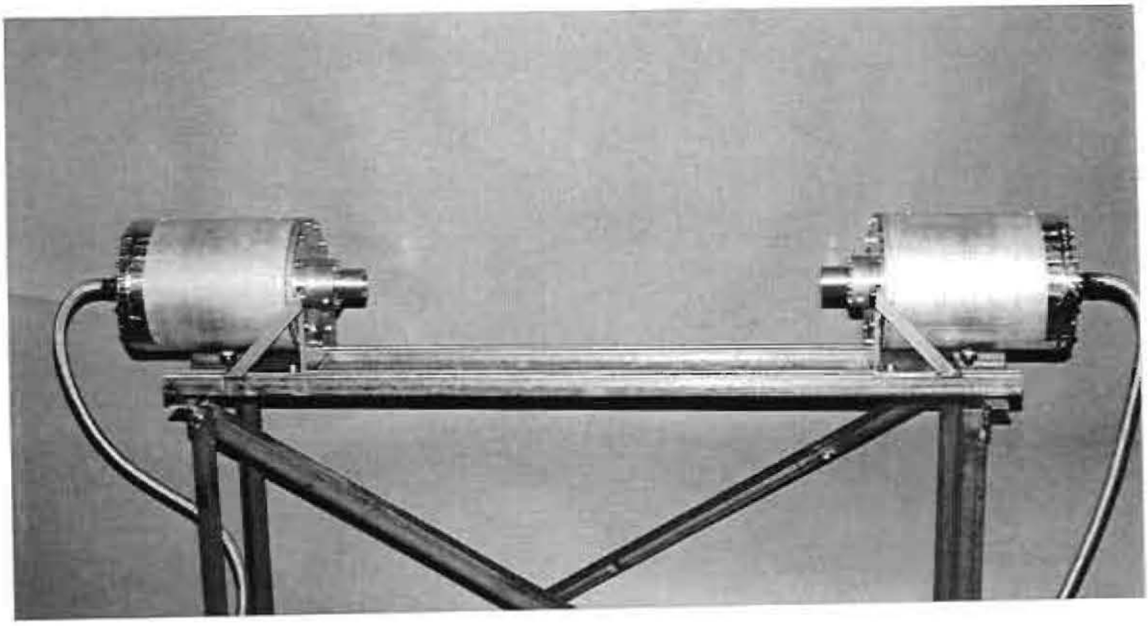


Figure 9. Smoke obscuration meter assembly.

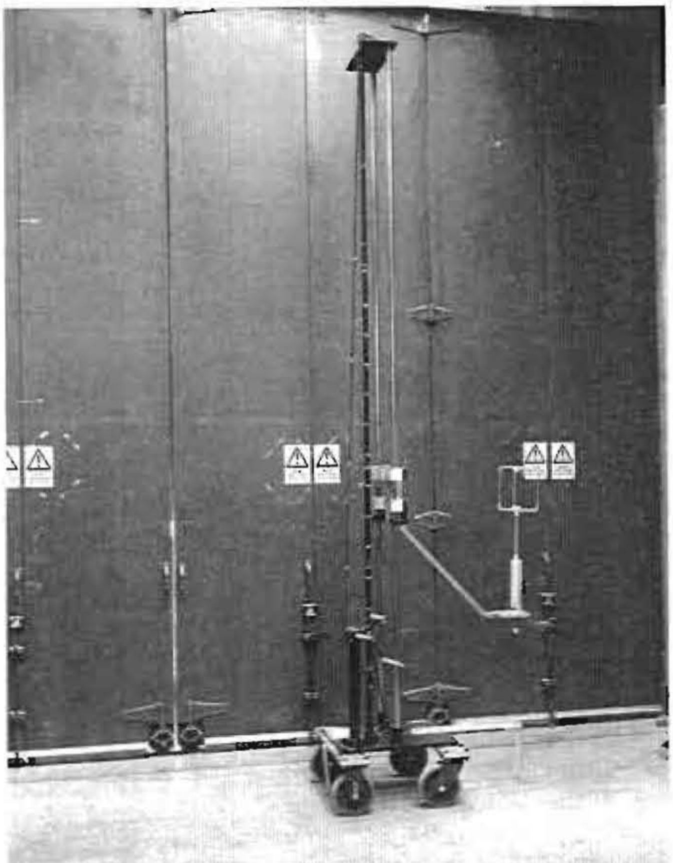


Figure 10. Ultrasonic anemometer rig.

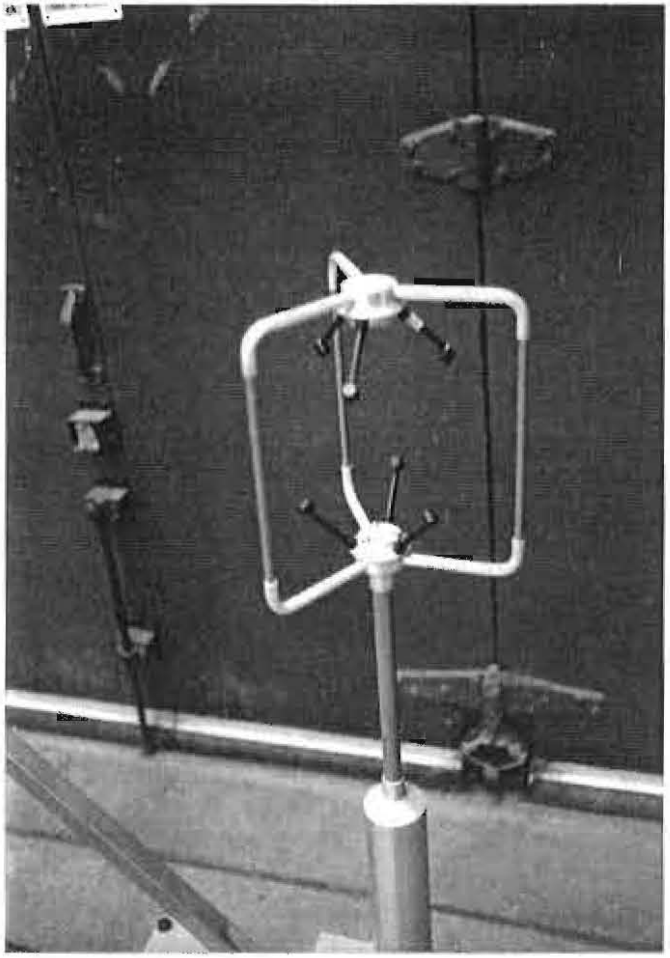


Figure 11. Ultrasonic anemometer sensing head.

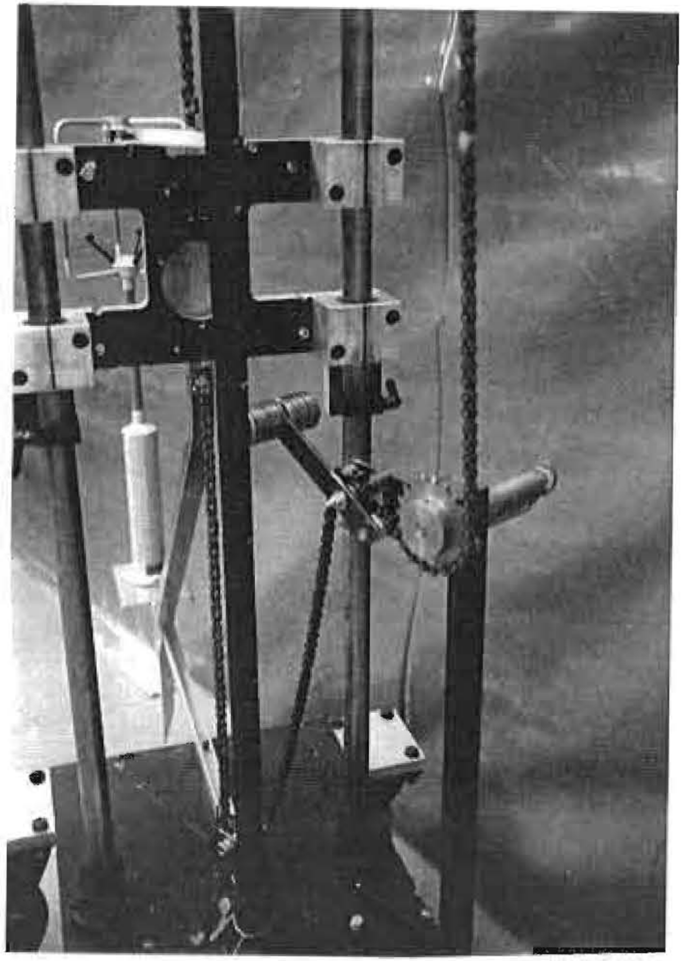


Figure 12. Ultrasonic anemometer rig - detail.

Figure 13. Ultrasonic anemometer – data processing and display trolley.

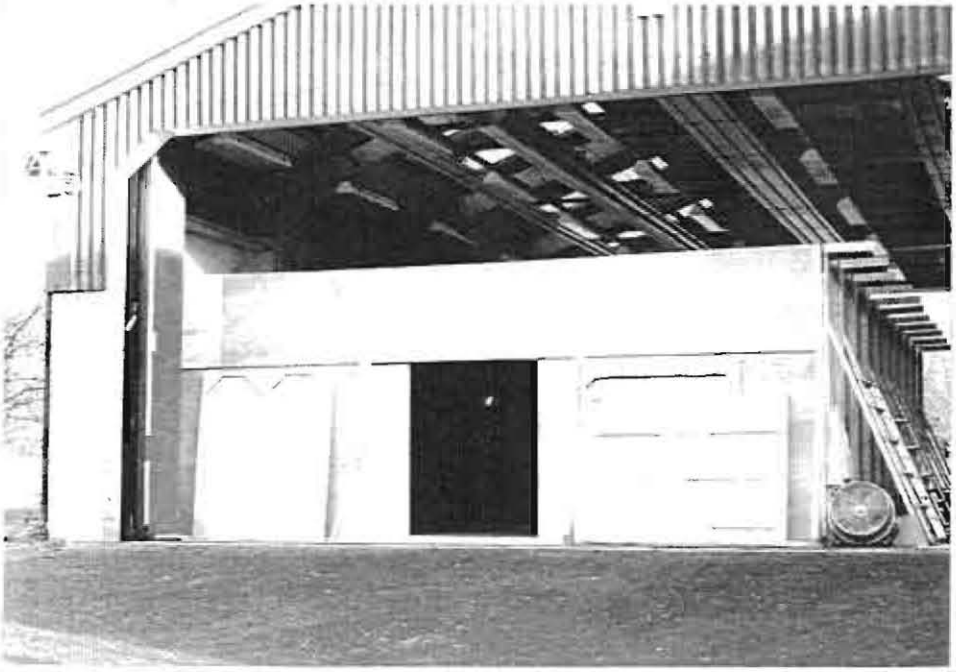


Figure 14. Temporary building – 7.0 metres wide with 1.52 metre (5'-0") wide central doorway.

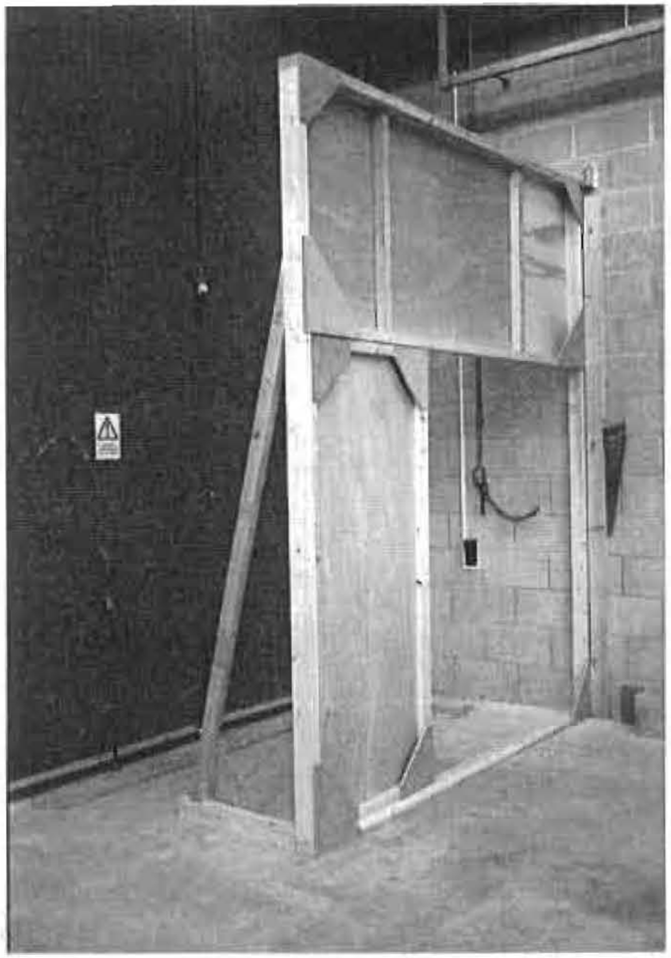


Figure 15. Temporary building under construction – first end panel.

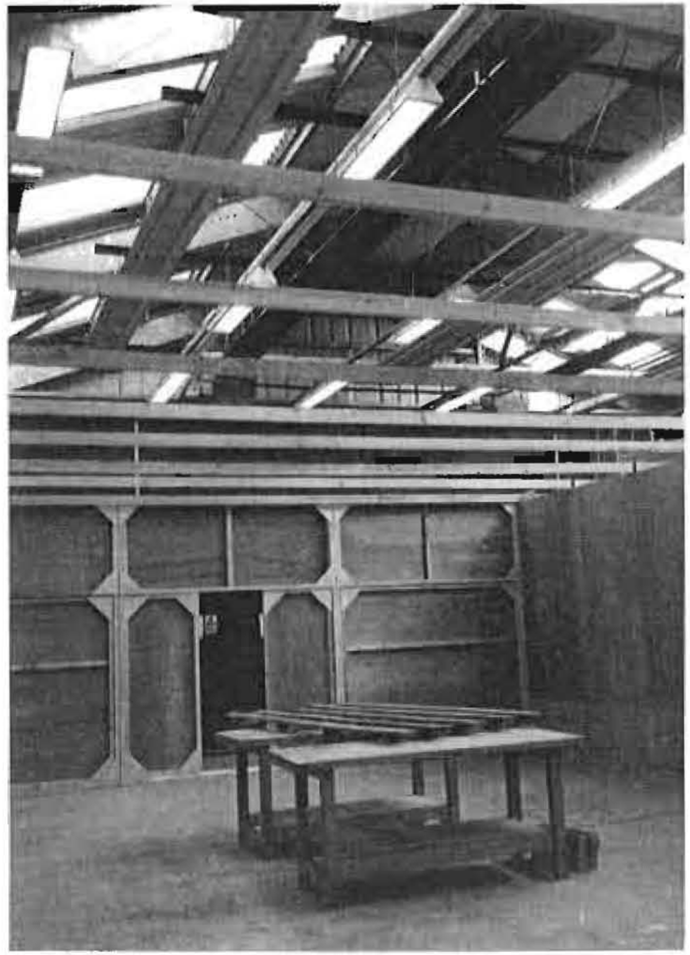


Figure 16. Temporary building under construction – roof beams being assembled.

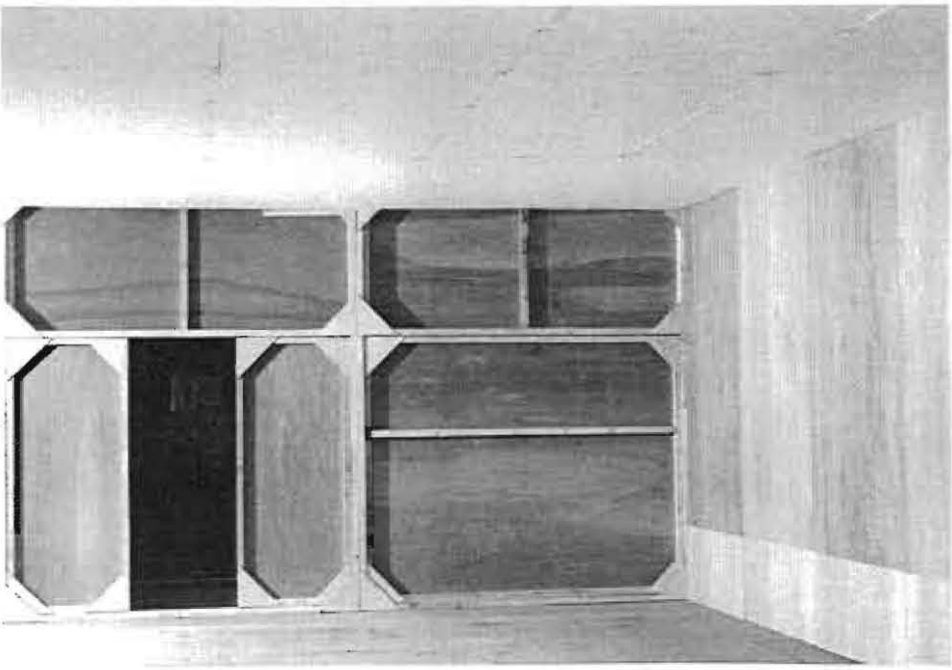


Figure 17. Temporary building with ceiling installed.

Figure 18. Doorway defining blank in position in F E U garage.

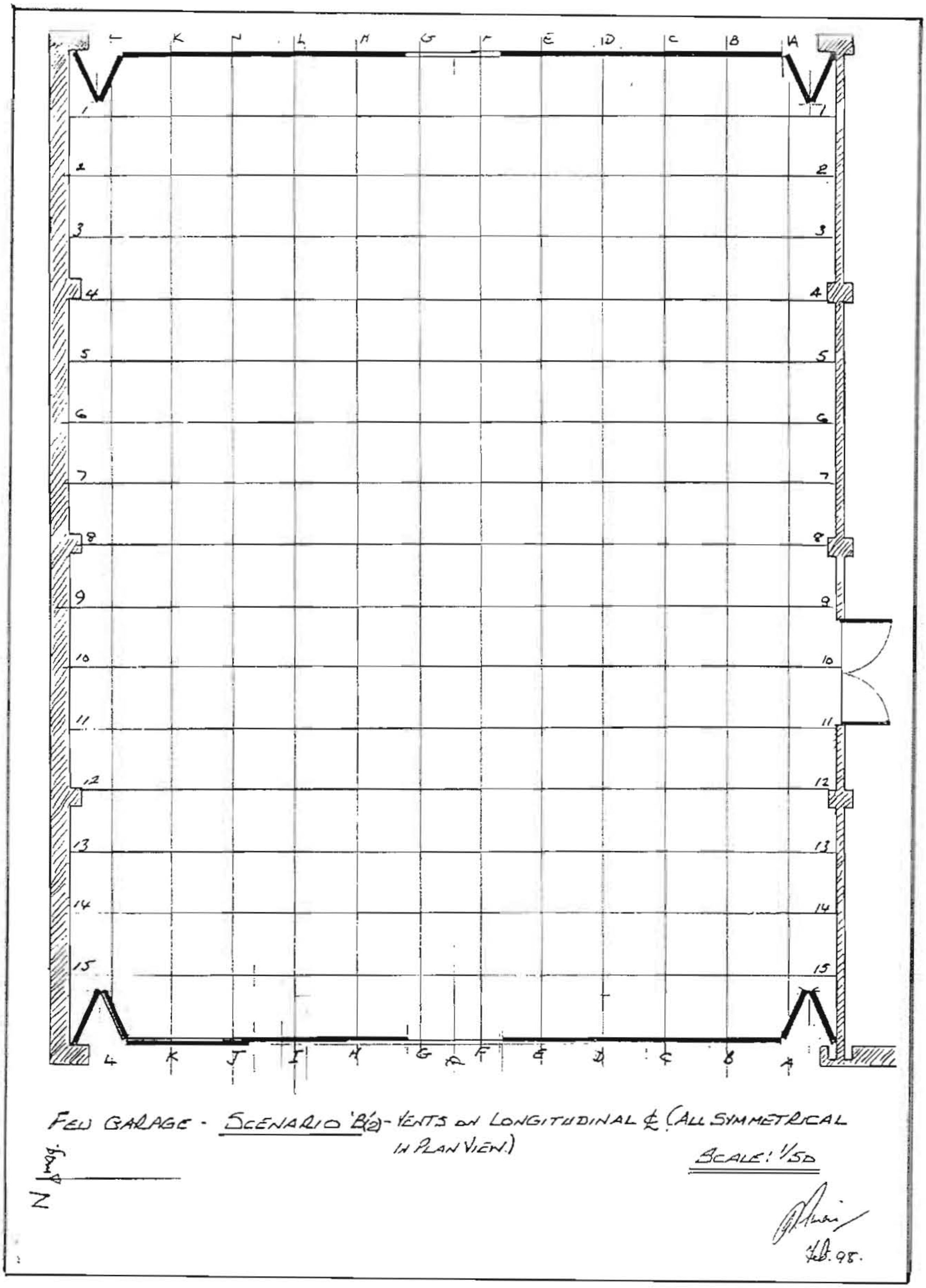


Figure 19. Positioning grid on the F E U garage floor.

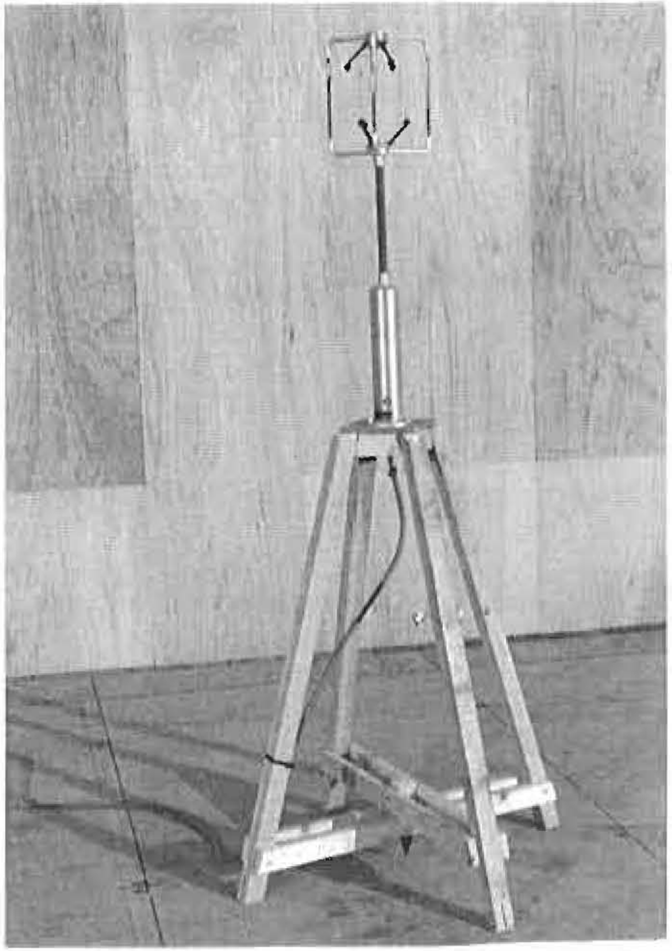


Figure 20. Simplified anemometer rig, fixed at 1.5 metre height.

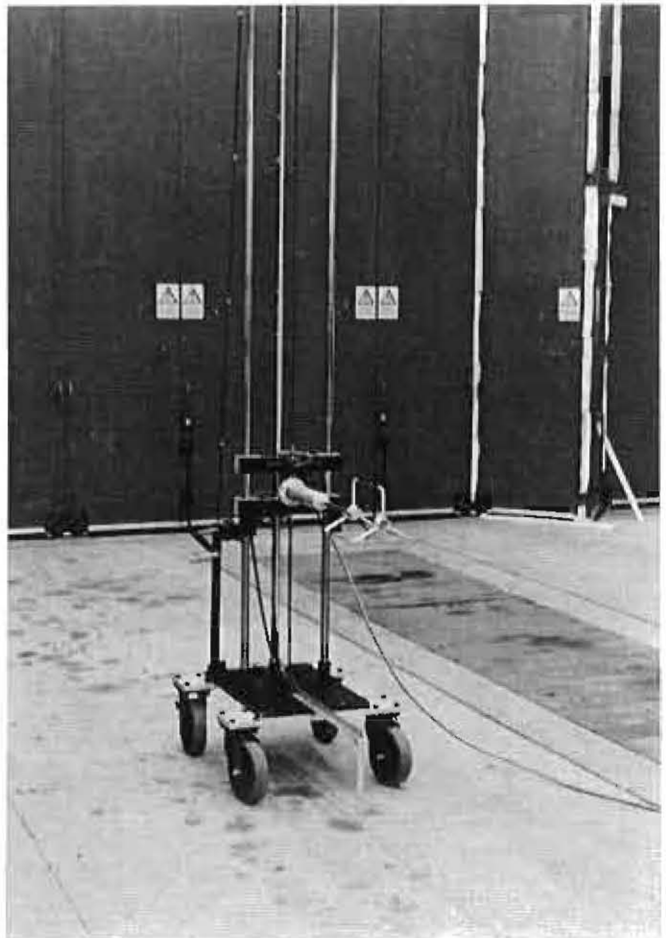


Figure 21 Anemometer mounted horizontally in positioning rig.

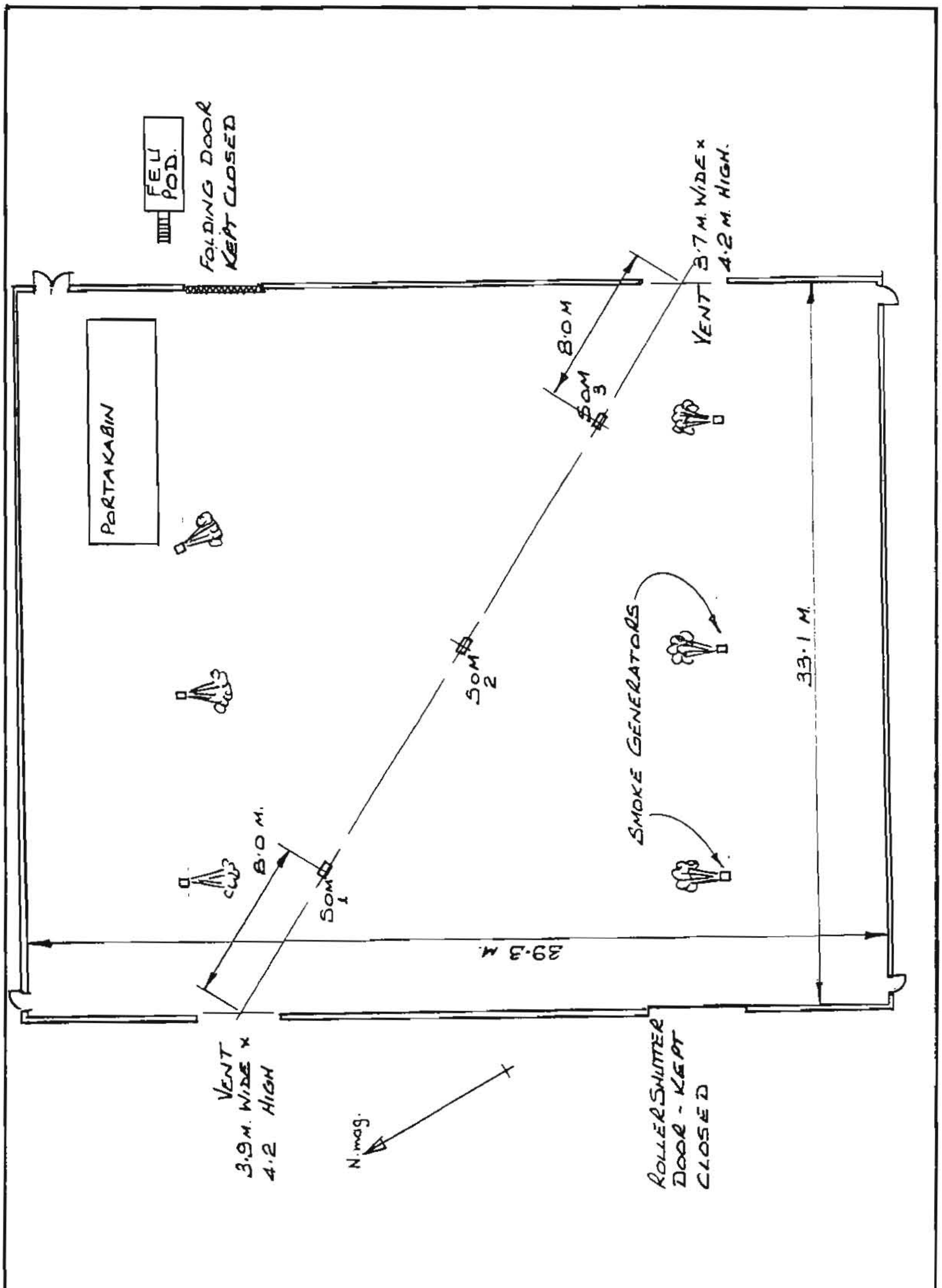


Figure 22. Arrangement within the 'green' garage for the cold smoke trials.

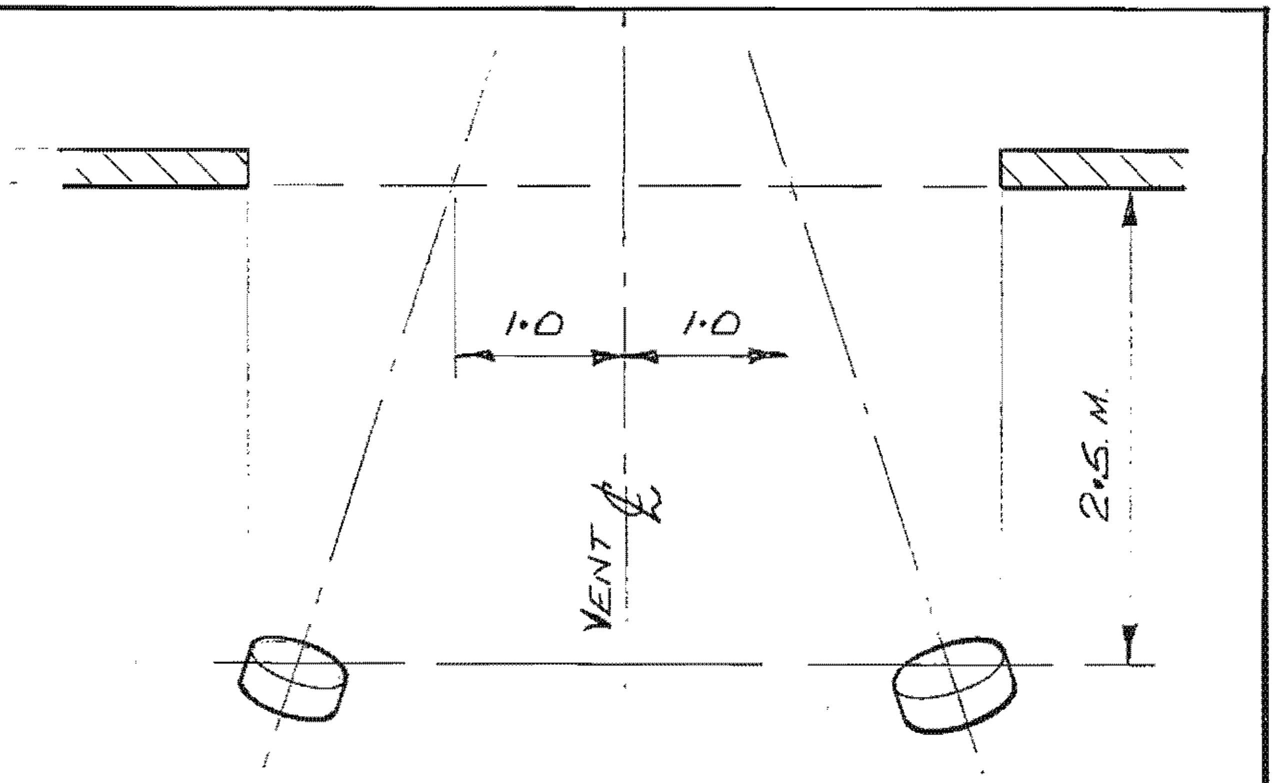


Figure 23. 'Green' garage trial no. 3: fan positions relative to vent in plan view, both fans tilted 15°.

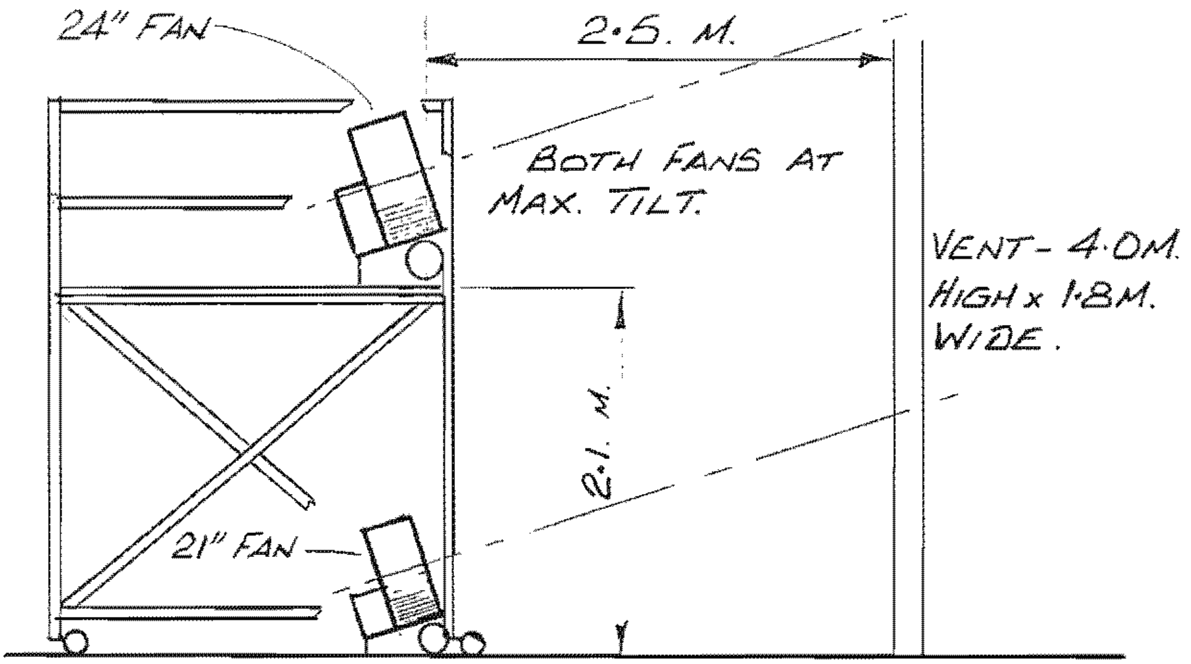


Figure 24. 'Green' garage trial no. 5: fan positions relative to vent, elevation.

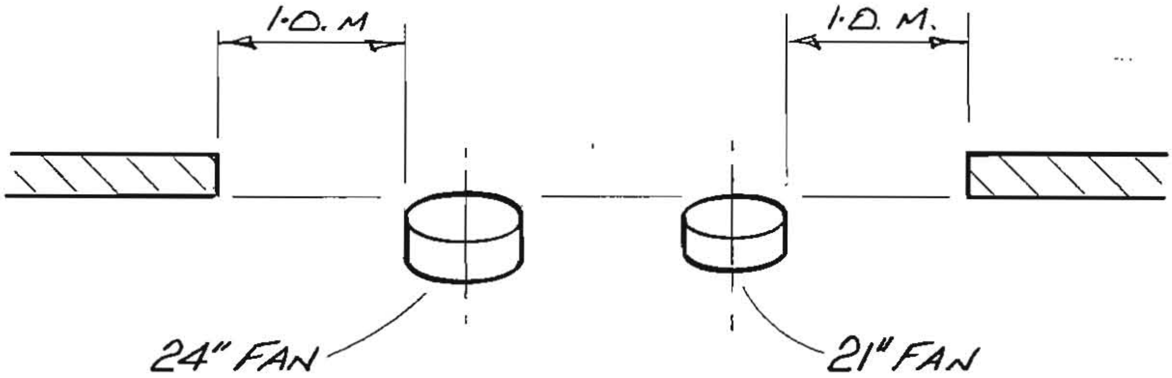


Figure 25. 'Green' garage trial no.7: fan positions relative to vent in plan view, both fans tilted 15°

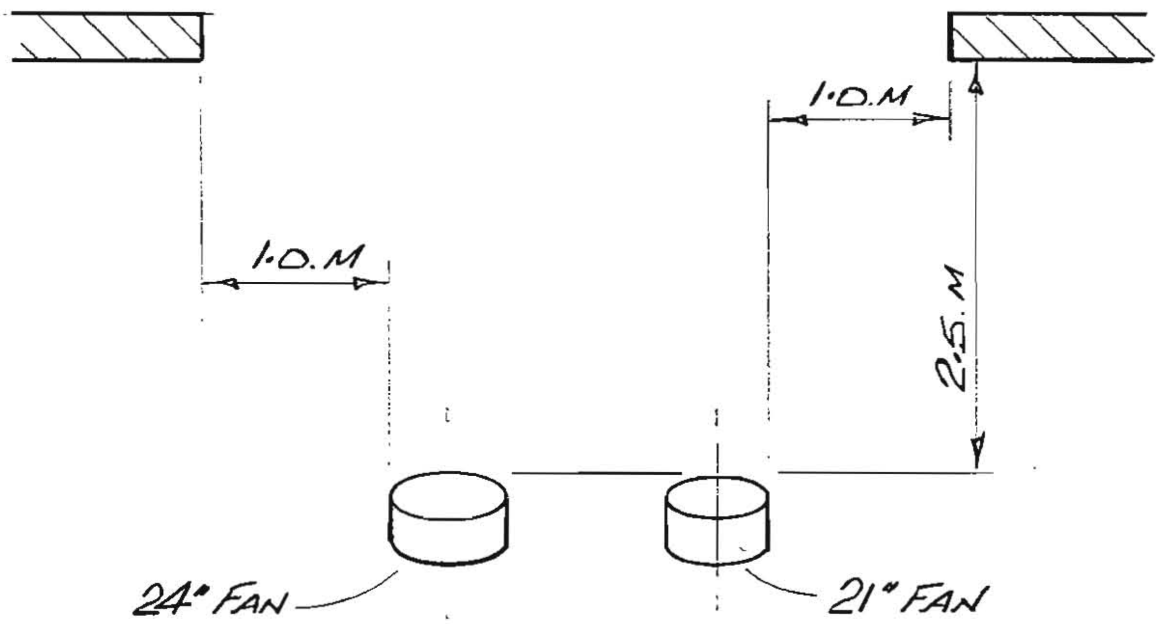


Figure 26. 'Green' garage trial no.8: fan positions relative to vent in plan view, both fans tilted 15°

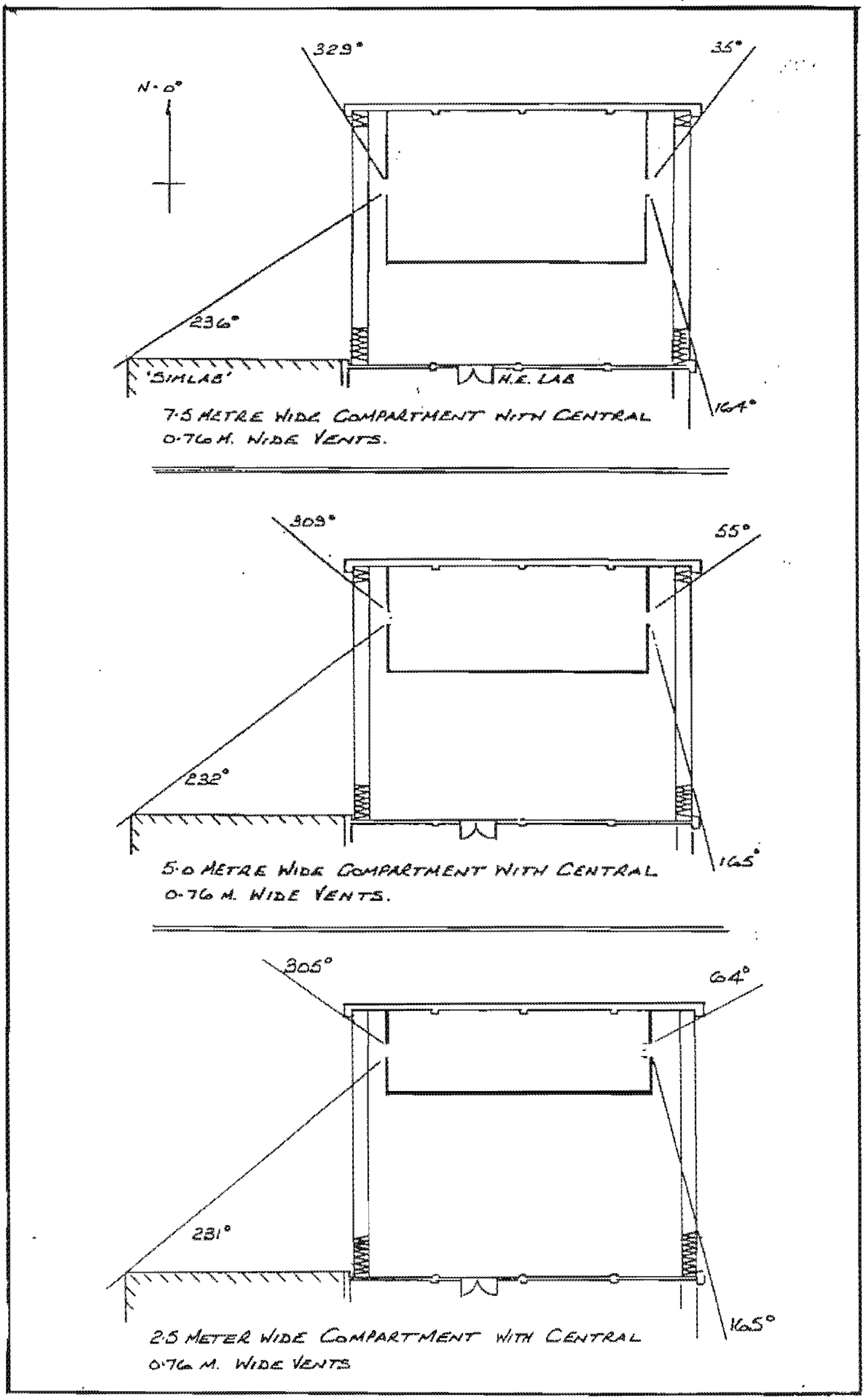


Figure 27. Plan views of the temporary compartments showing the angles open to the natural wind.

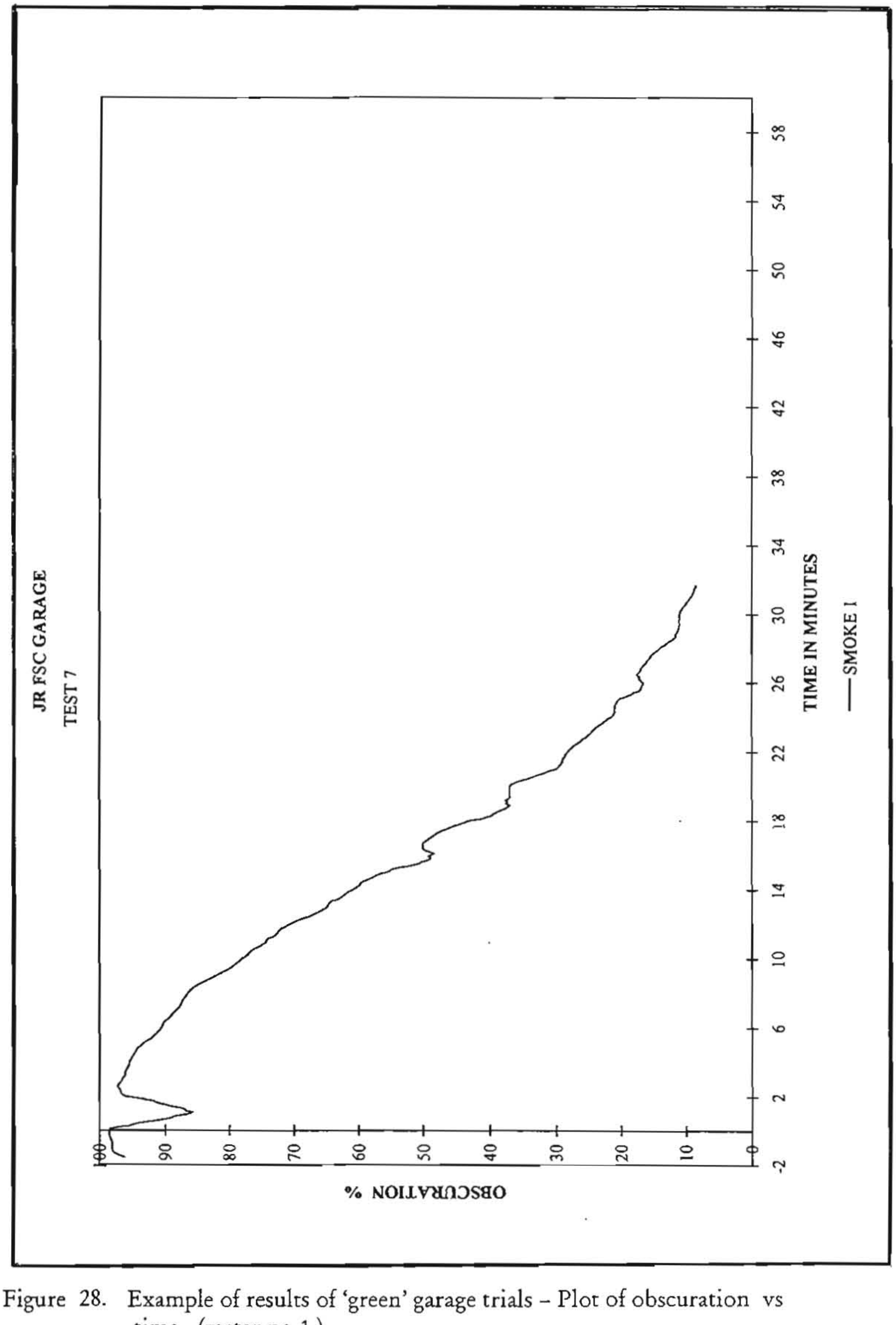


Figure 28. Example of results of 'green' garage trials – Plot of obscuration vs time (meter no.1.)

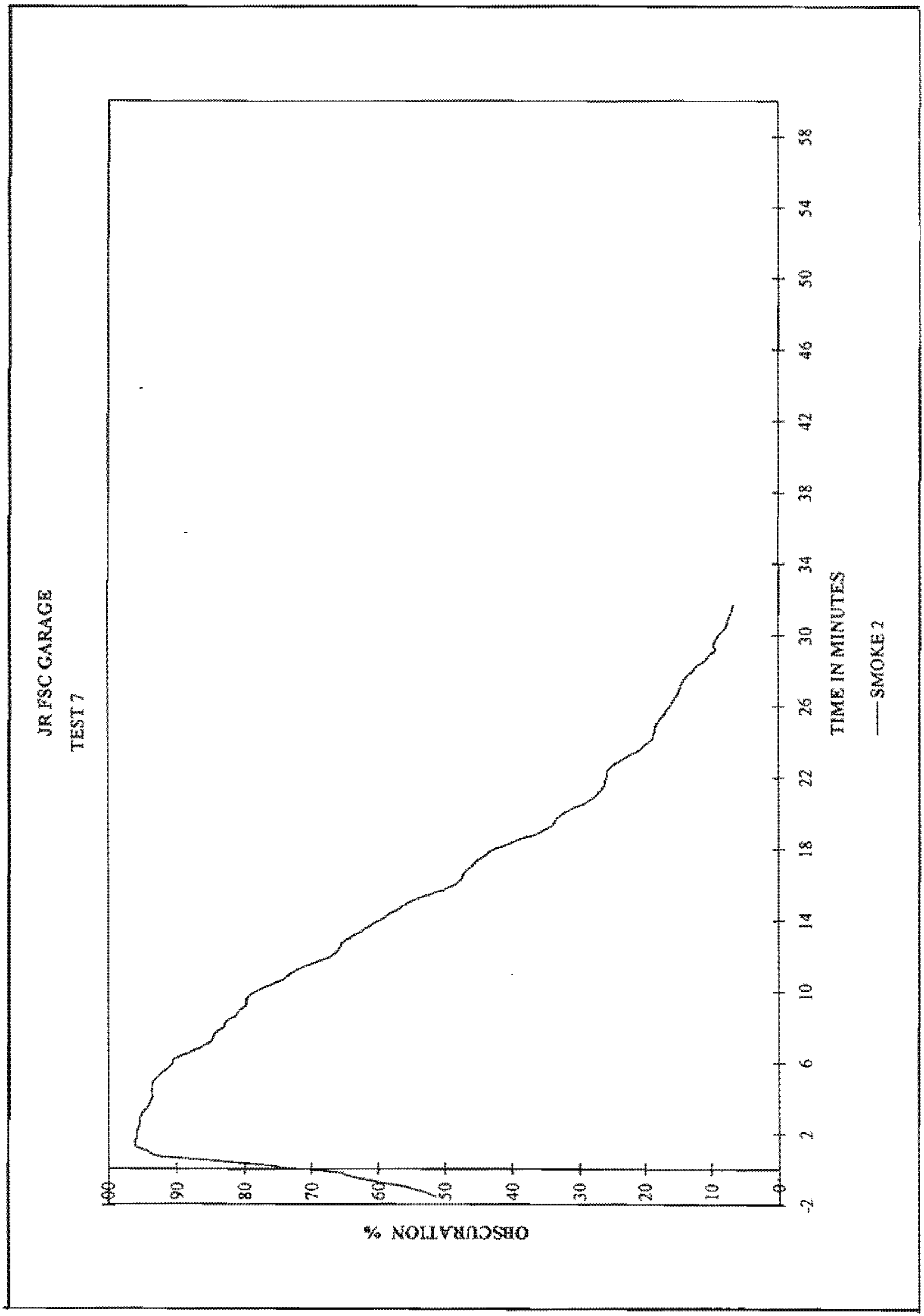


Figure 29. Example of results of 'green' garage trials – Plot of obscuration vs time (meter no.2.)

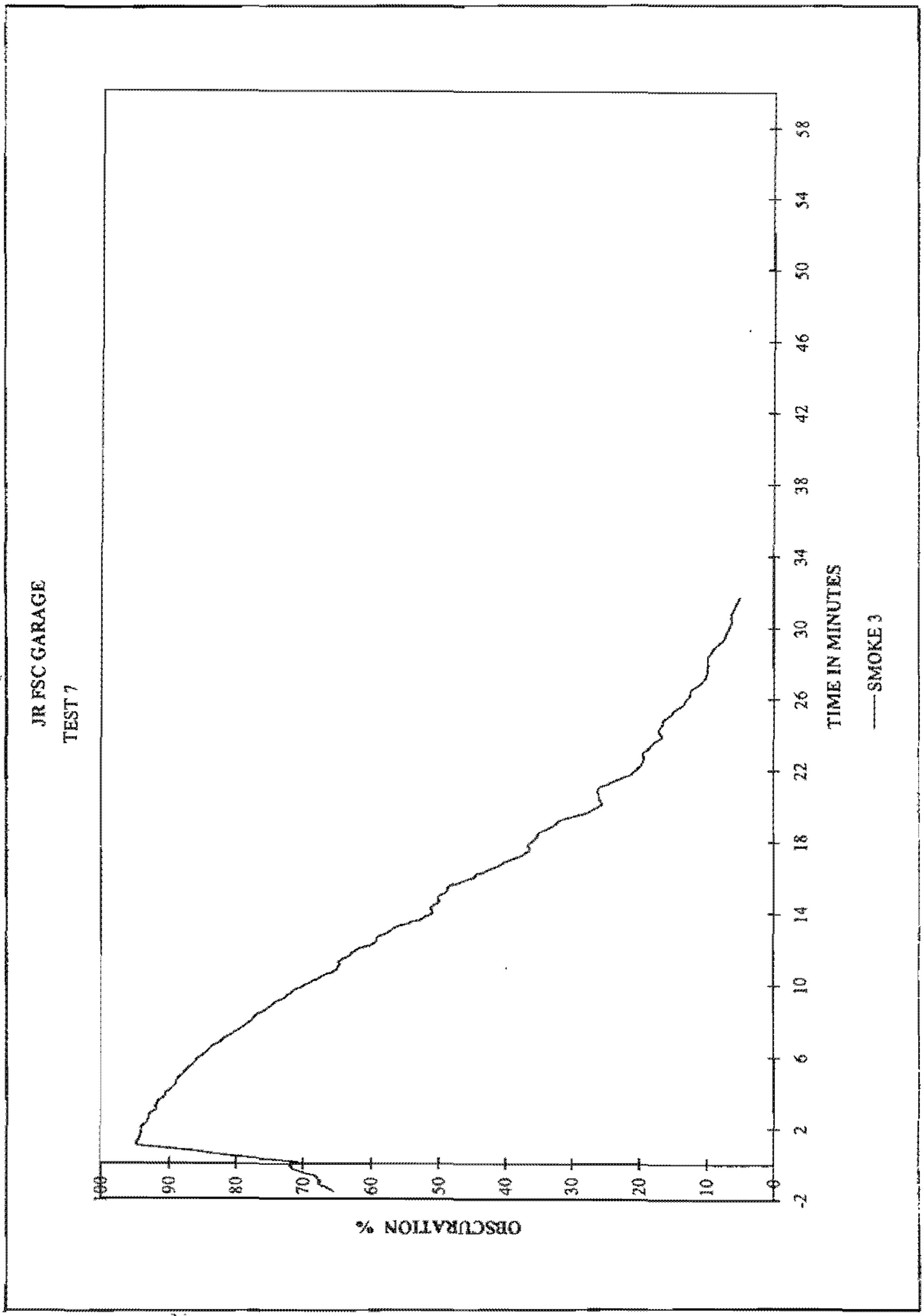


Figure 30. Example of results of 'green' garage trials - Plot of obscuration vs time (meter no.3.)

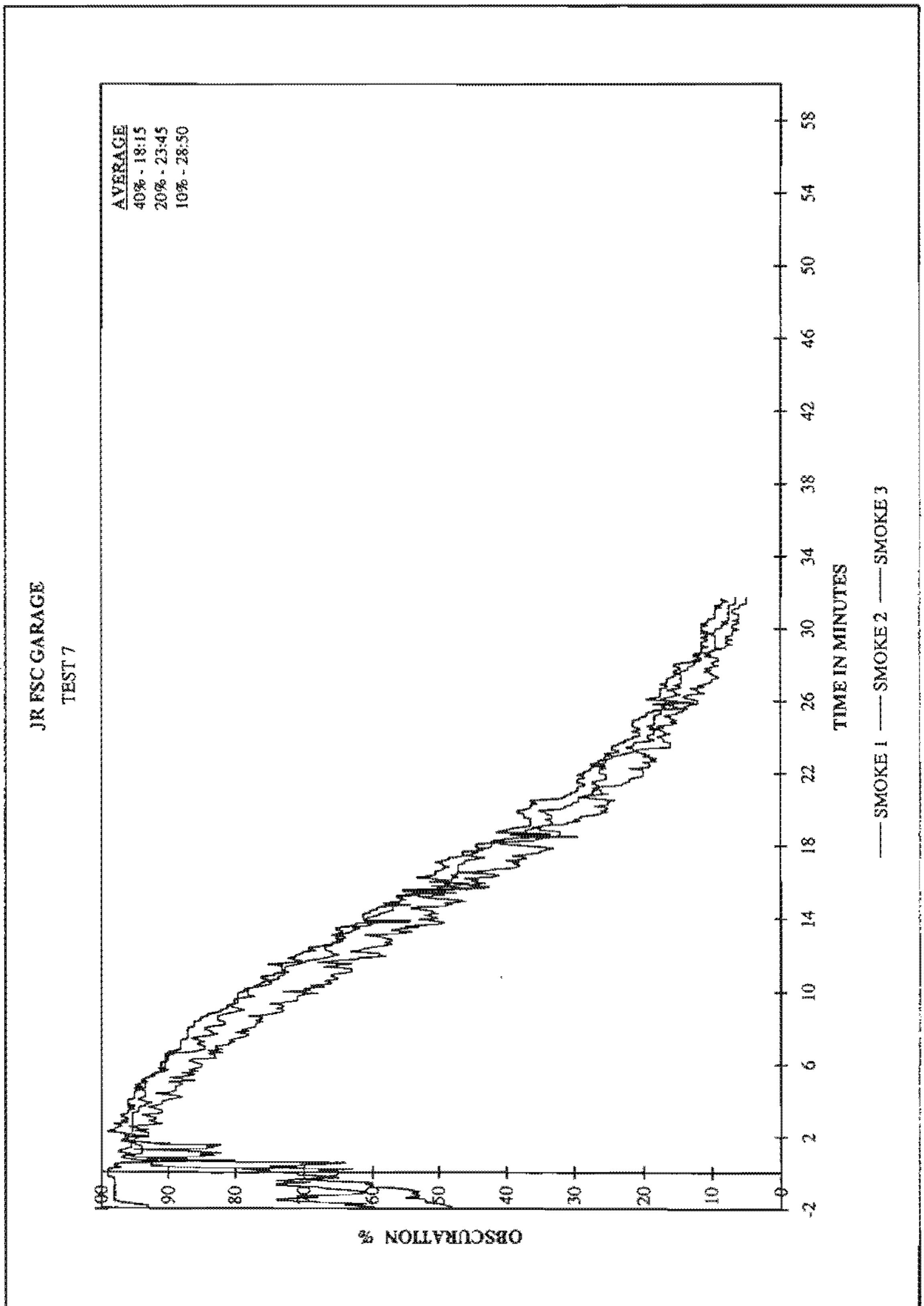


Figure 31. Example of results of 'green' garage trials – Un smoothed plot of obscuration Vs. time, for all three meters, with calculated average clearance times superimposed.

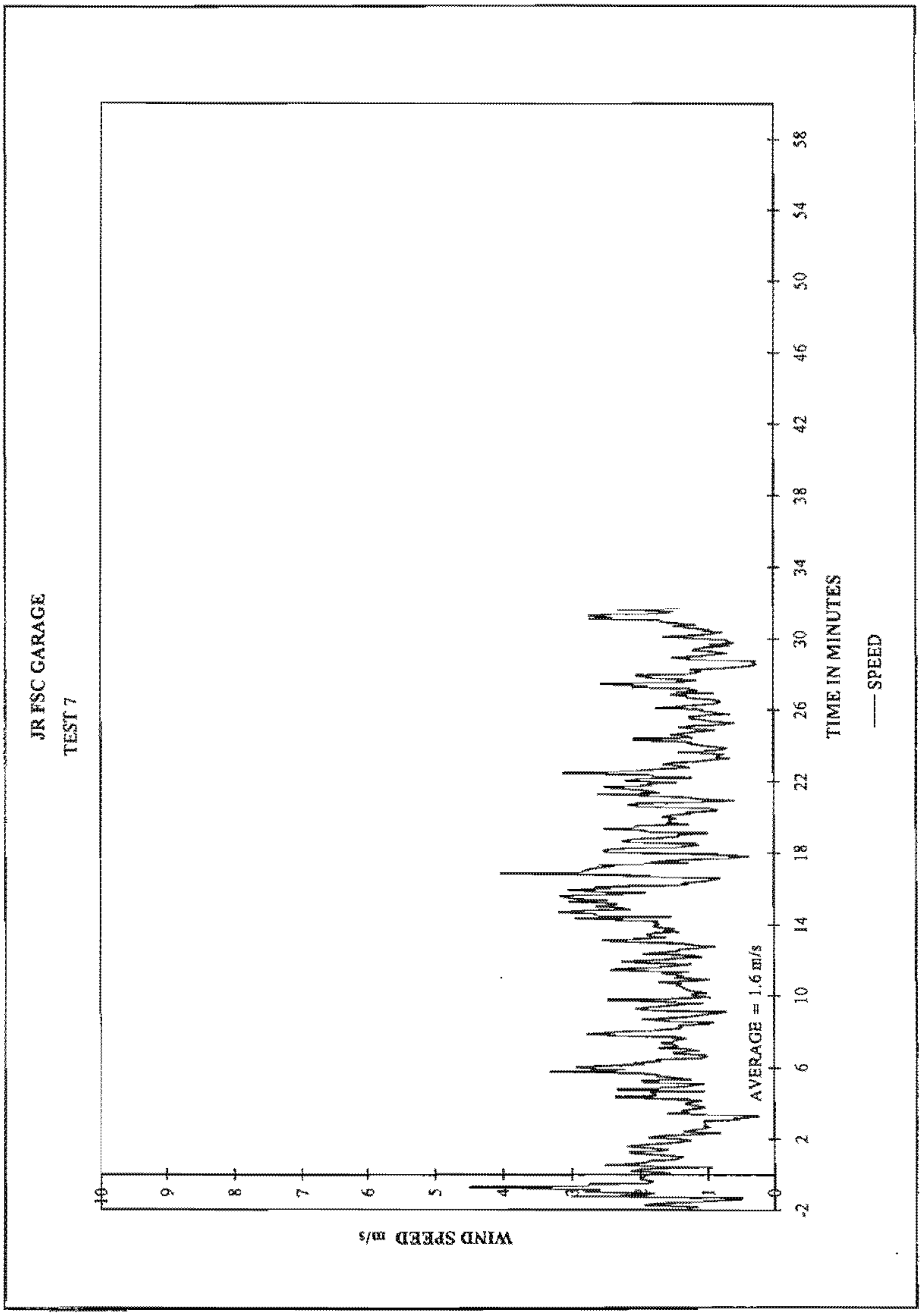


Figure 32. Example of results of 'green' garage trials – Natural wind speed Vs. time, with calculated average superimposed.

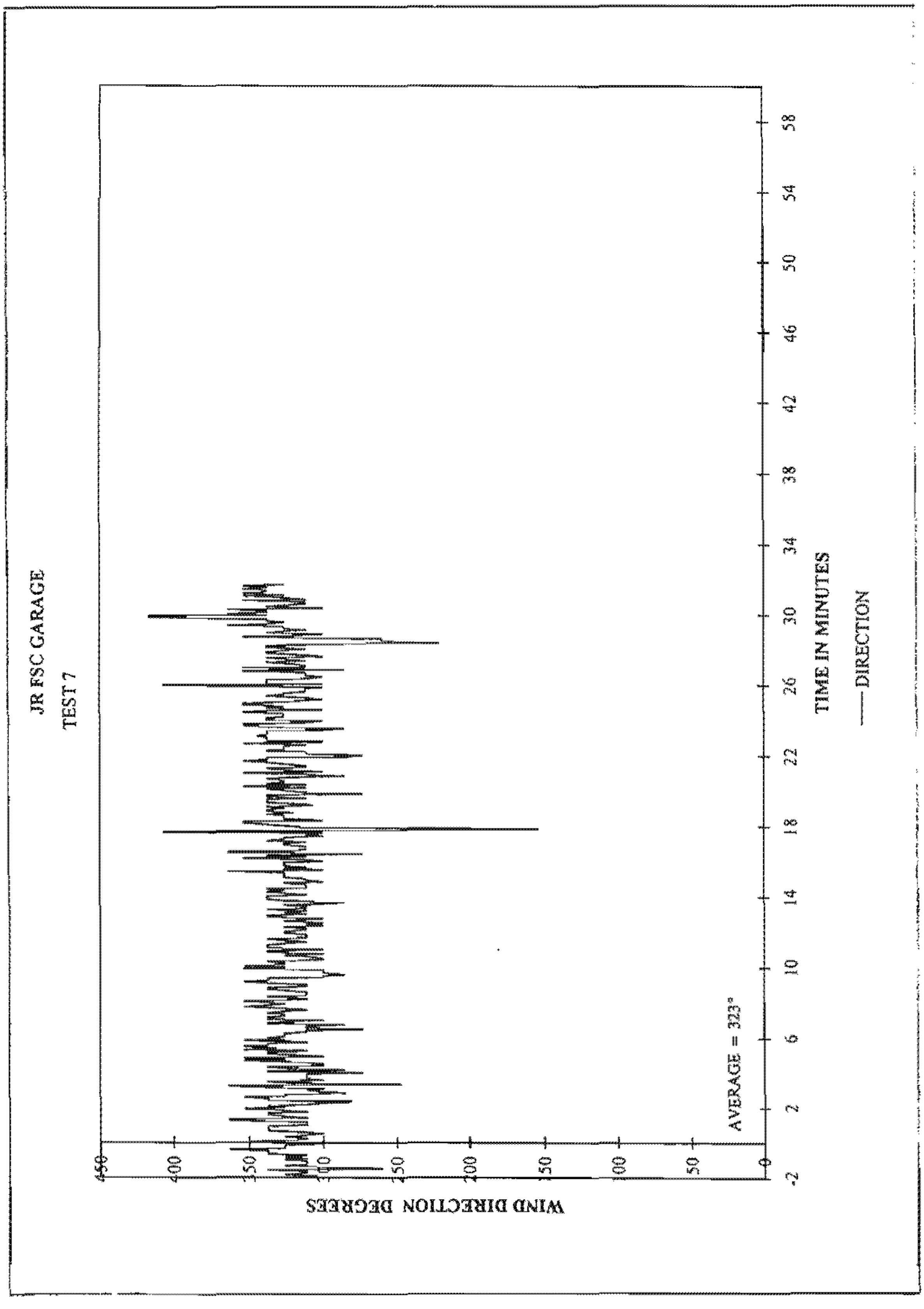


Figure 33. Example of results of 'green' garage trials – Natural wind direction Vs. time, with calculated average superimposed.

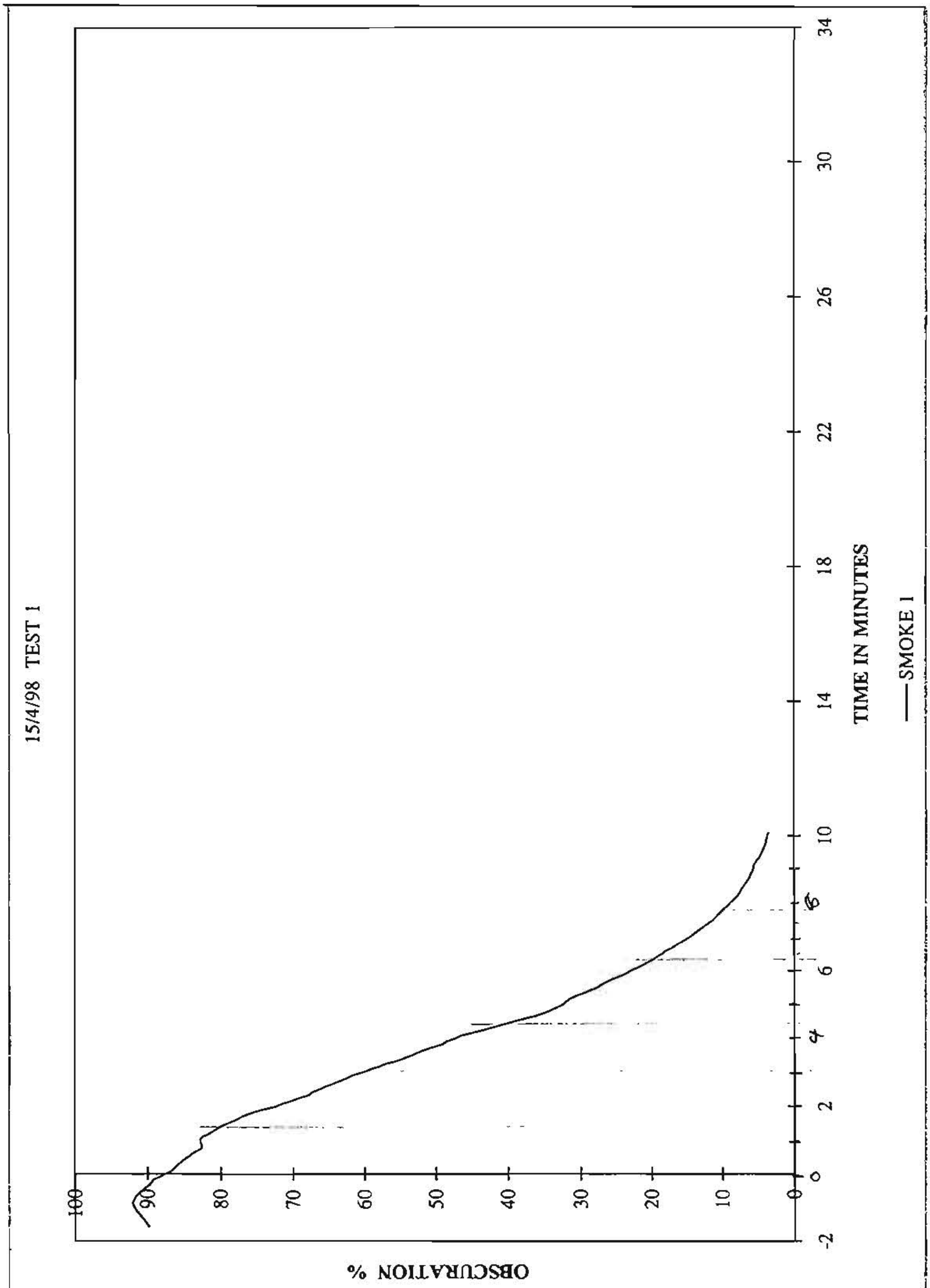


Figure 34. Example of FEU garage trials results – Plot of obscuration Vs. time, (meter No. 1).

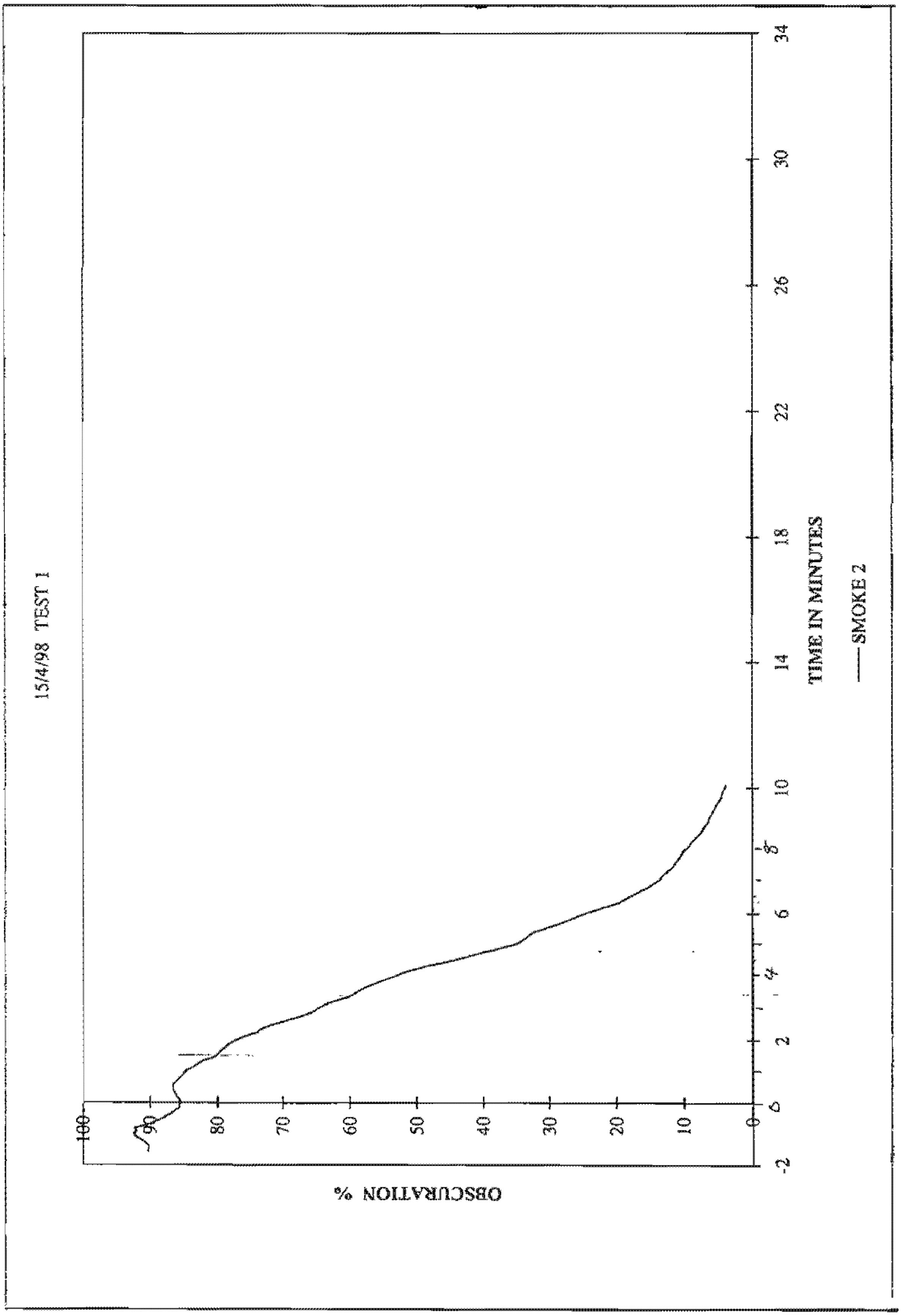


Figure 35. Example of FEU garage trials results – Plot of obscuration Vs. time, (meter No. 2).

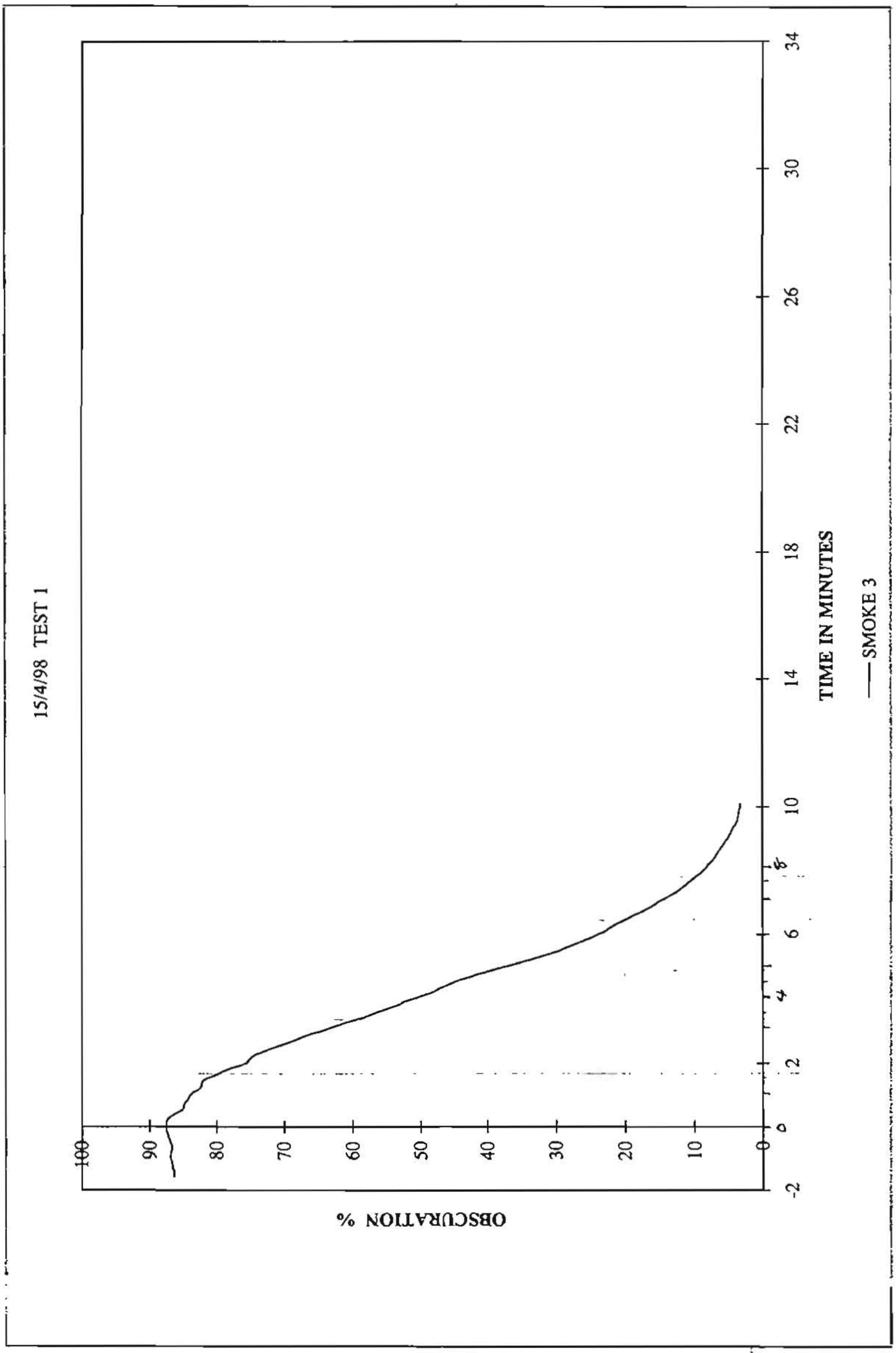


Figure 36. Example of FEU garage trials results - Plot of obscuration Vs. time (meter No.3).

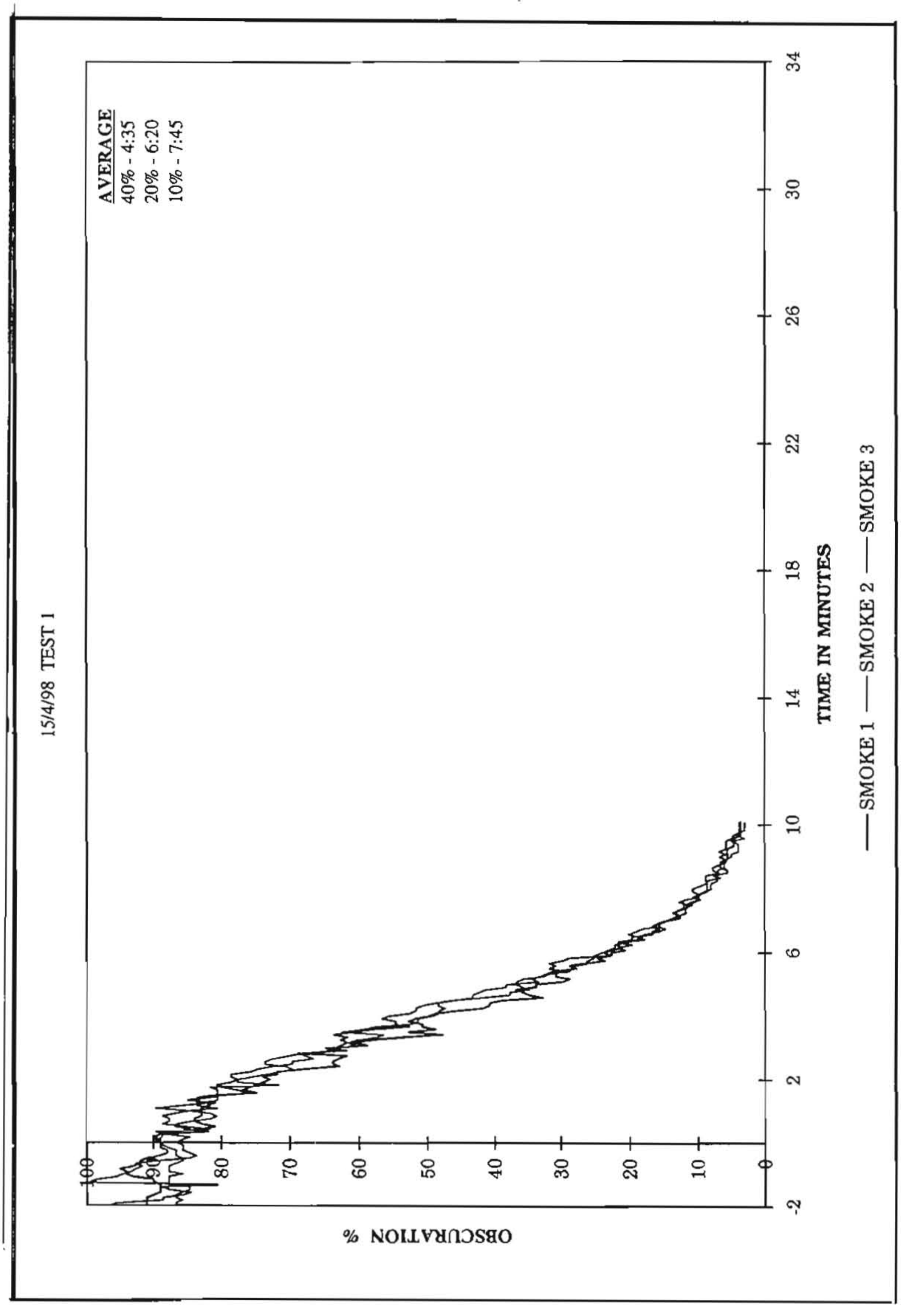


Figure 37. Example of FEU garage trials results – Un smoothed plots of obscuration Vs. time, for all three meters, with calculated average clearance times superimposed.

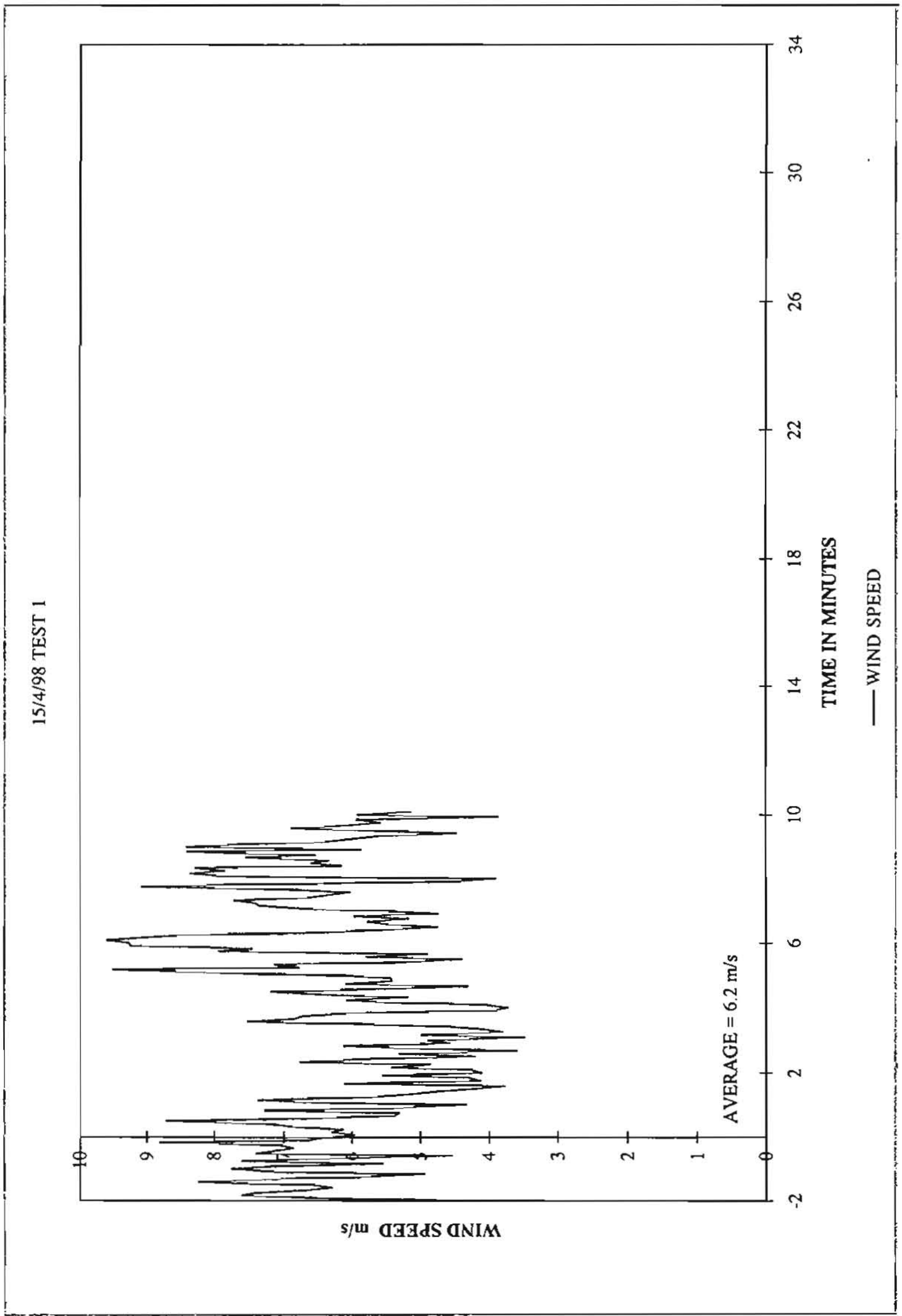


Figure 38. Example of FEU garage trials results - Plot of natural wind speed Vs. time, with calculated average superimposed.

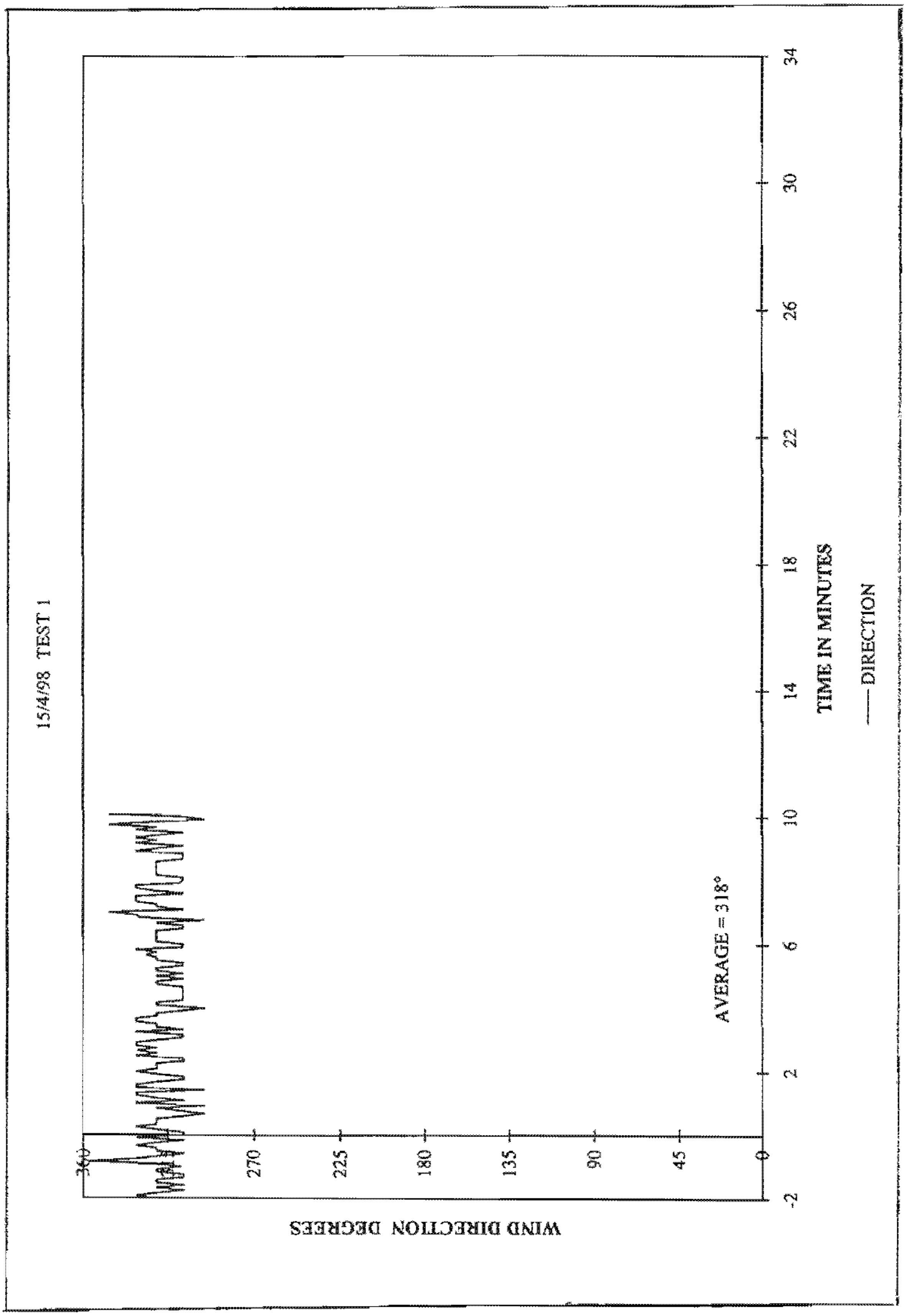


Figure 39. Example of FEU garage trials results – Plot of natural wind direction Vs. time, with calculated superimposed.

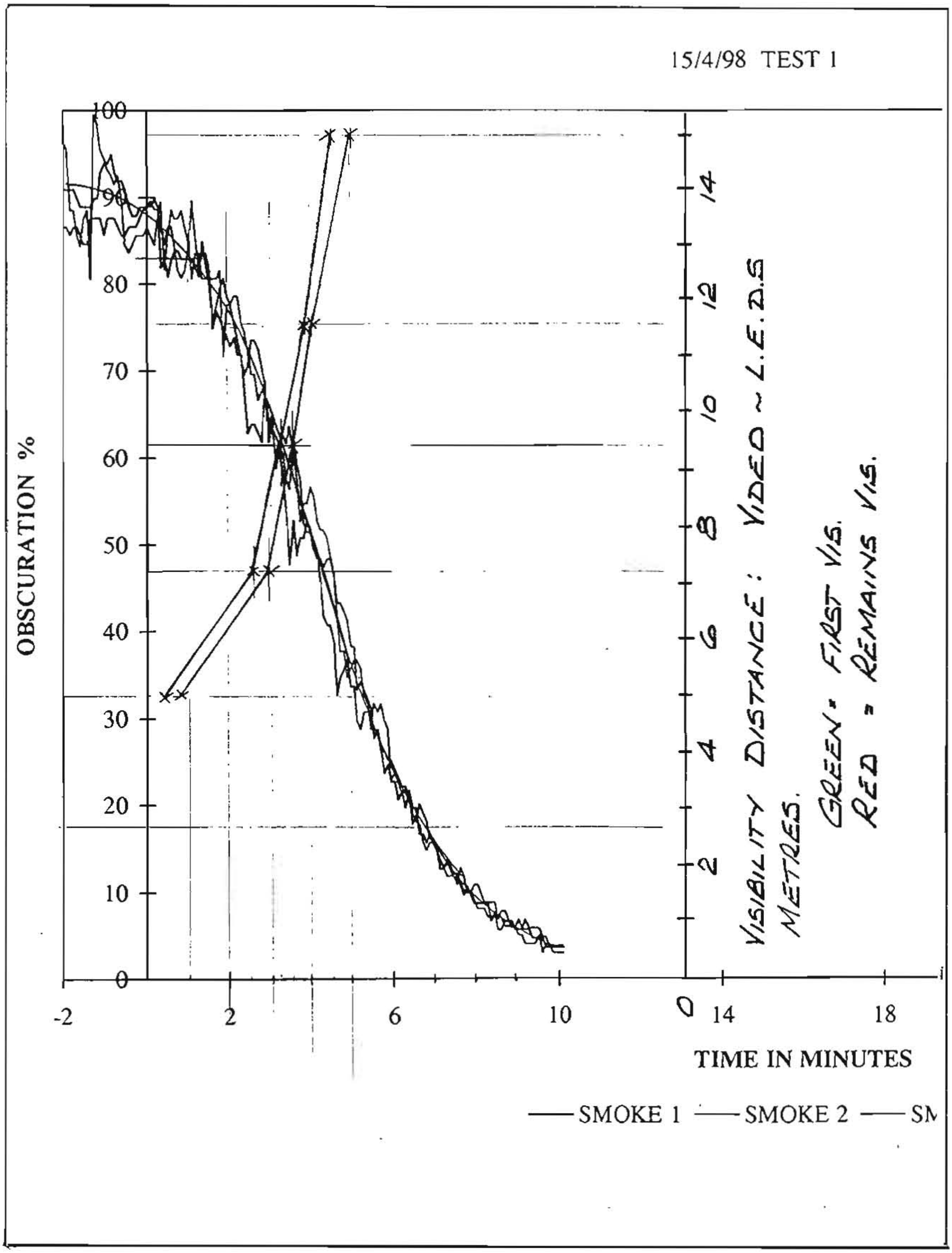


Figure 40. Example of F E U garage trials results – Plot of 'visibility distance' vs time (superimposed upon overall obscuration vs time graph).

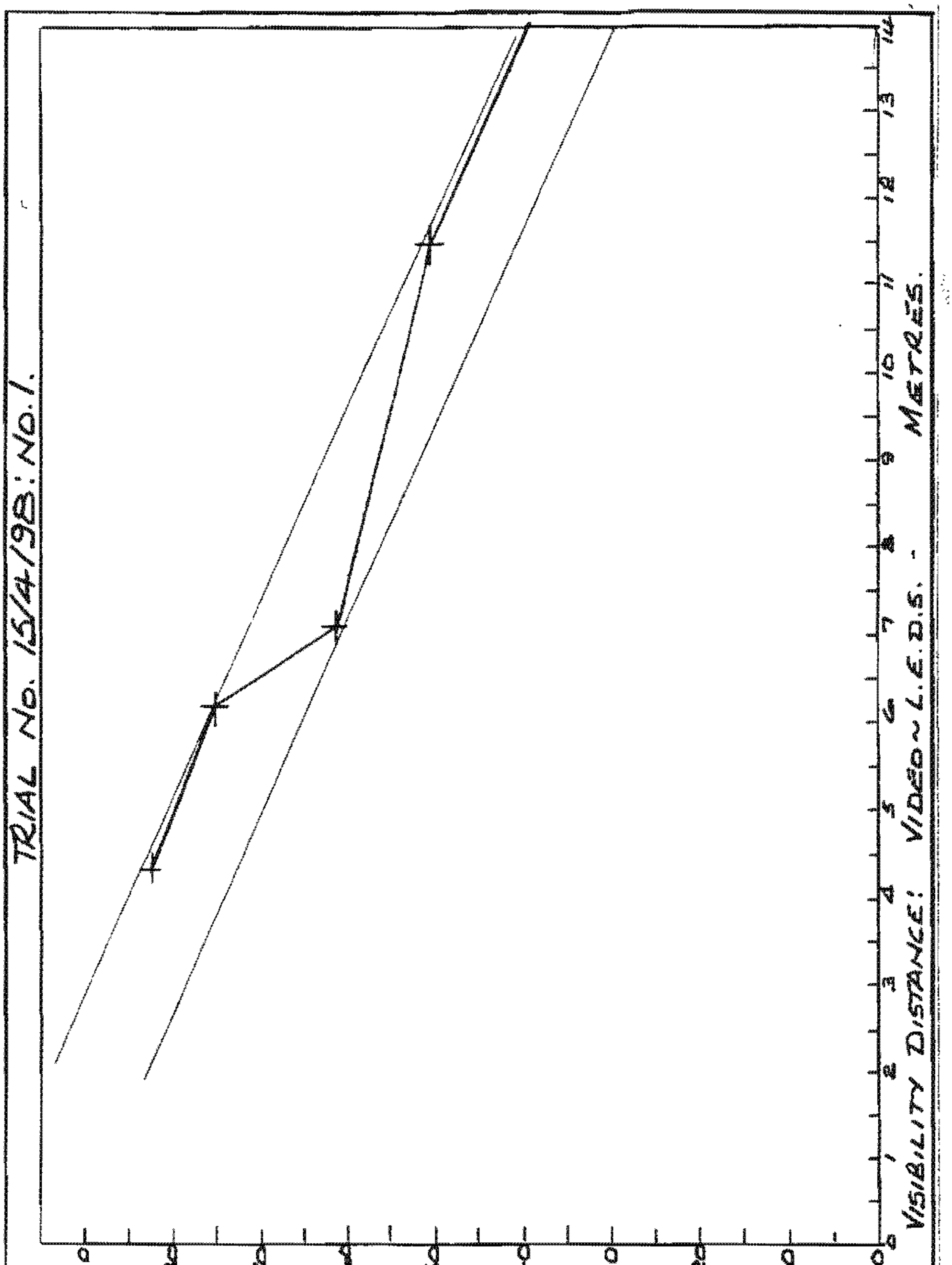


Figure 41. Example of FEU garage trials results – Plot of average obscuration Vs. 'visibility distance' (at the same time).

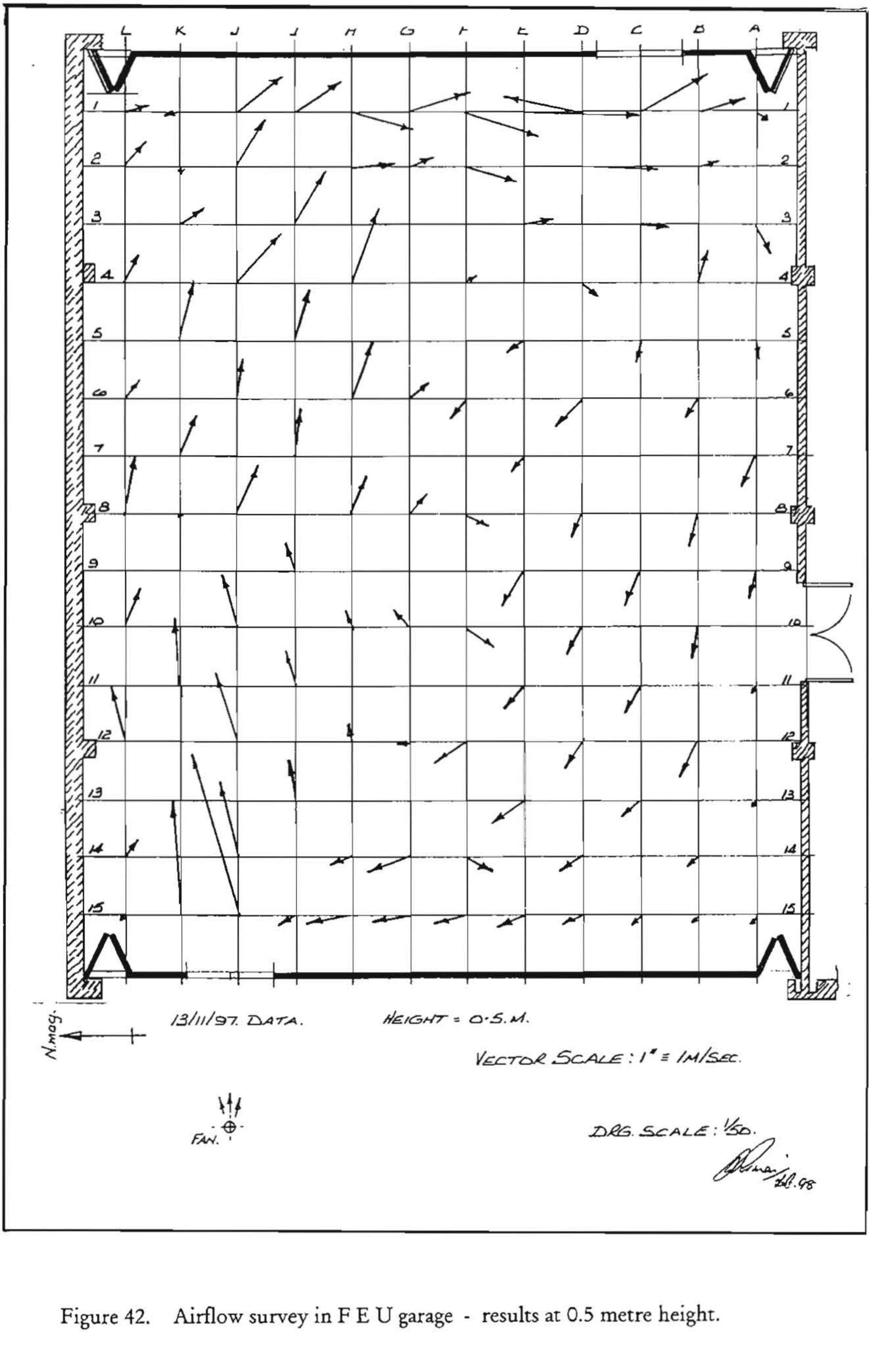


Figure 42. Airflow survey in F E U garage - results at 0.5 metre height.

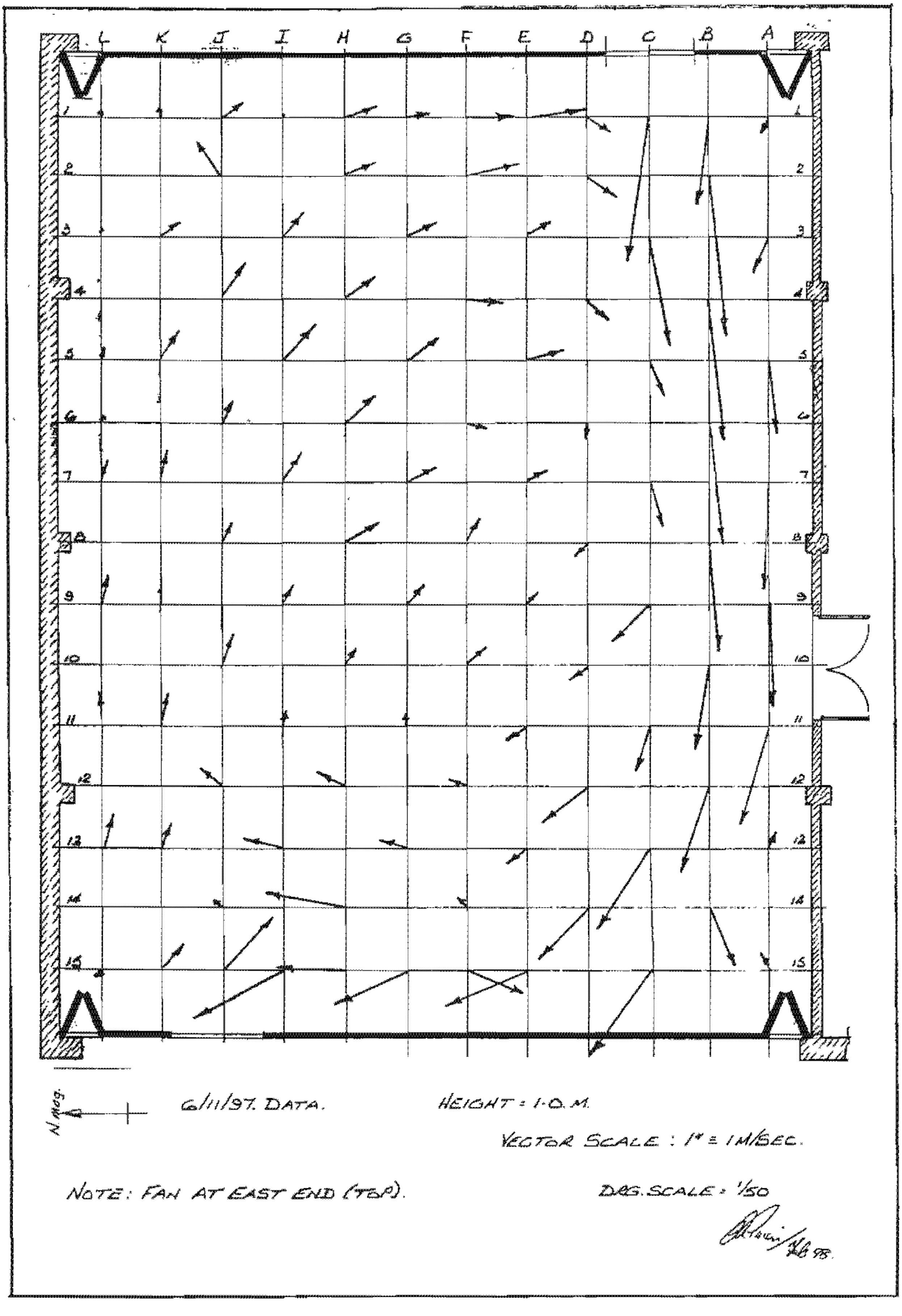


Figure 43. Airflow survey in F E U garage - result at 1.0 metre height.

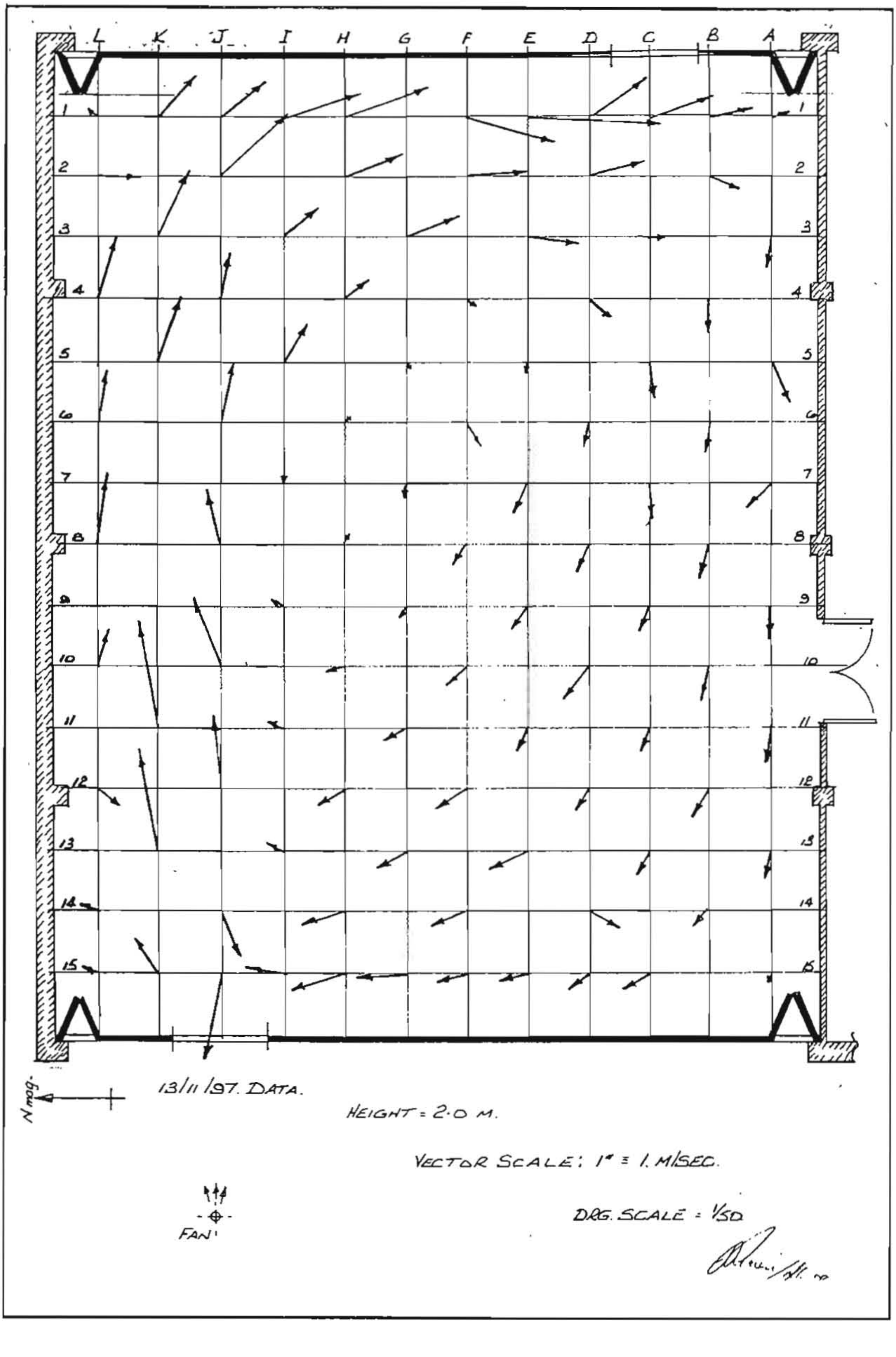


Figure 44 Airflow survey in F E U garage - result at 2.0 metres height.

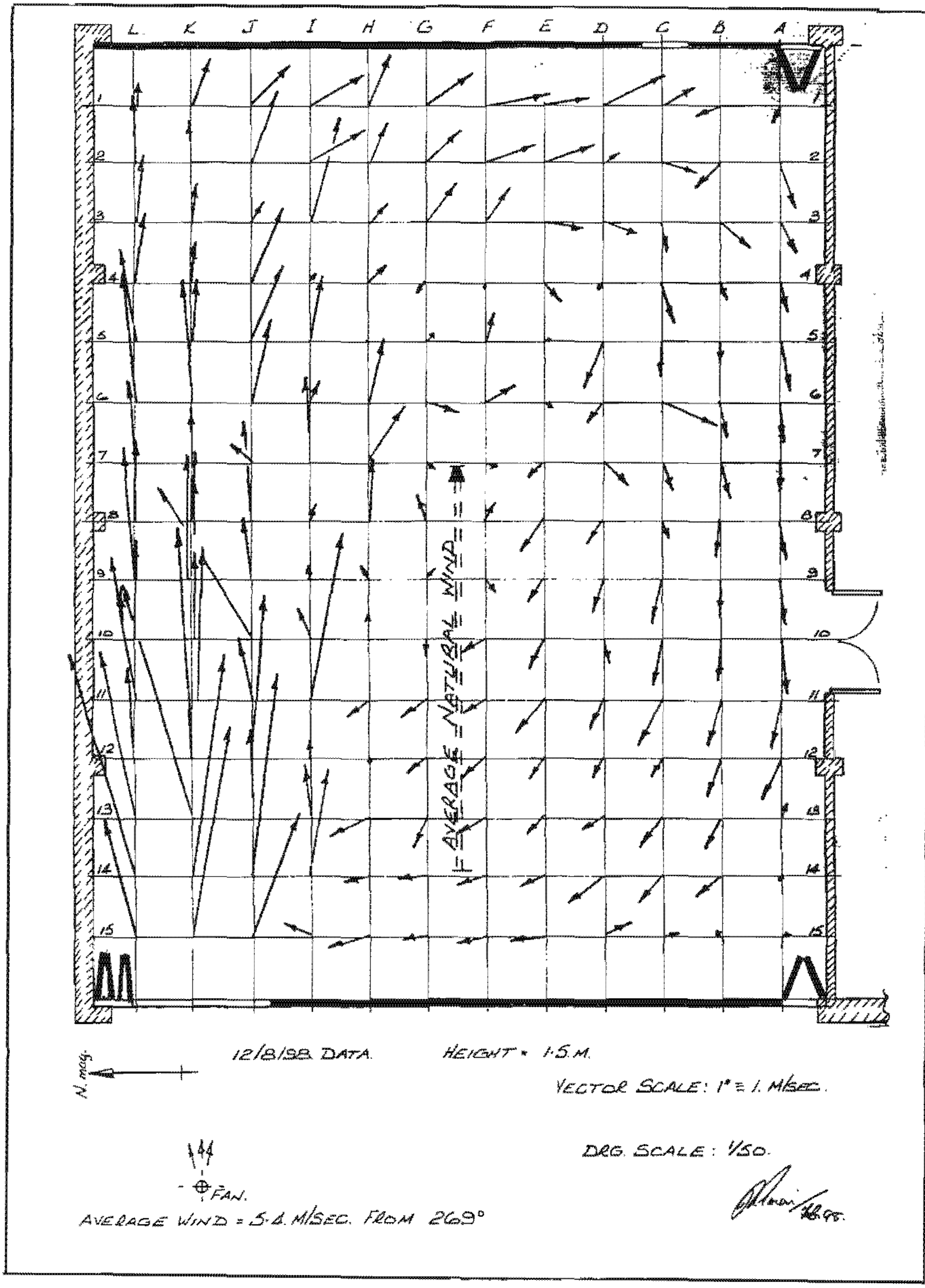
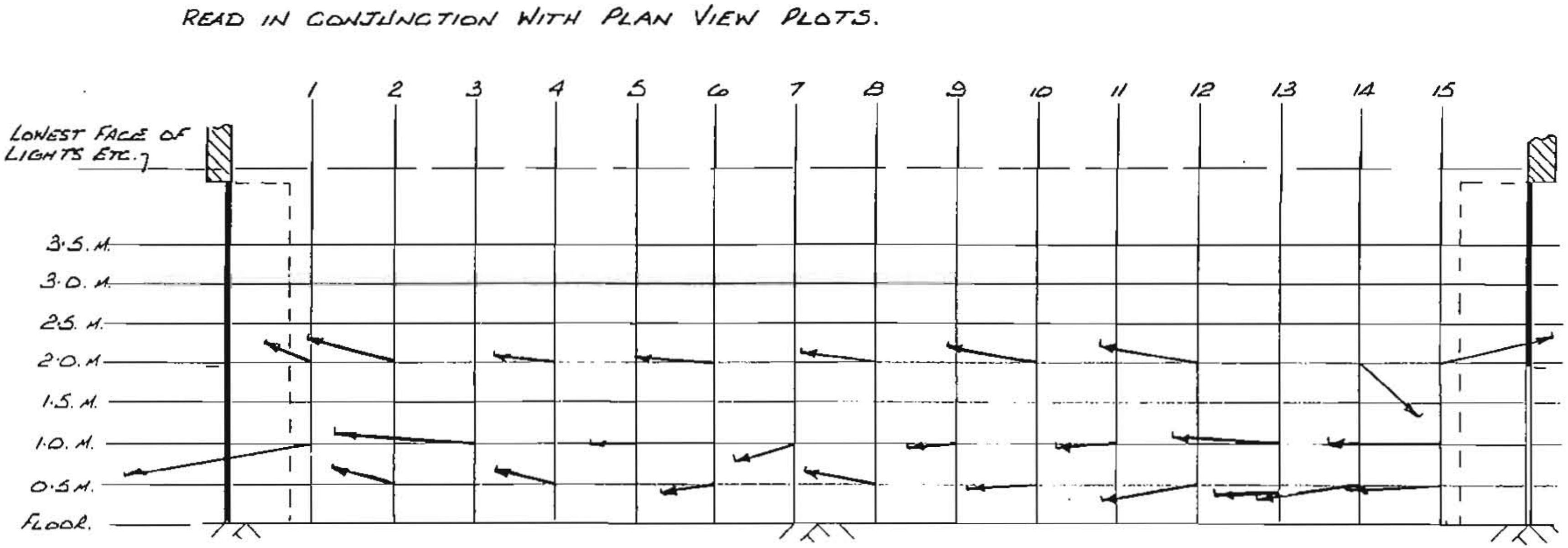


Figure 45. Airflow survey in F E U garage with 8'-0" wide inlet vent and 2' 6" wide outlet vent positioned diagonally - result at 1.5 metres height.



VERTICAL CROSS-SECTION THRO. FEU GARAGE ON ℄ OF INLET VENT, LINE 'C' & 'J' (SEE BELOW) *

VIEWED FROM NORTH:

INLET AND OUTLET POSITIONS, FAN ETC. AS STATED ON 6/11/97 & 13/11/97 DATA.

VECTOR SCALE: 1 INCH ≡ 1·0 METRE/SEC

DRG SCALE: 1/50.

* THE 6/11/97 DATA WAS TAKEN WITH THE FAN IN THE S.W. CORNER DOORWAY. THE 13/11/97 DATA WAS TAKEN WITH THE FAN IN THE N.E. CORNER DOORWAY (WIND HAD REVERSED). SINCE THE INSIDE OF THE BUILDING IS SYMMETRICAL, AND OUR GRID SYMMETRICAL WITHIN IT, WE ROTATED THE FINAL VECTOR PLOT OF 6/11/97 TO SUPERIMPOSE IT UPON THE 13/11/97 PLOTS.
∴ THIS PLOT IS OK: CONSIDER IT AS A STRAIGHTFORWARD 'LINE J' SECTION.

Figure 46. Example of an airflow survey chart - longitudinal vertical cross section on centre of inlet vent.

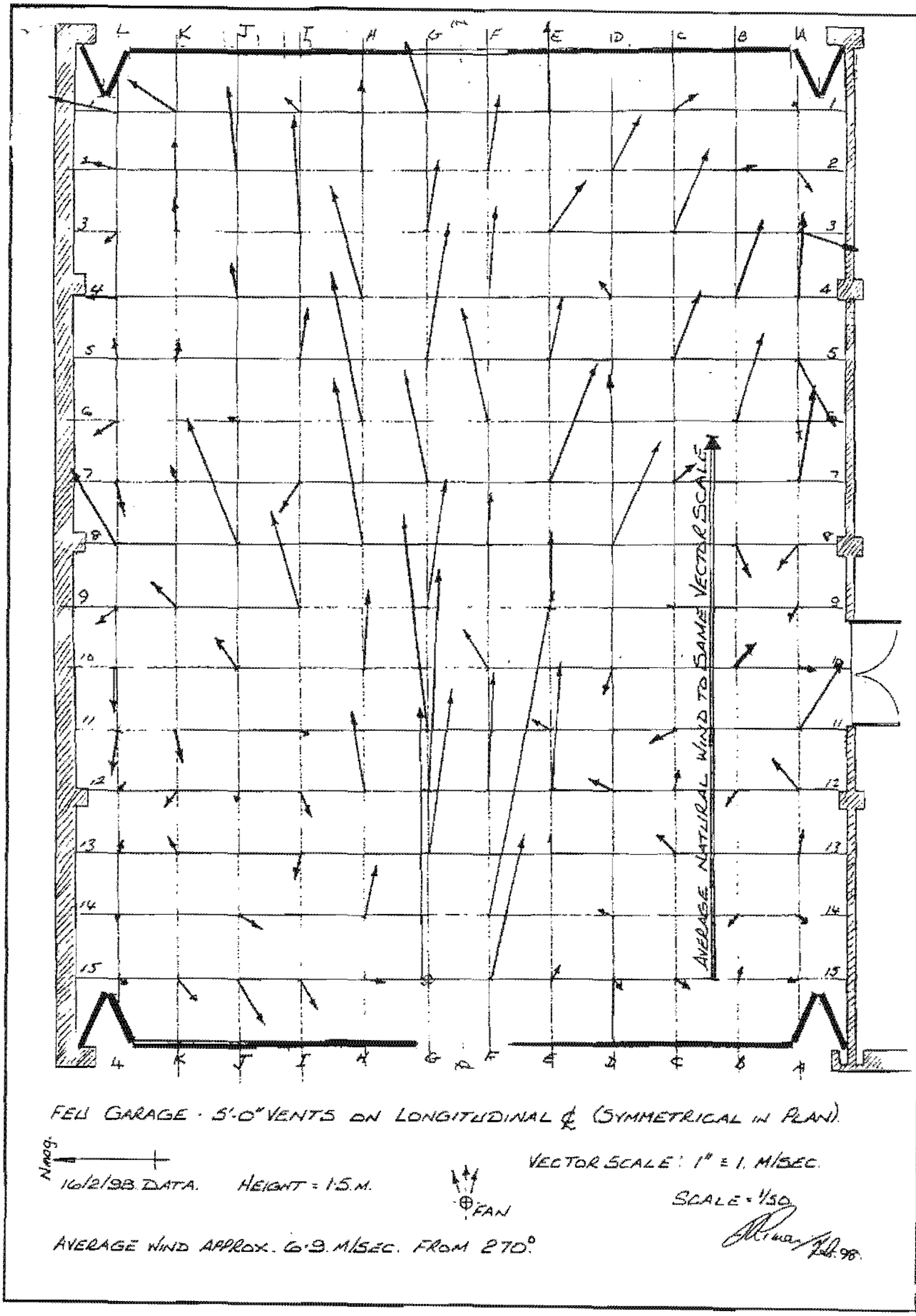


Figure 47. Airflow survey in F E U garage at 1.5 metre height – vents on centreline – average natural wind vector superimposed (virtually directly into vent).

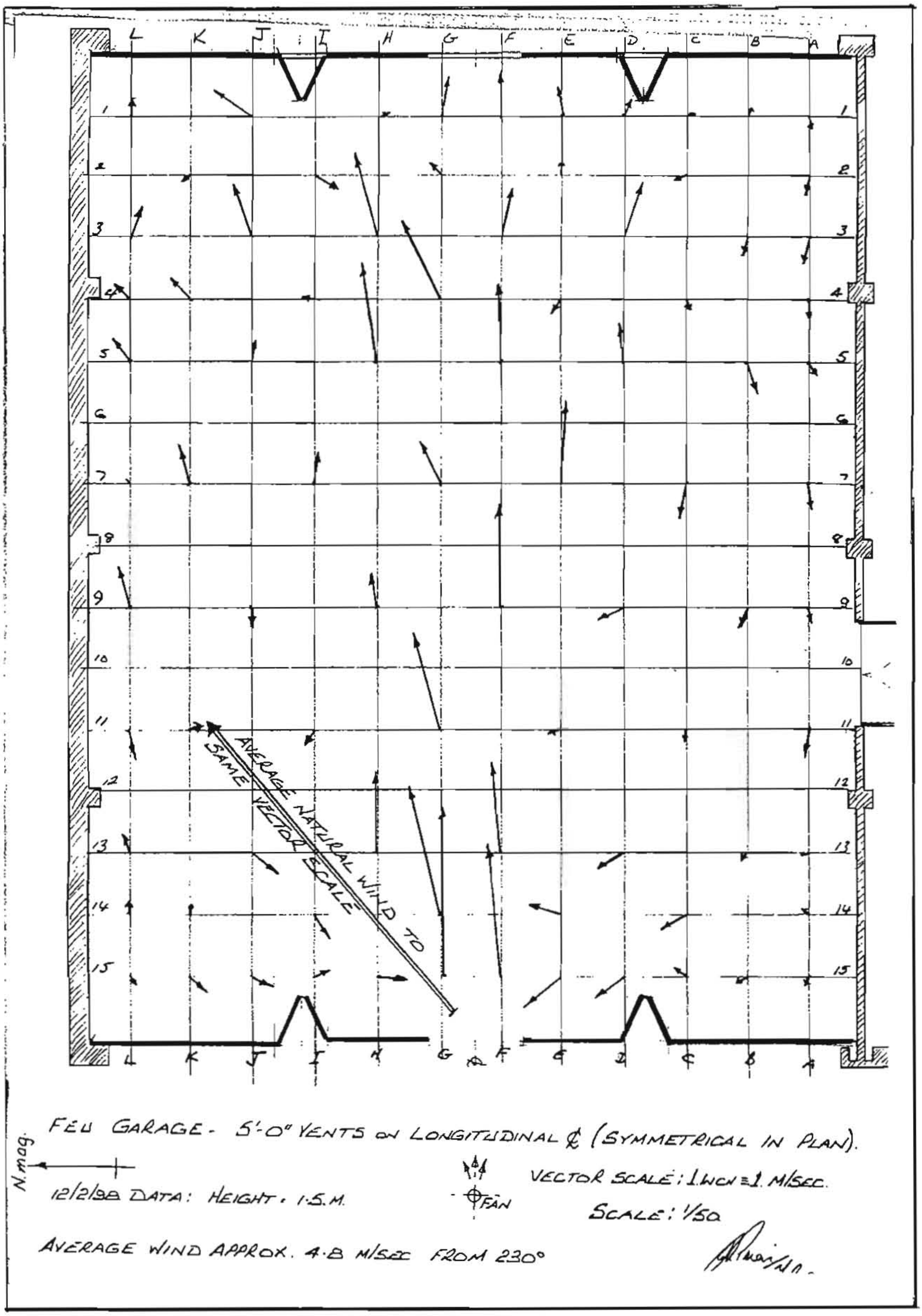


Figure 48. Airflow survey in F E U garage at 1.5 metres height - vents on centreline – average natural wind vector superimposed (roughly 45° to vent).

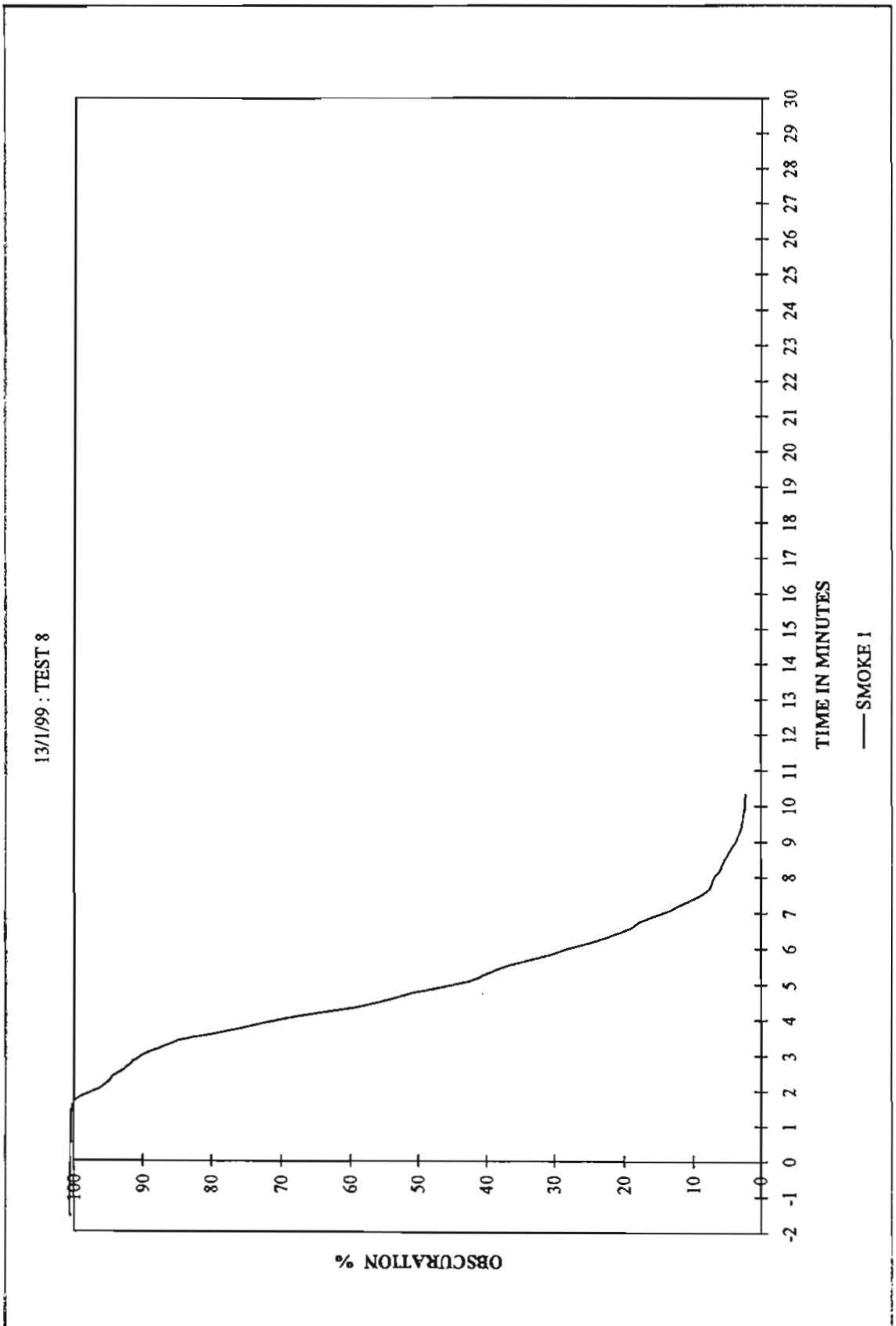


Figure 49. Example of temporary compartment (7.5 metres wide) trials results - Plot of obscuration Vs. time (meter No.1).

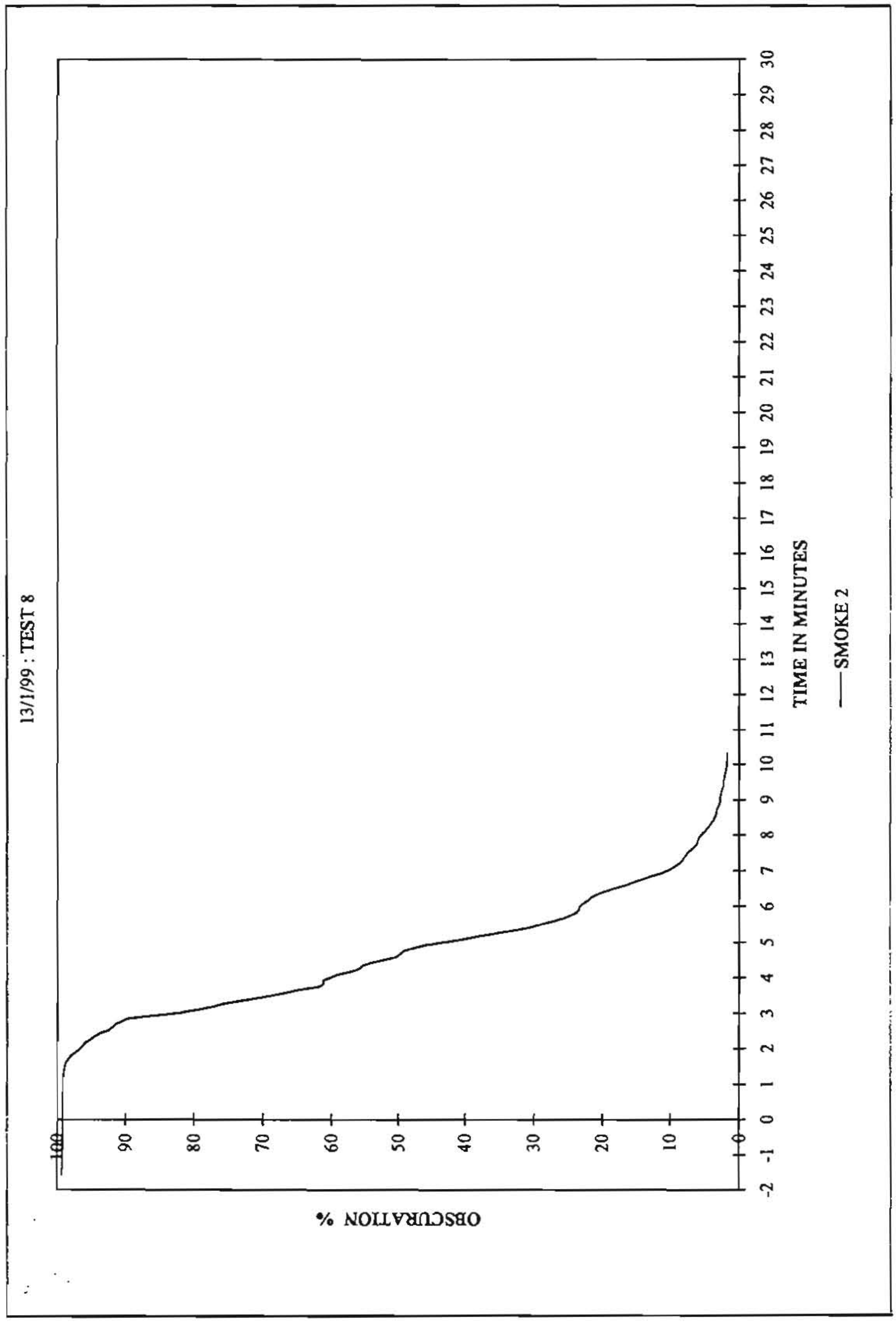


Figure 50. Example of temporary compartment (7.5 metres wide) trials results – Plot of obscuration Vs. time (meter No.2).

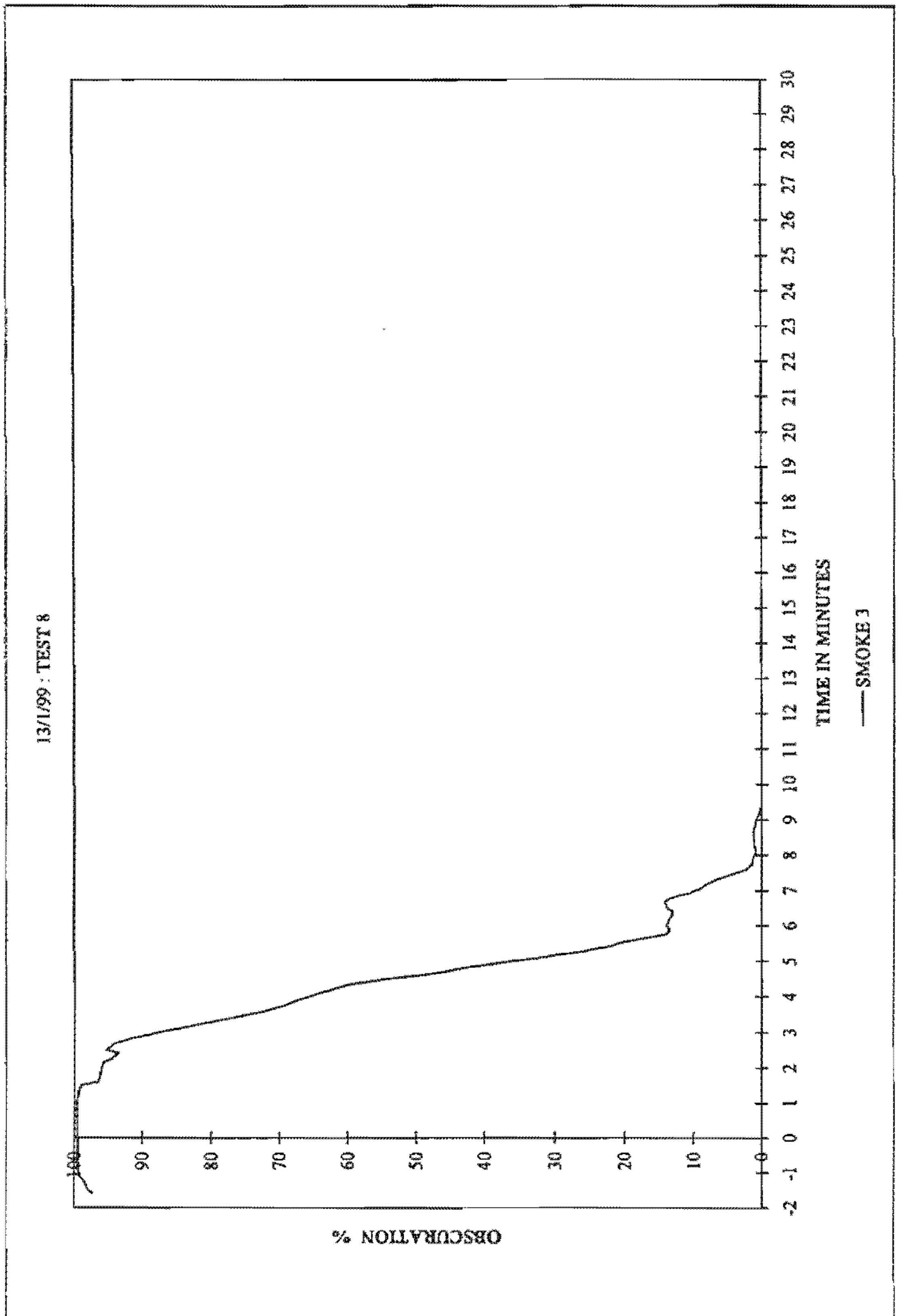


Figure 51. Example of temporary compartment (7.5 metres wide) trials results – Plot of obscuration Vs. time (meter No.3).

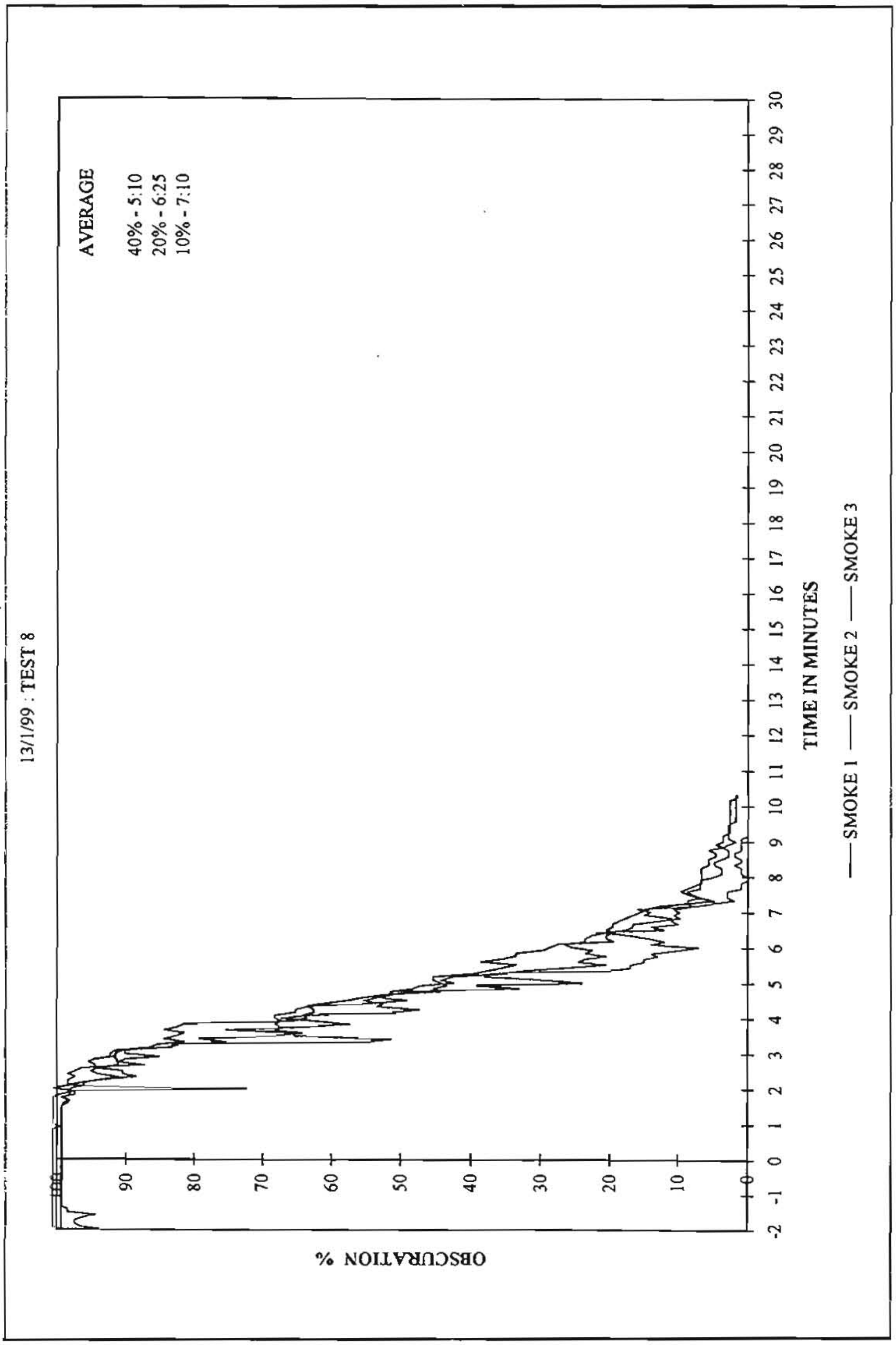


Figure 52. Example of temporary compartment (7.5 metres wide) trials results – Un smoothed plots of obscuration Vs. time, for all three meters, with calculated average clearance times superimposed.

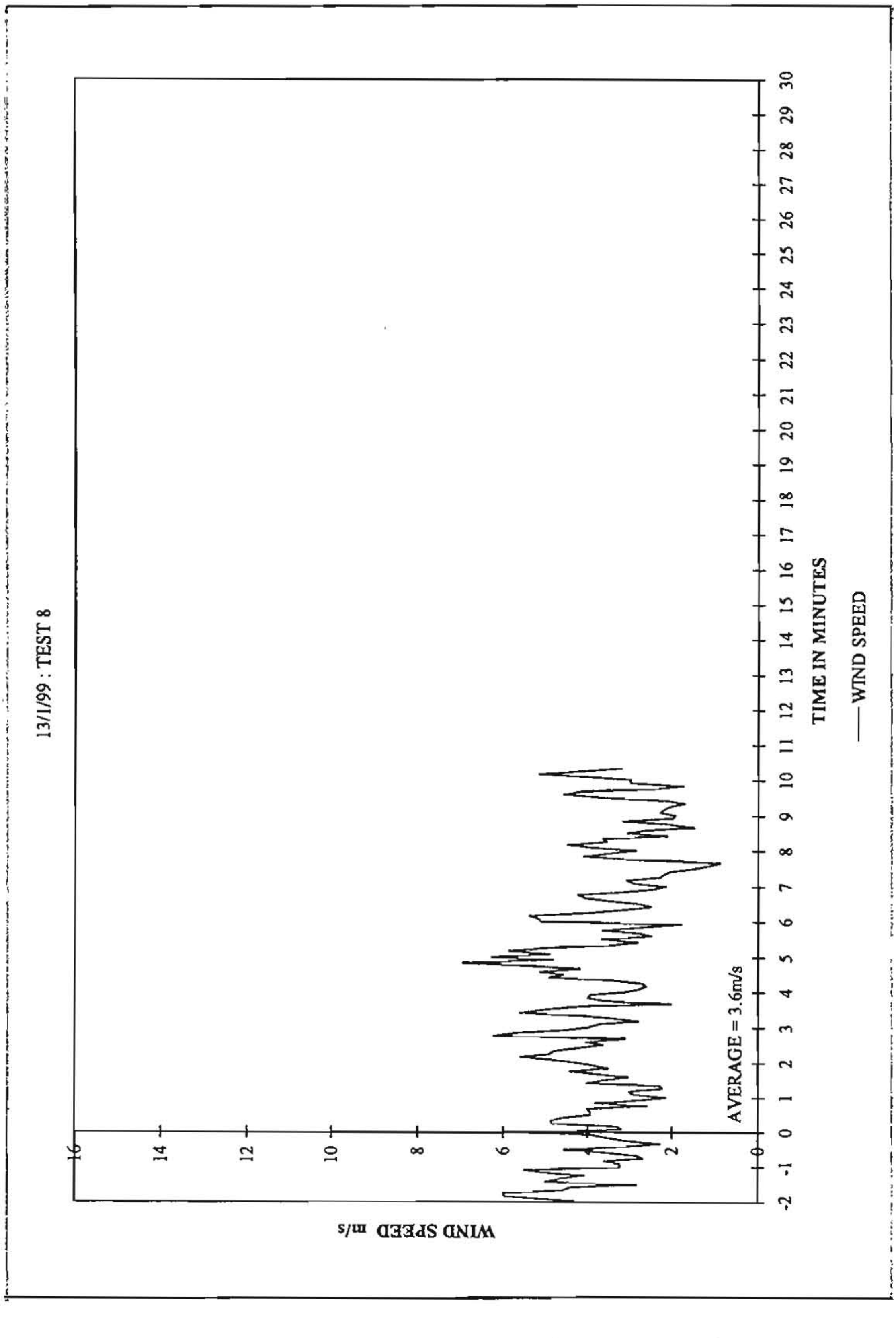


Figure 53. Example of temporary compartment (7.5 metres wide) trials results – Plot of natural wind speed Vs. time, with calculated average superimposed.

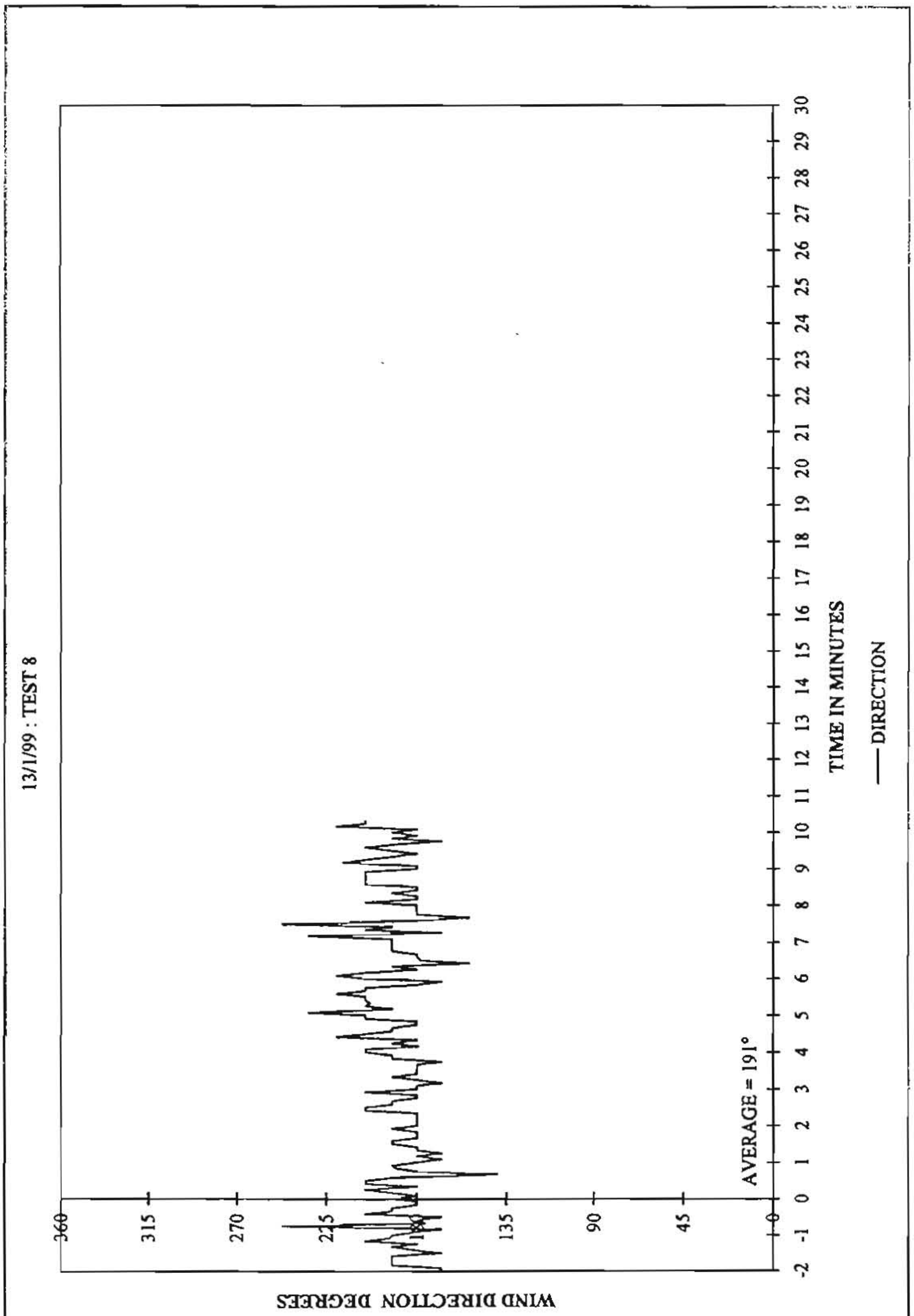


Figure 54. Example of temporary compartment (7.5 metres wide) trials results – Plot of natural wind direction Vs. time, with calculated average superimposed.

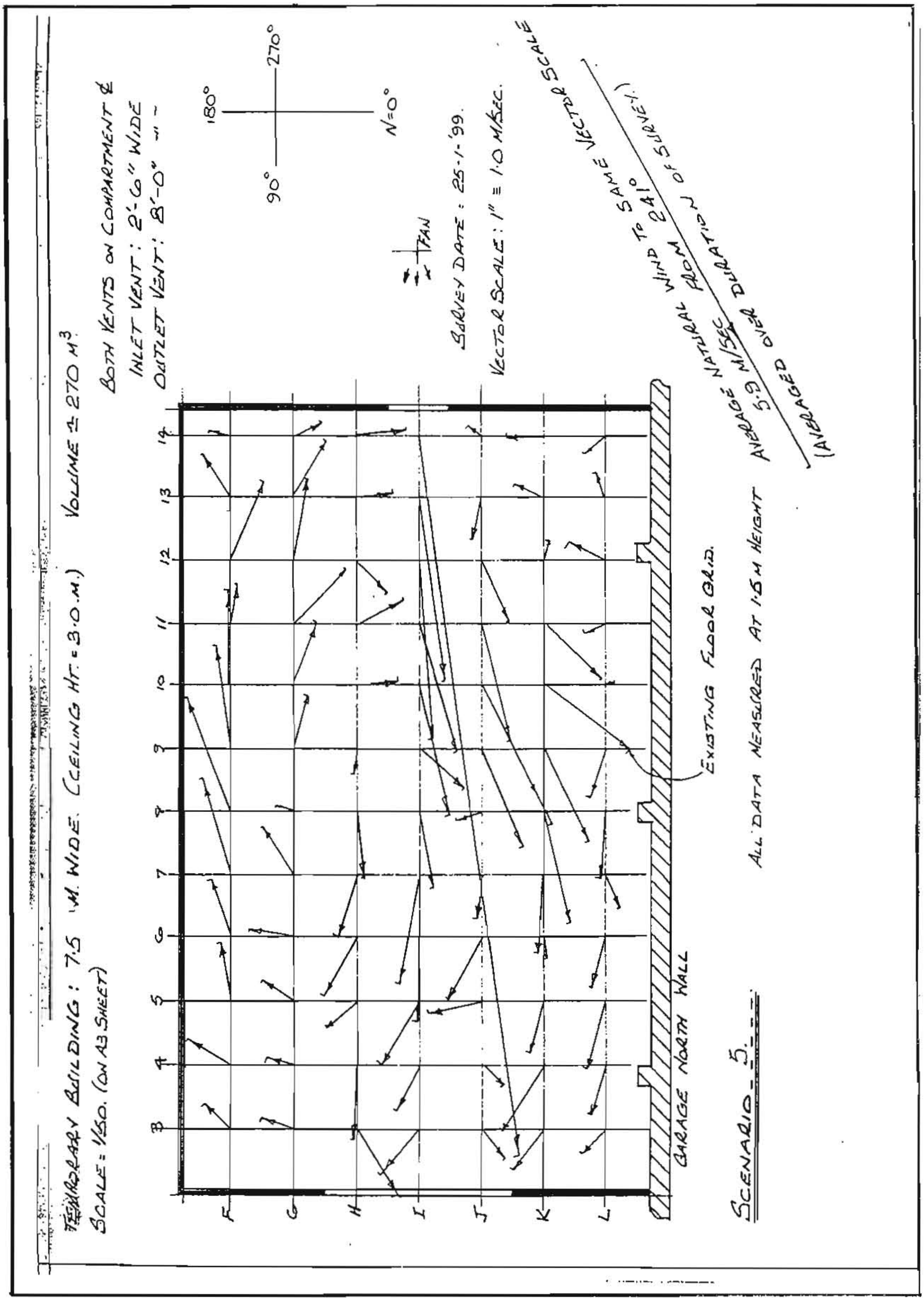


Figure 55. Airflow survey in 7.5 metre wide compartment: 2' 6"inlet - 8' 0" outlet, with P P V.

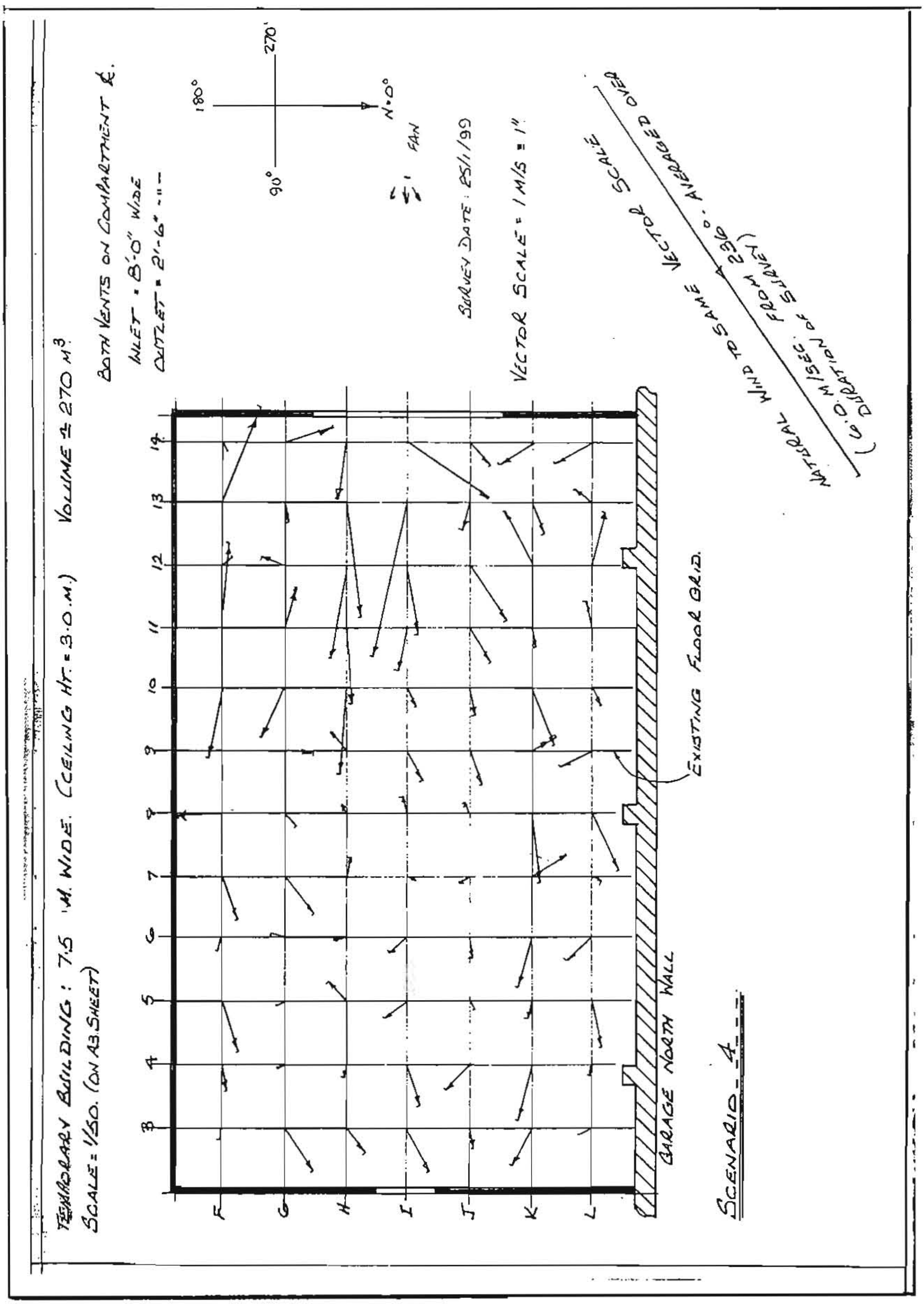


Figure 56. Airflow survey in 7.5 metre wide compattment: 8' 0" inlet – 2' 6" outlet, with P P V.

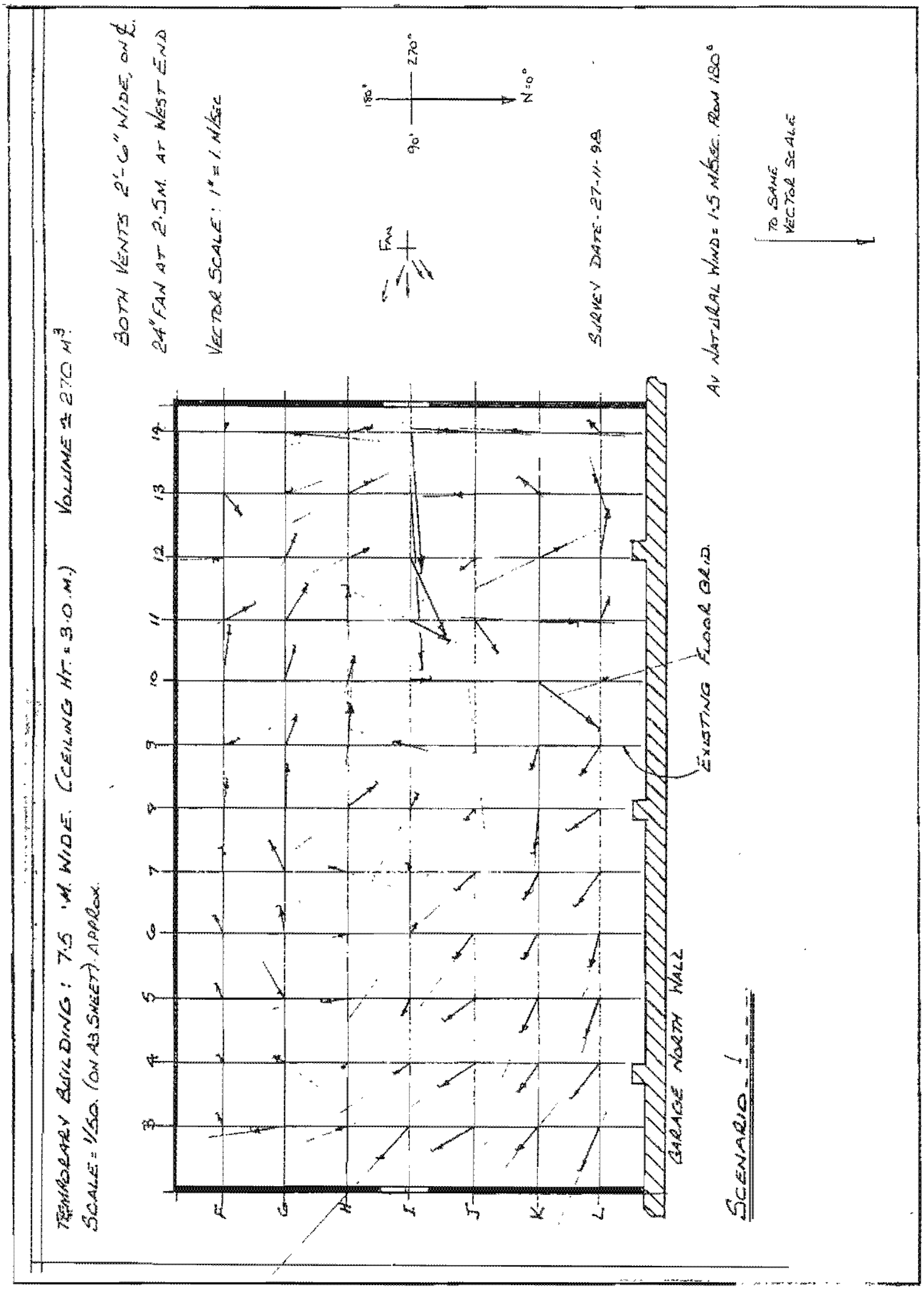


Figure 57. Airflow survey in 7.5 metre wide compartment: 2' 6" inlet and outlet, with P P V.

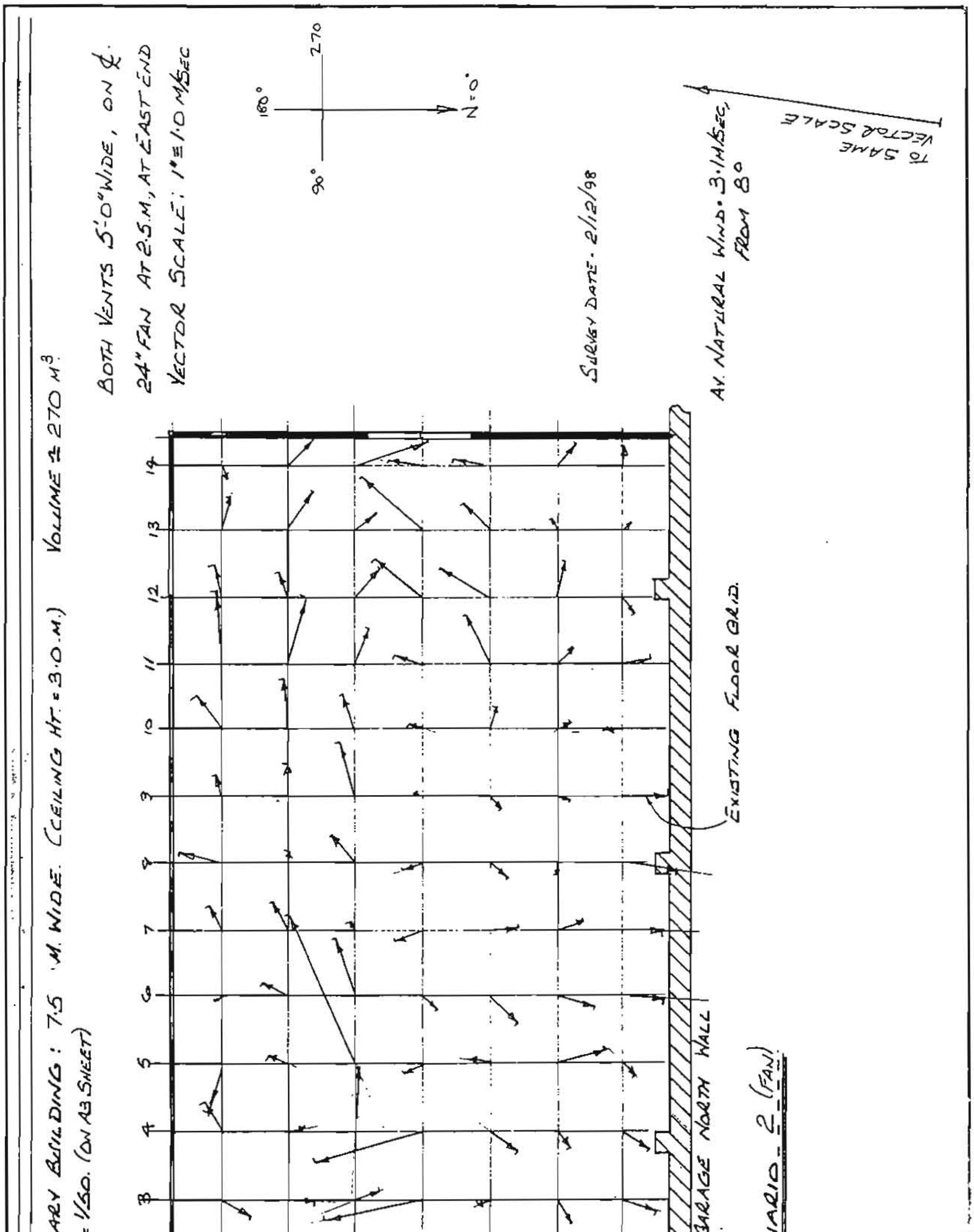


Figure 58. Airflow survey in 7.5 metre wide compartment: 5' 0" inlet and outlet, with P P V.

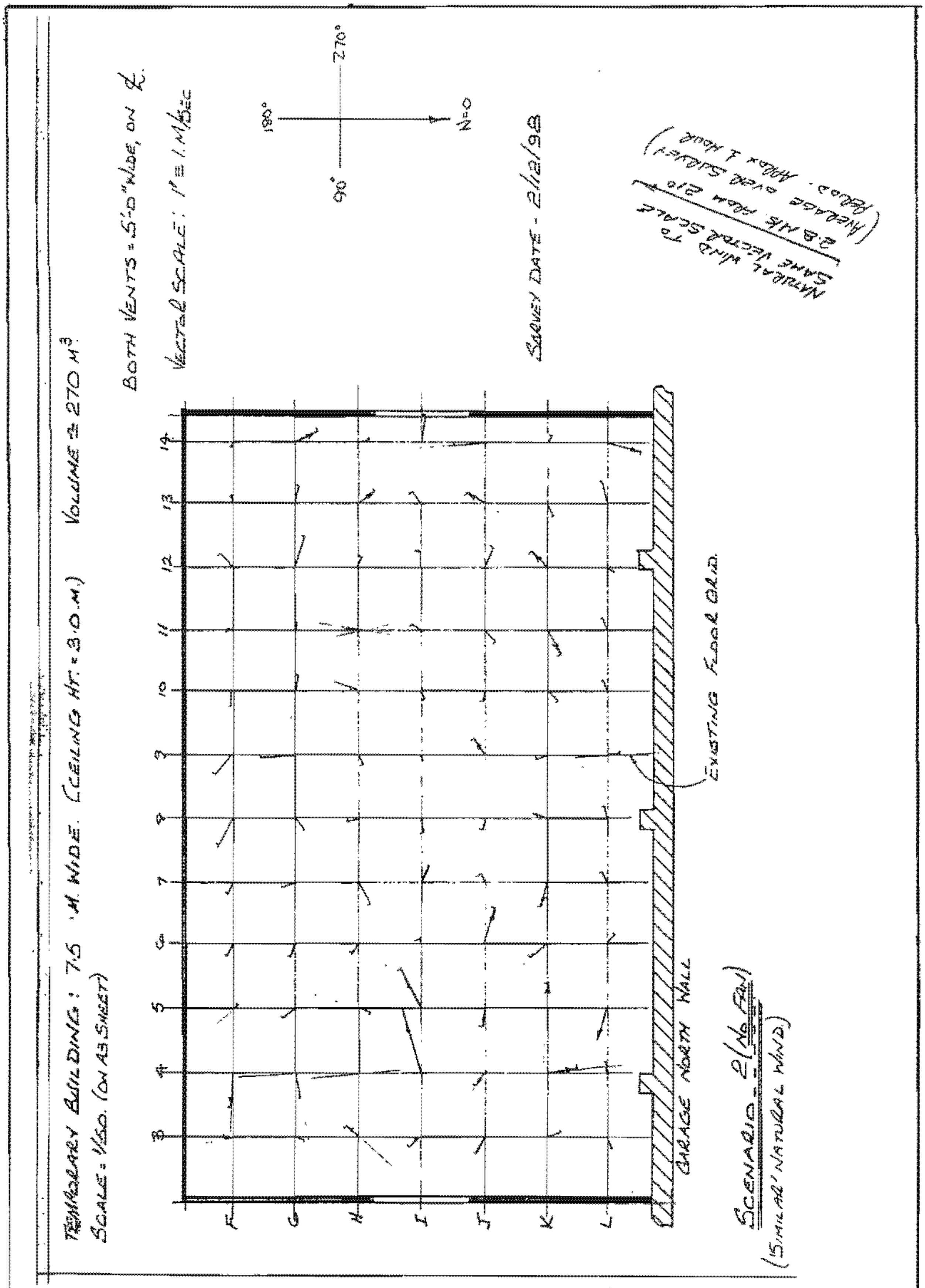


Figure 59. Airflow survey in 7.5 metre wide compartment: 5' 0" inlet and outlet, natural ventilation only.

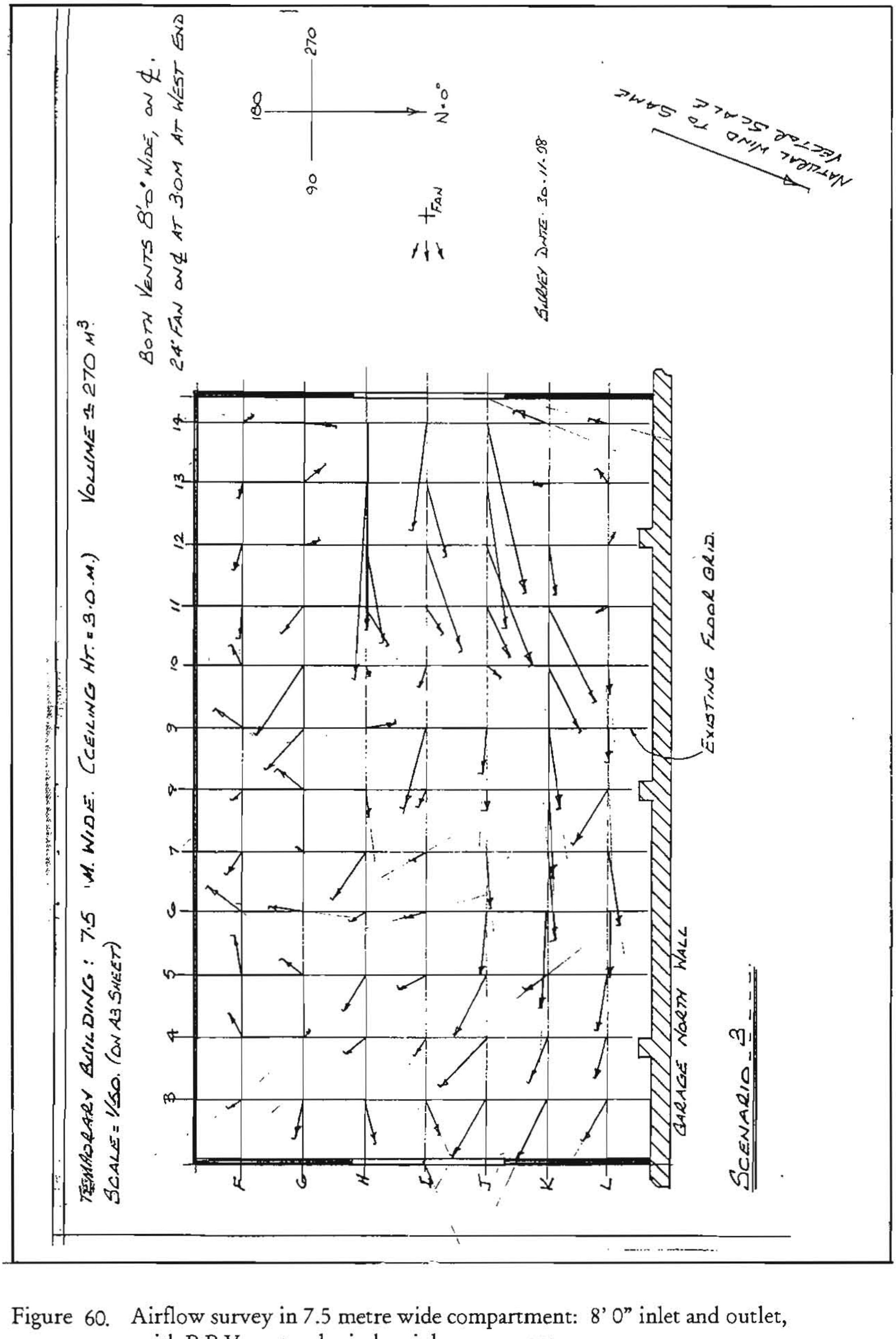


Figure 60. Airflow survey in 7.5 metre wide compartment: 8' 0" inlet and outlet, with P P V, natural wind mainly across vent.

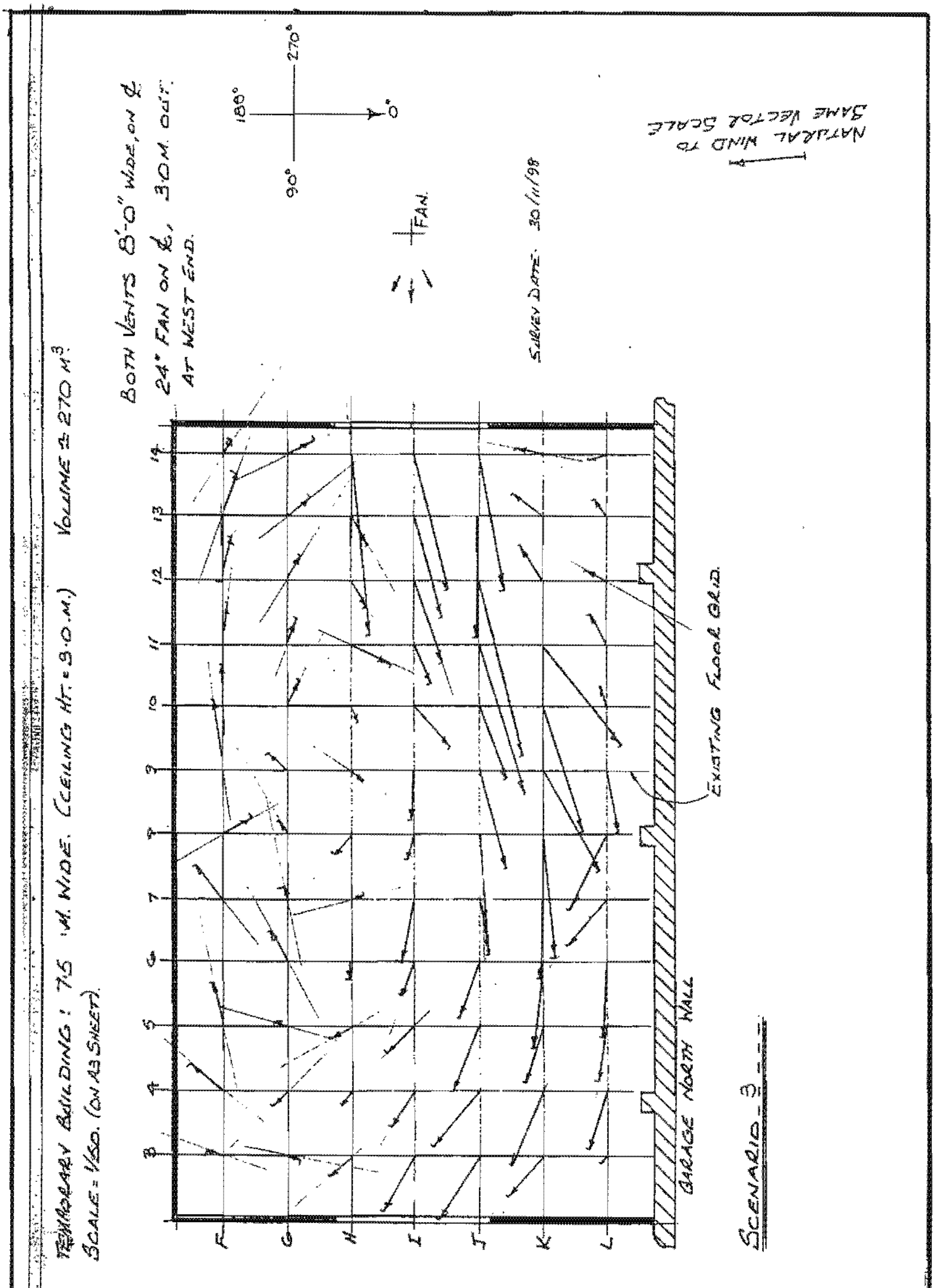


Figure 61. Airflow survey in 7.5 metre wide compartment: 8' 0" inlet and outlet, with P P V, natural wind across vents.

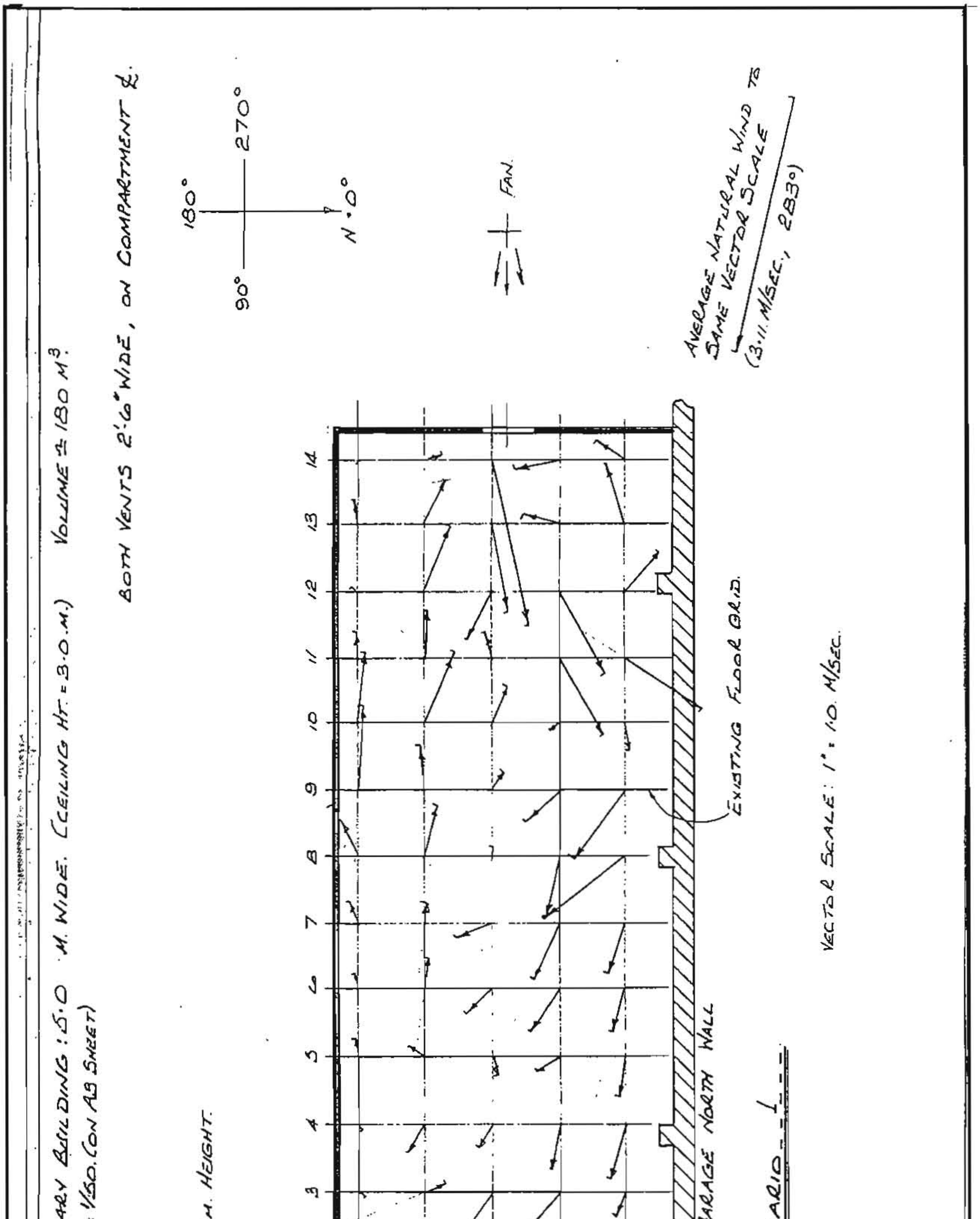


Figure 62. Airflow survey in 5.0 metres wide compartment: 2' 6" inlet – 2' 6" outlet.

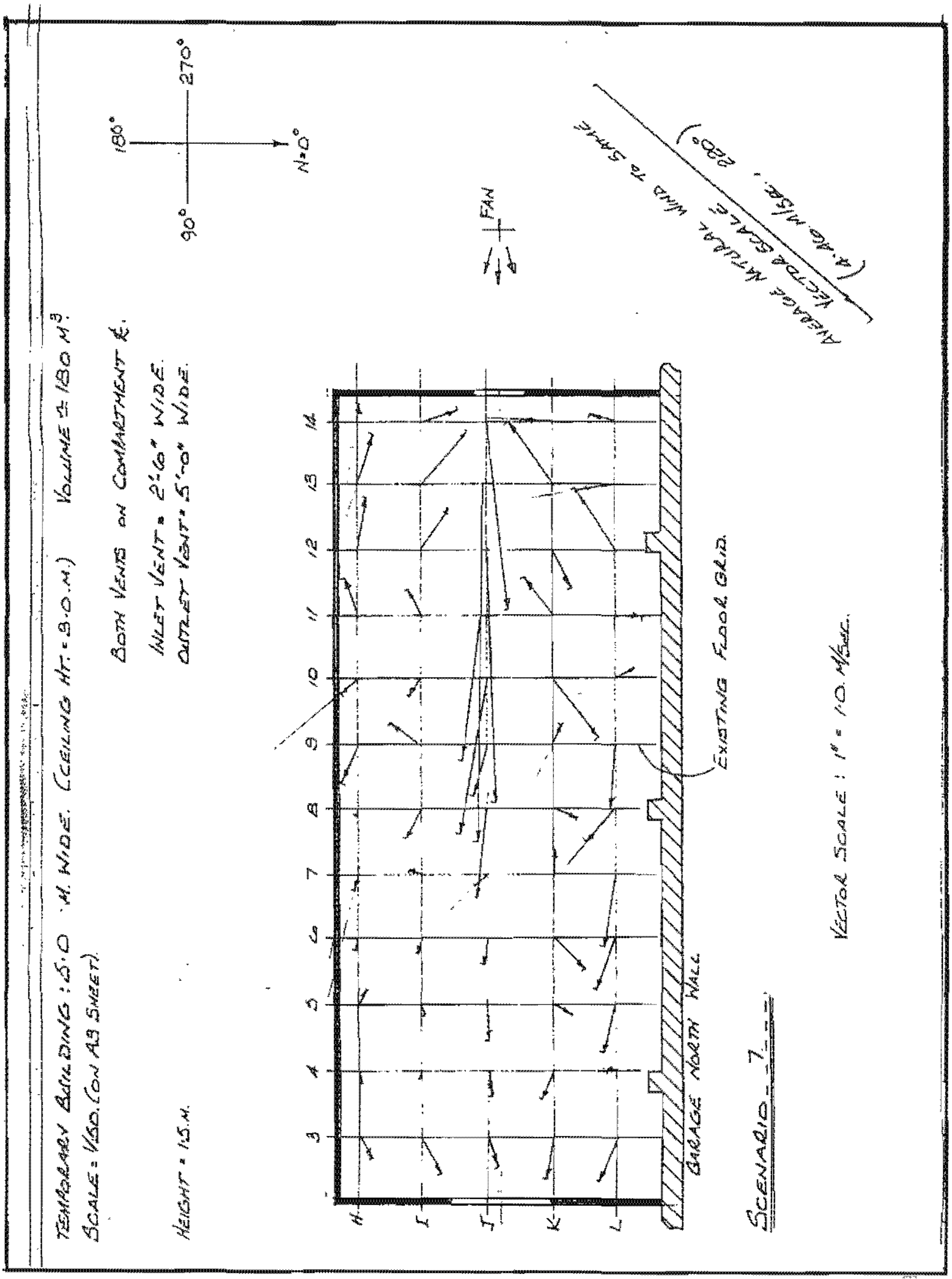


Figure 63. Airflow survey in 5.0 metres wide compartment: 2' 6" inlet – 5' 0" outlet.

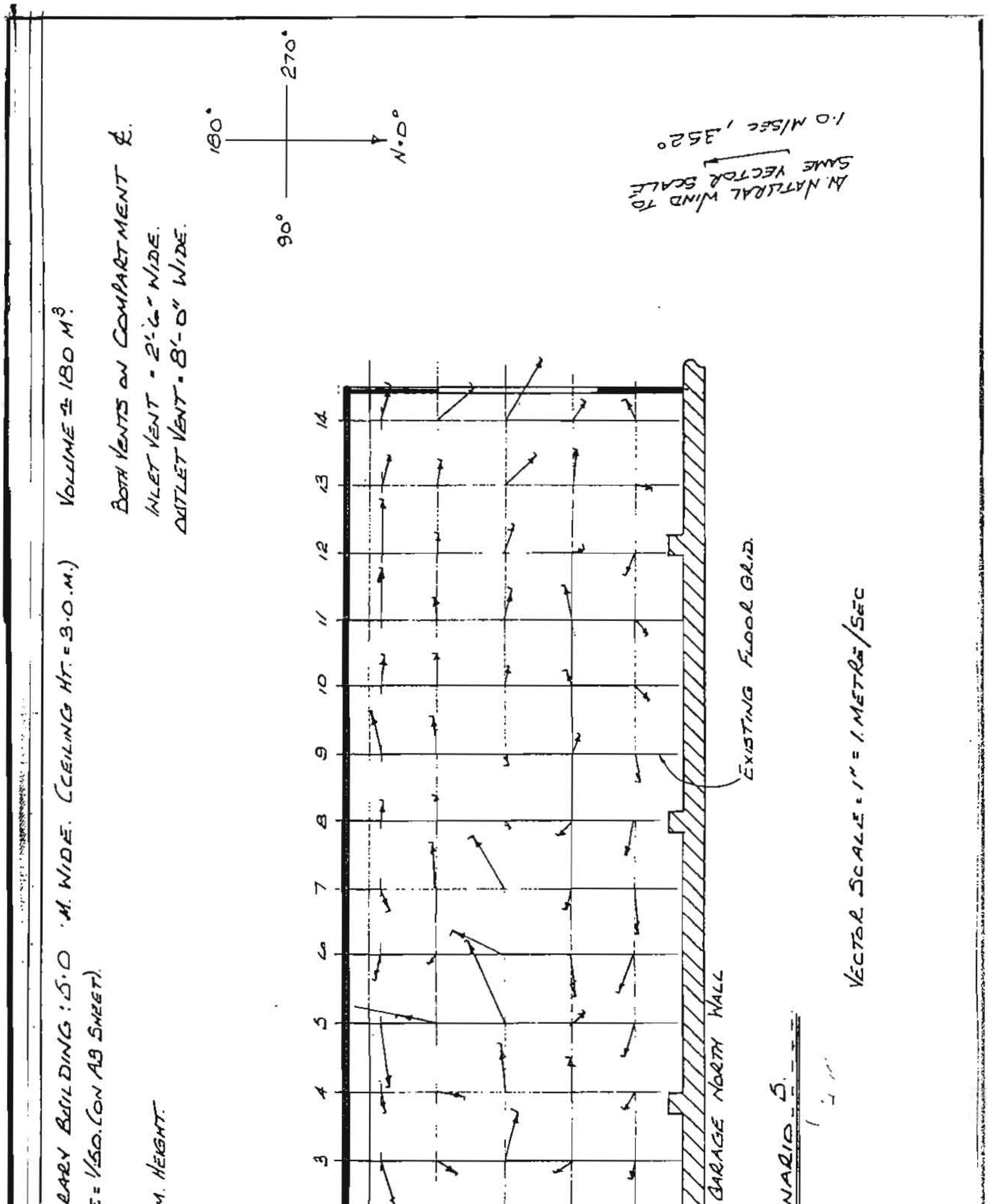


Figure 64. Airflow survey in 5.0 metrs wide compartment: 2' 6" inlet – 8' 0" outlet.

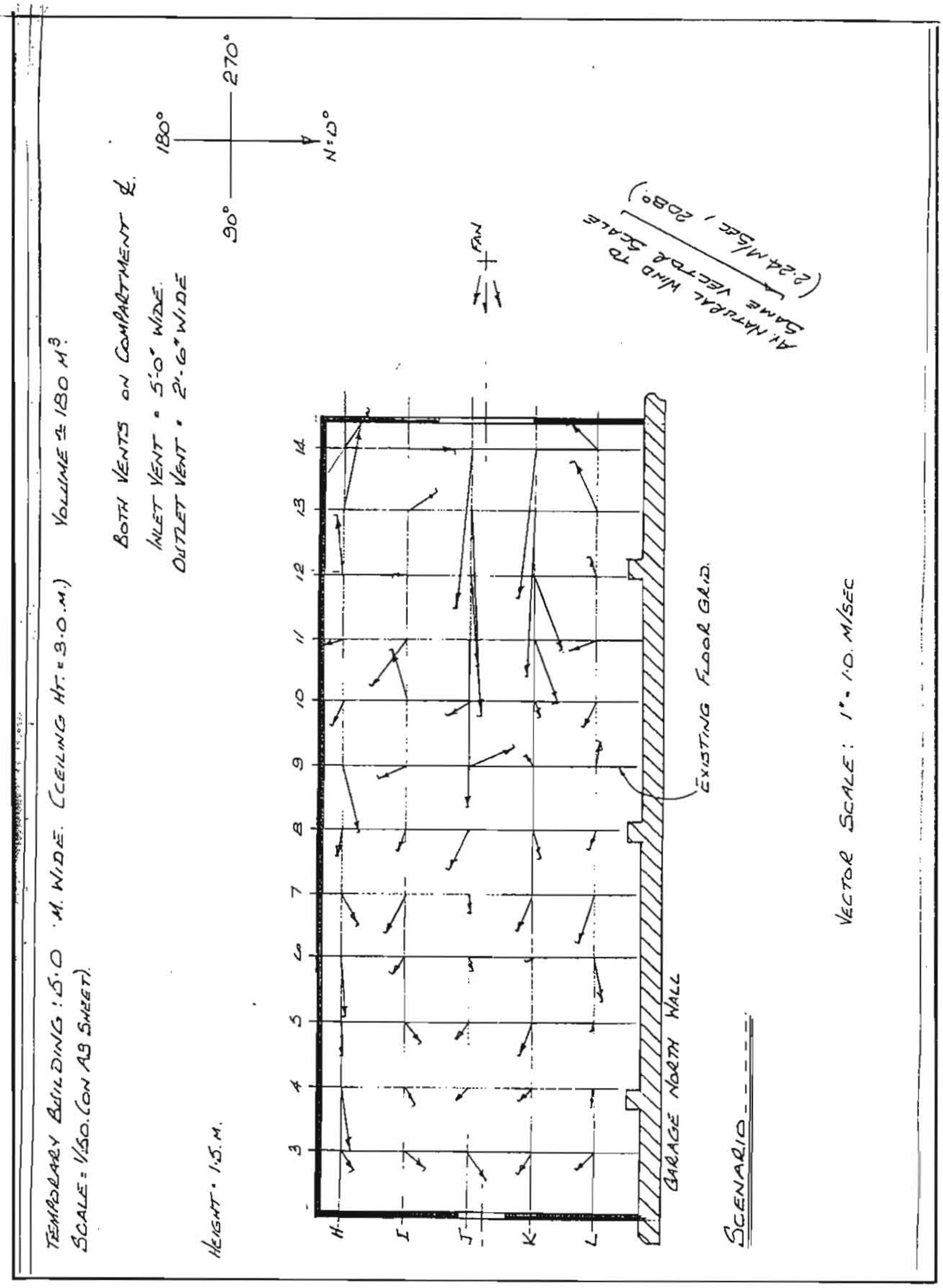


Figure 65. Airflow survey in 5.0 metres wide compartment: 5' 0" inlet - 2' 6" outlet.

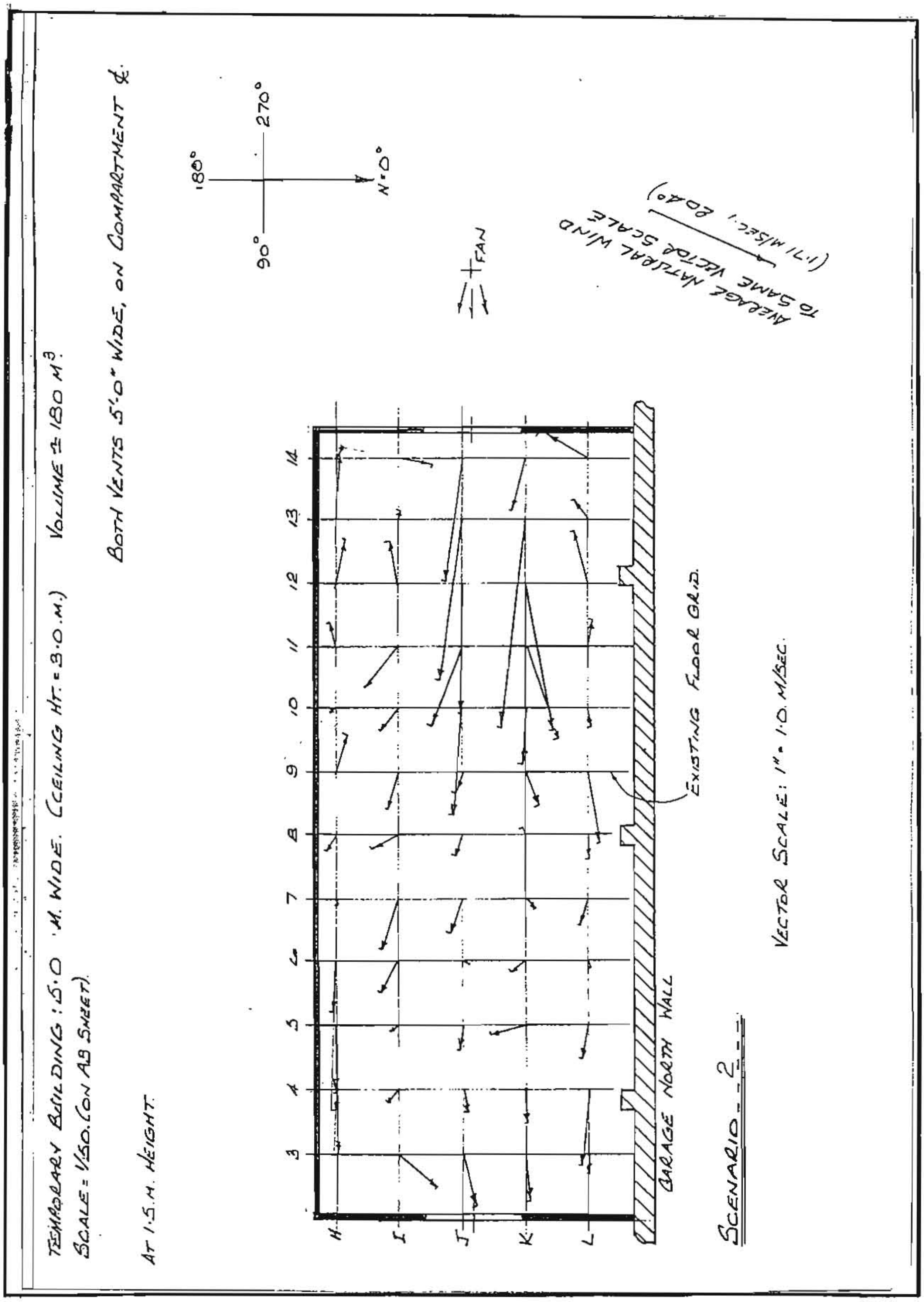


Figure 66. Airflow survey in 5.0 metres wide compartment: 5' 0" inlet – 5' 0" outlet.

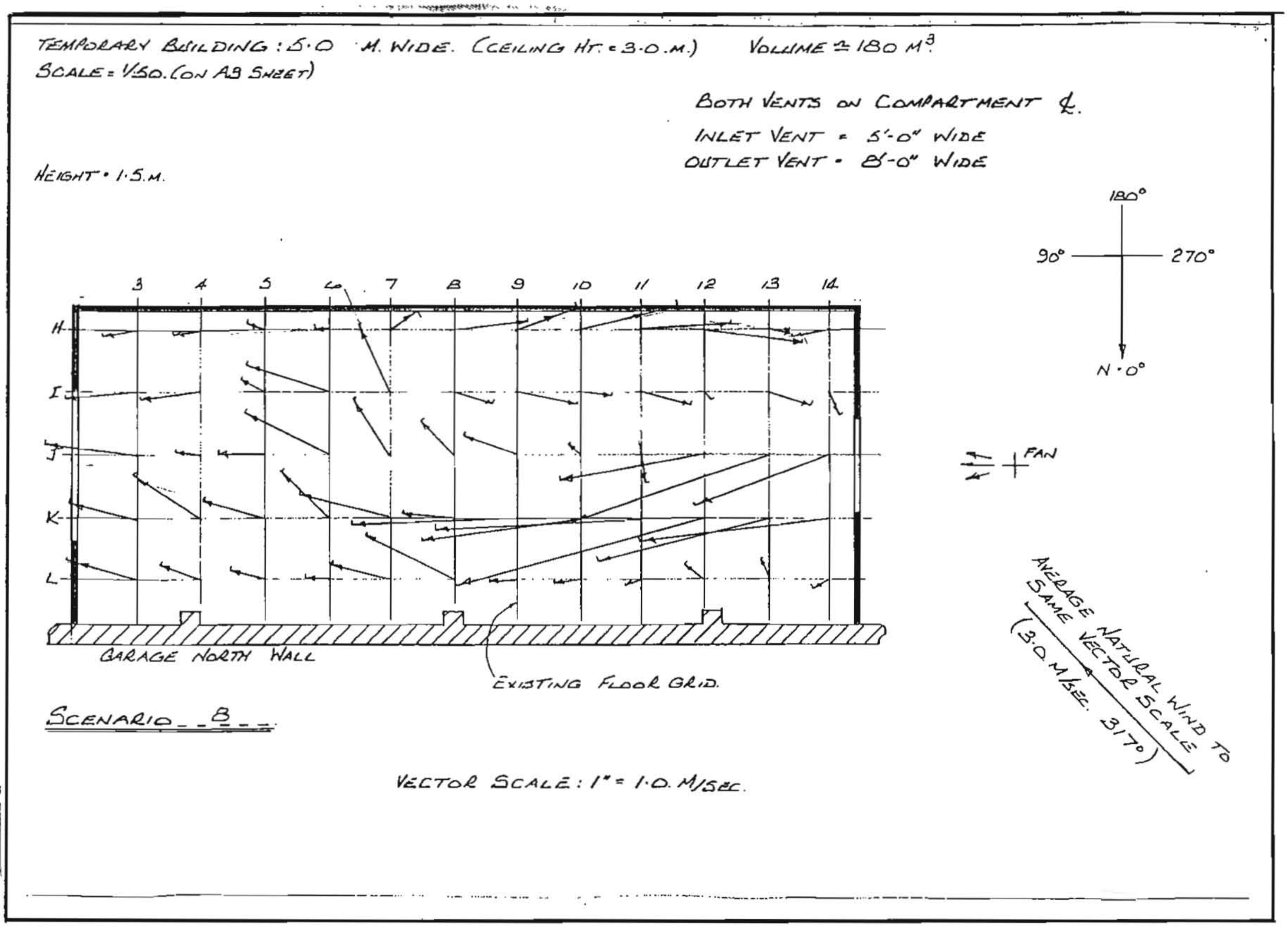


Figure 67. Airflow survey in 5.0 metres wide compartment: 5'0" inlet - 8'0" outlet.

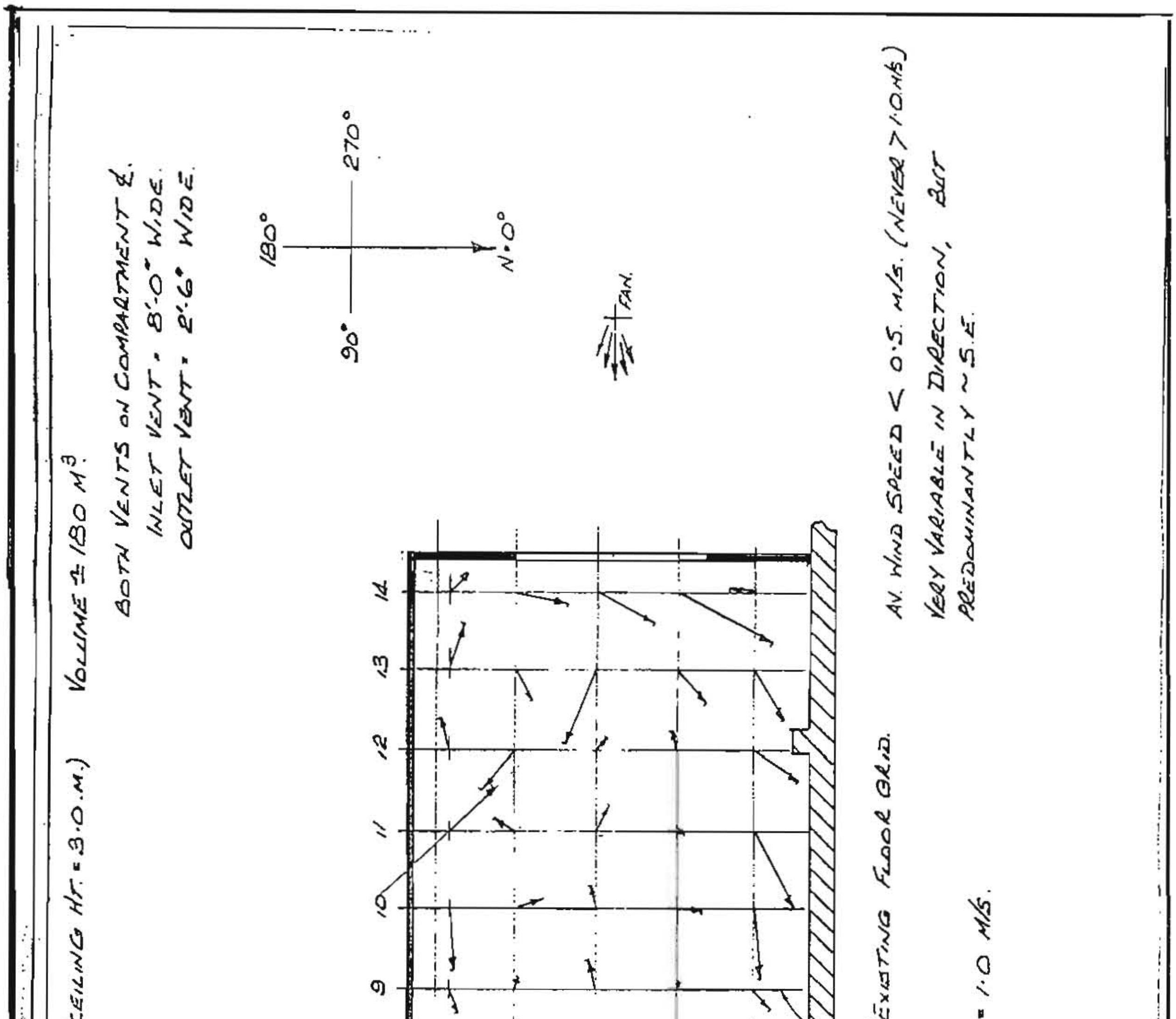


Figure 68. Airflow survey in 5.0 metres wide compartment: 8' 0" inlet – 2' 6" outlet.

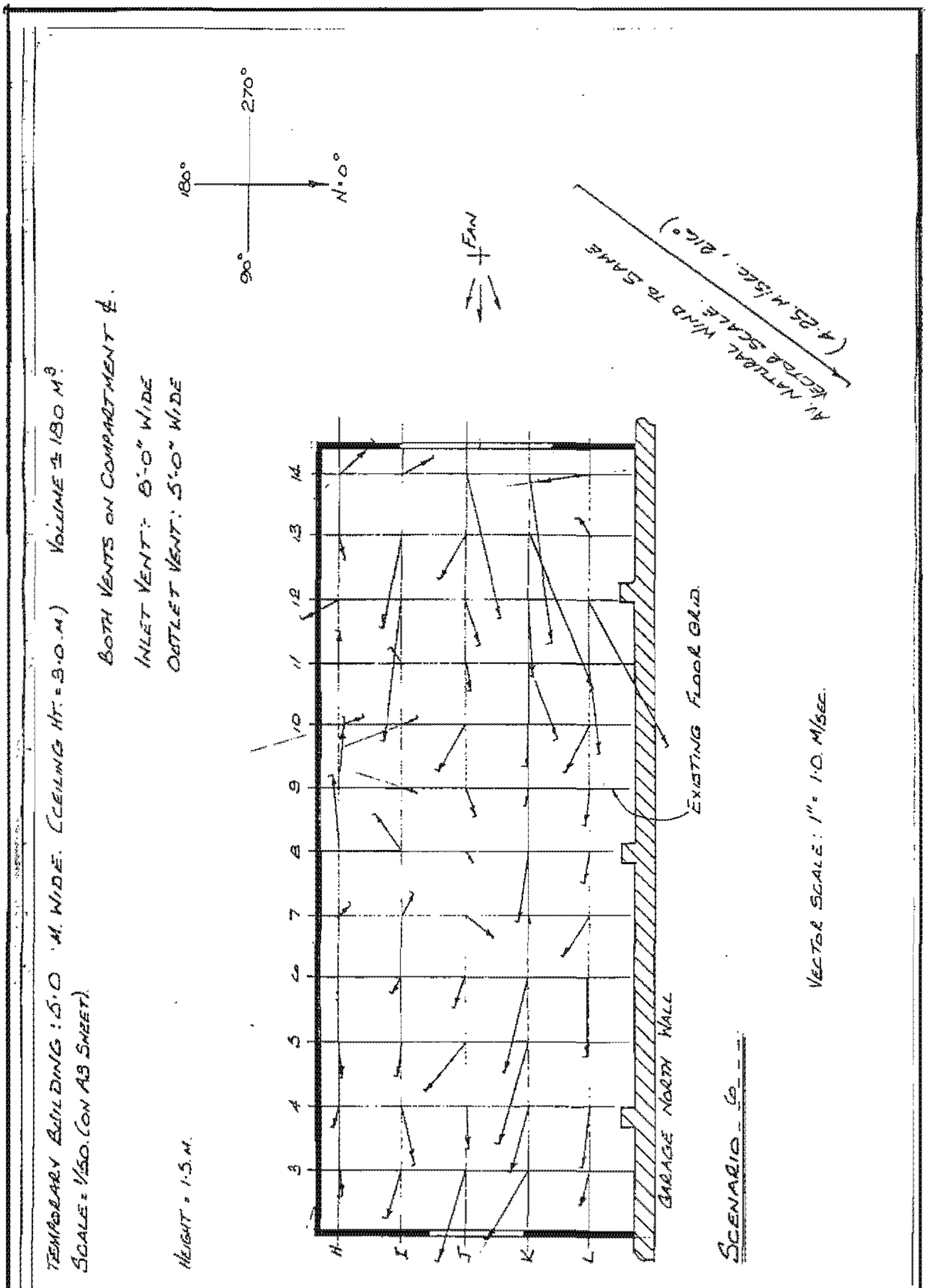


Figure 69. Airflow survey in 5.0 metres wide compartment: 8' 0" inlet – 5' 0" outlet.

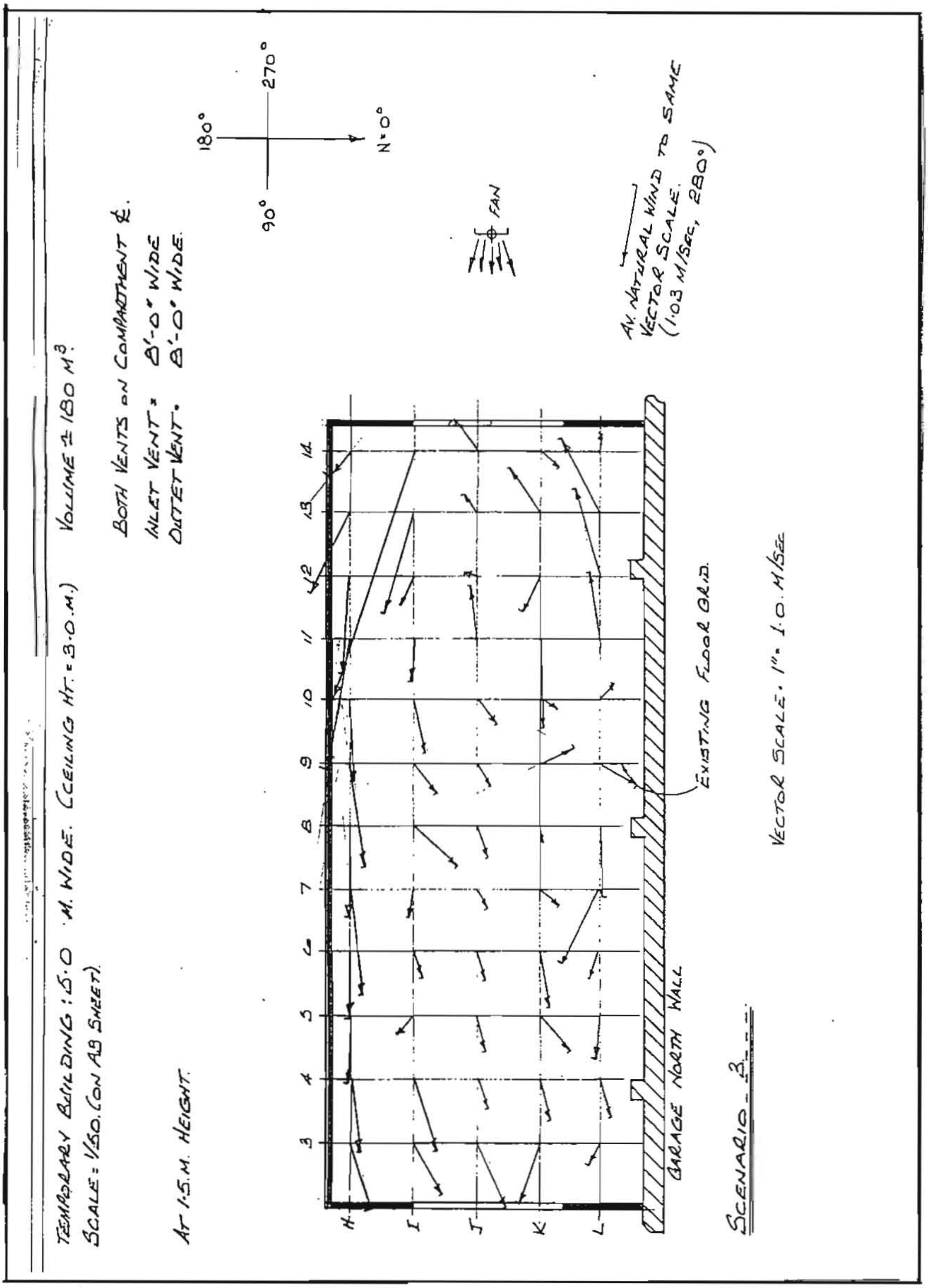


Figure 70. Airflow survey in 5.0 metres wide compartment: 8' 0" inlet – 8' 0" outlet.

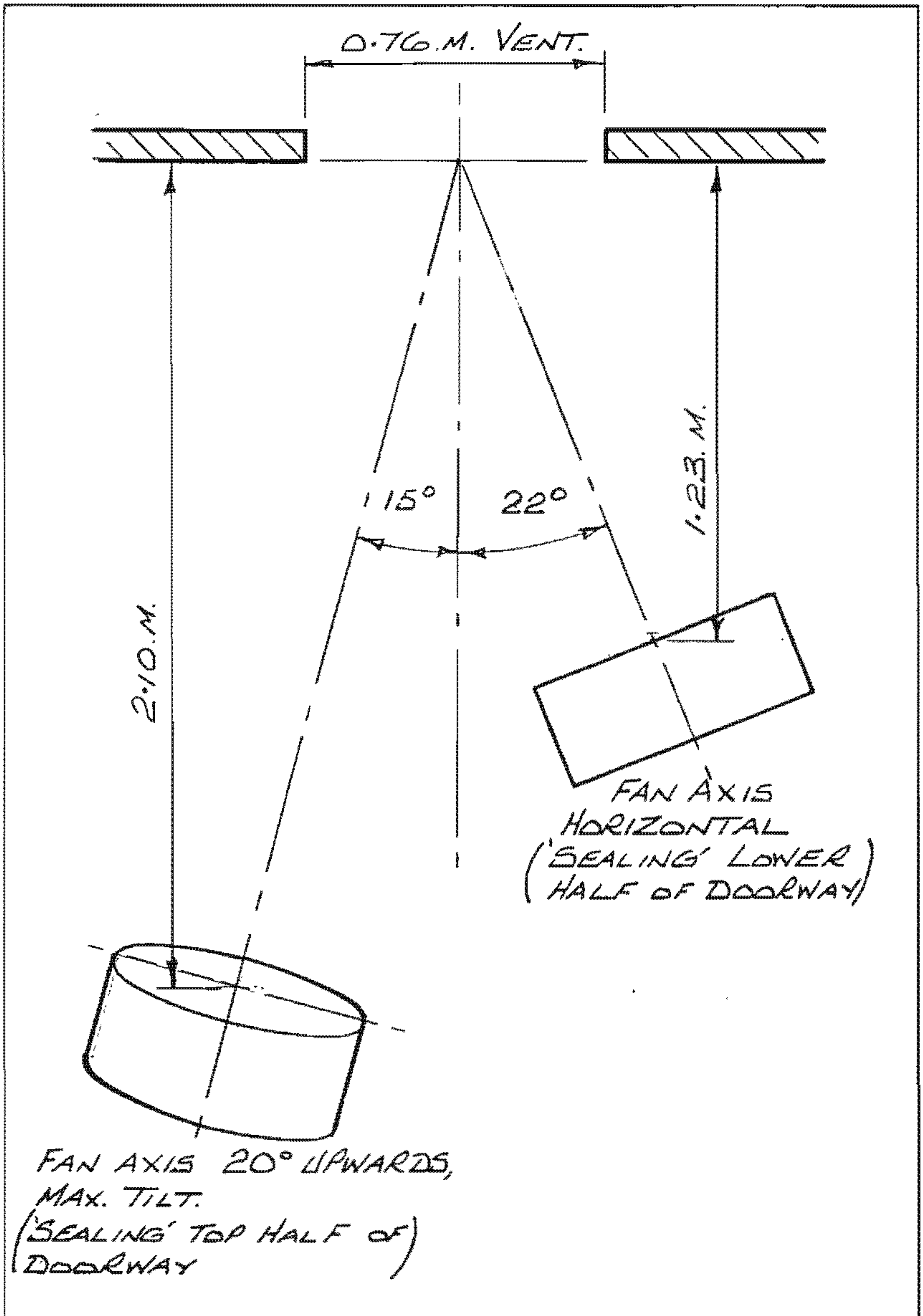


Figure 71. Two P P V fans in use: positions relative to doorway to try a new tactic.

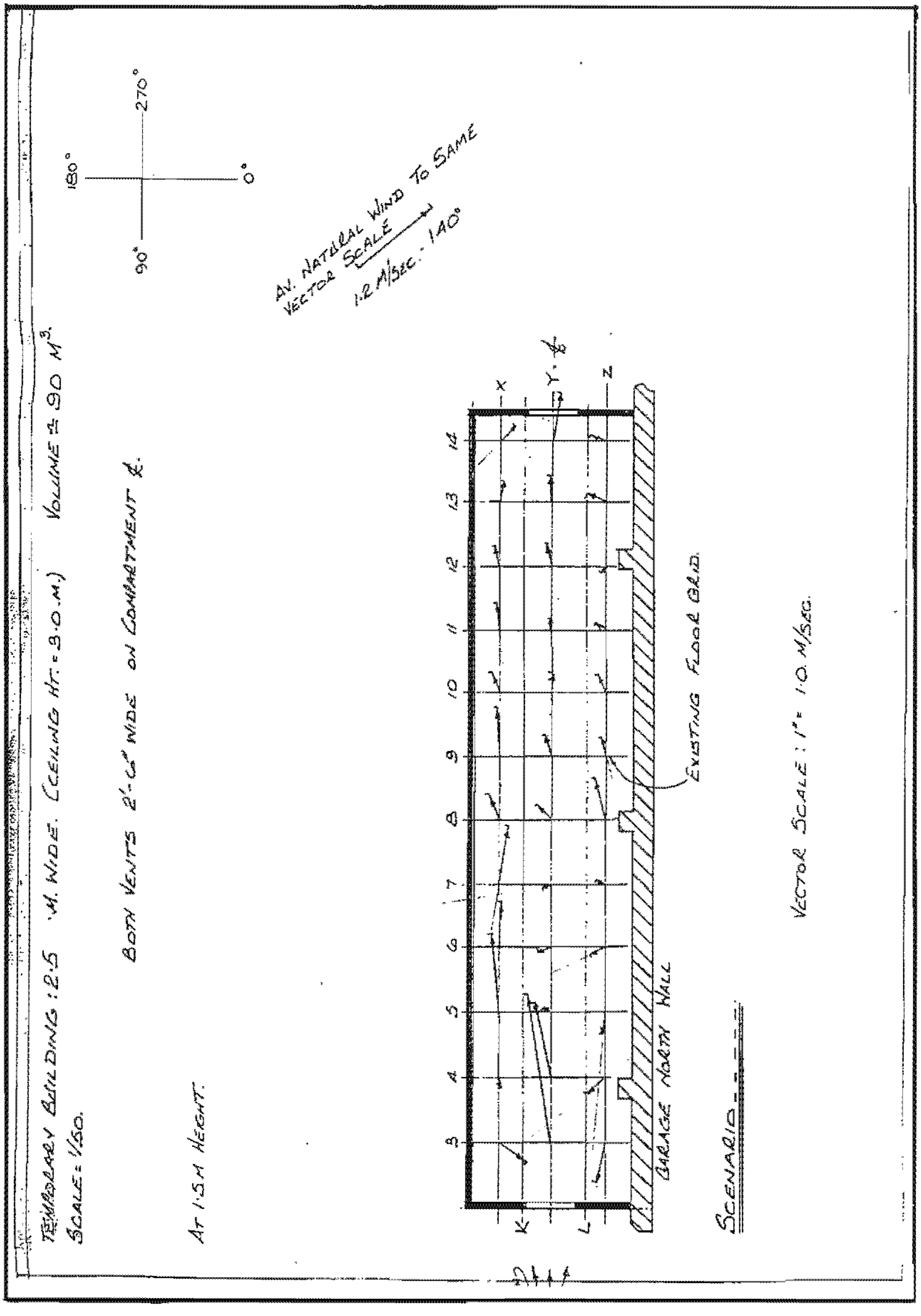


Figure 72. Airflow survey in 2.5 metres wide compartment: 2' 6" inlet – 2' 6" outlet.

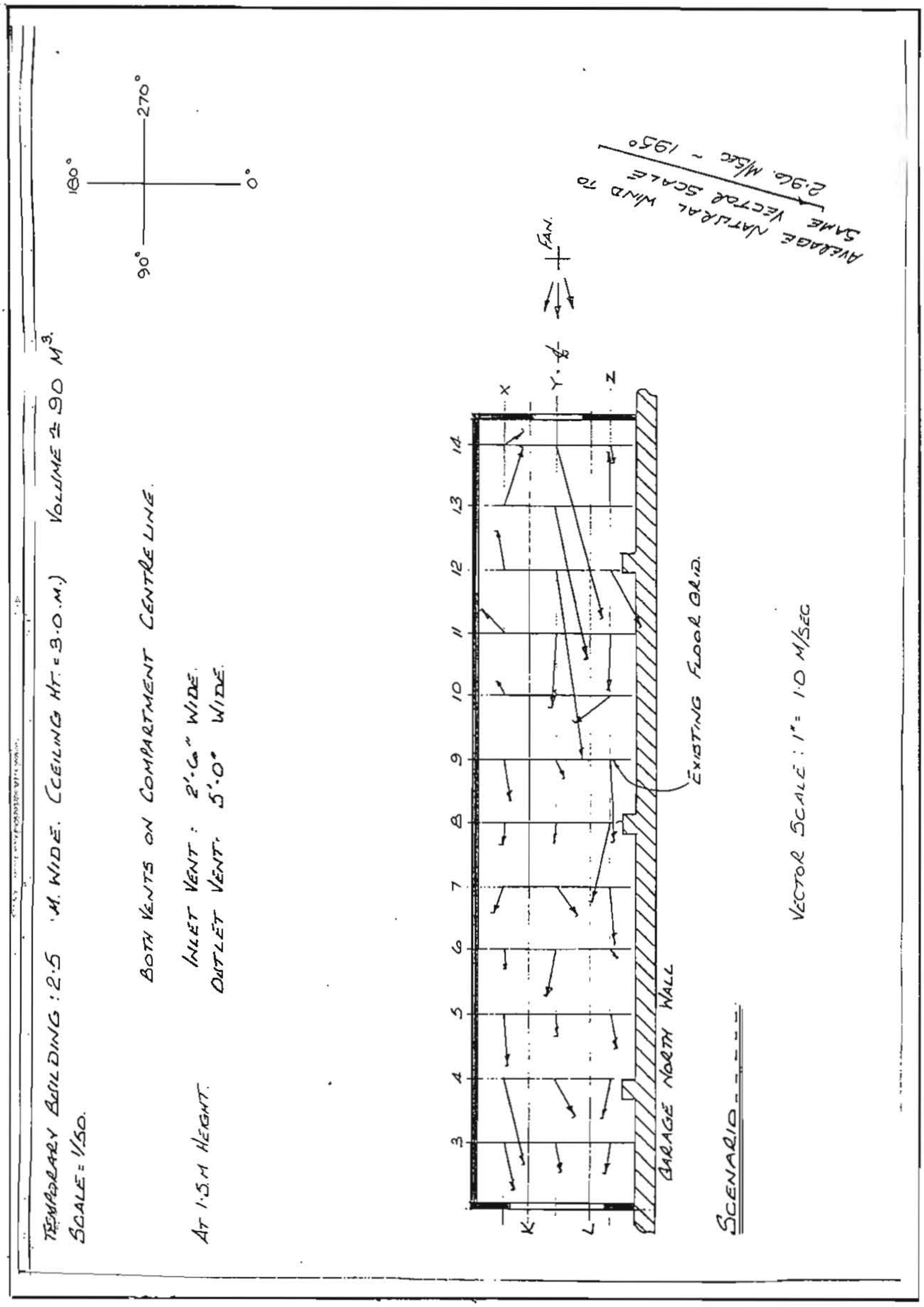


Figure 73. Airflow survey in 2.5 metres wide compartment: 2' 6" inlet – 5' 0" outlet.

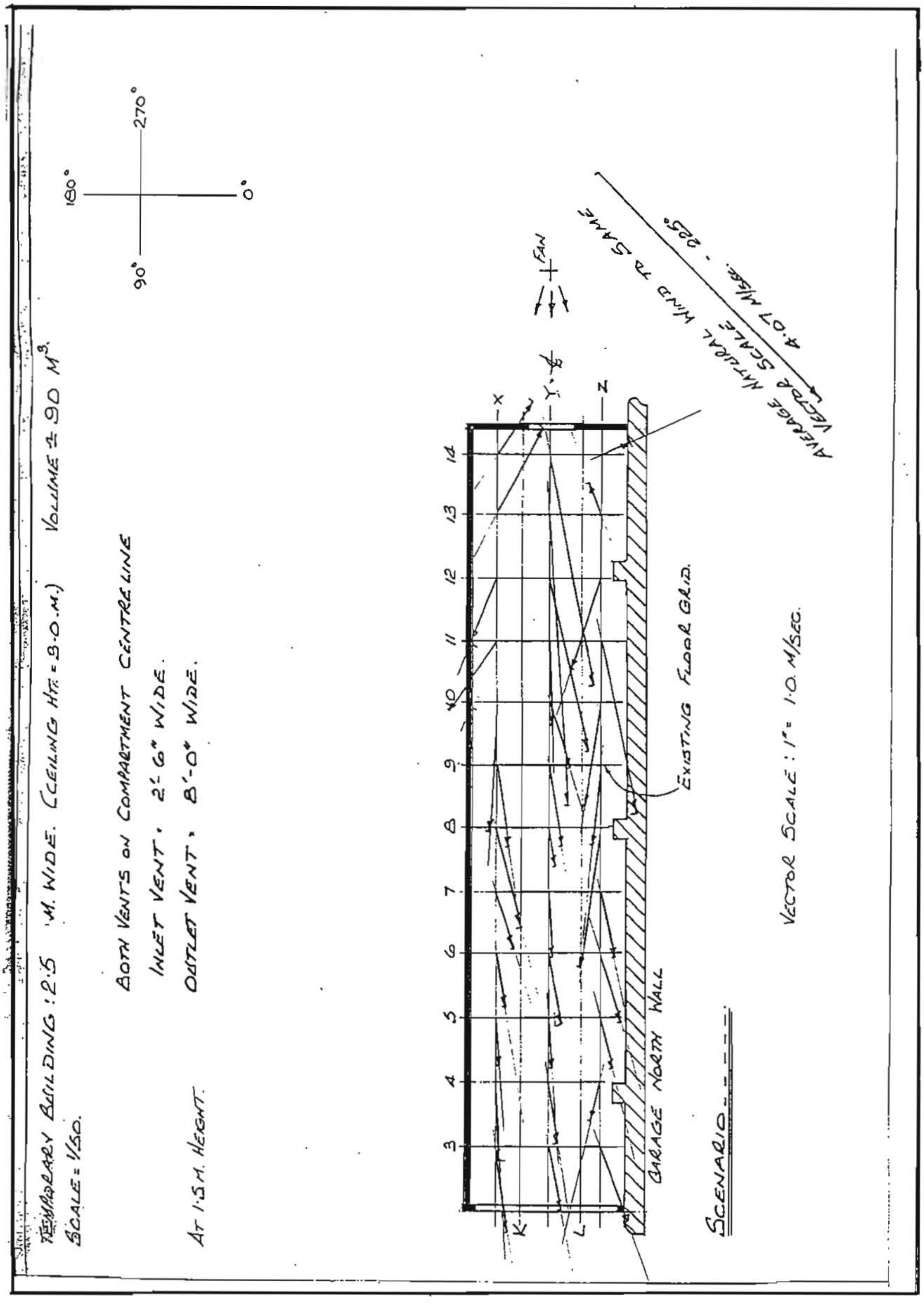


Figure 74. Airflow suvey in 2.5 metres wide compartment: 2' 6" inlet – 8' 0" outlet.

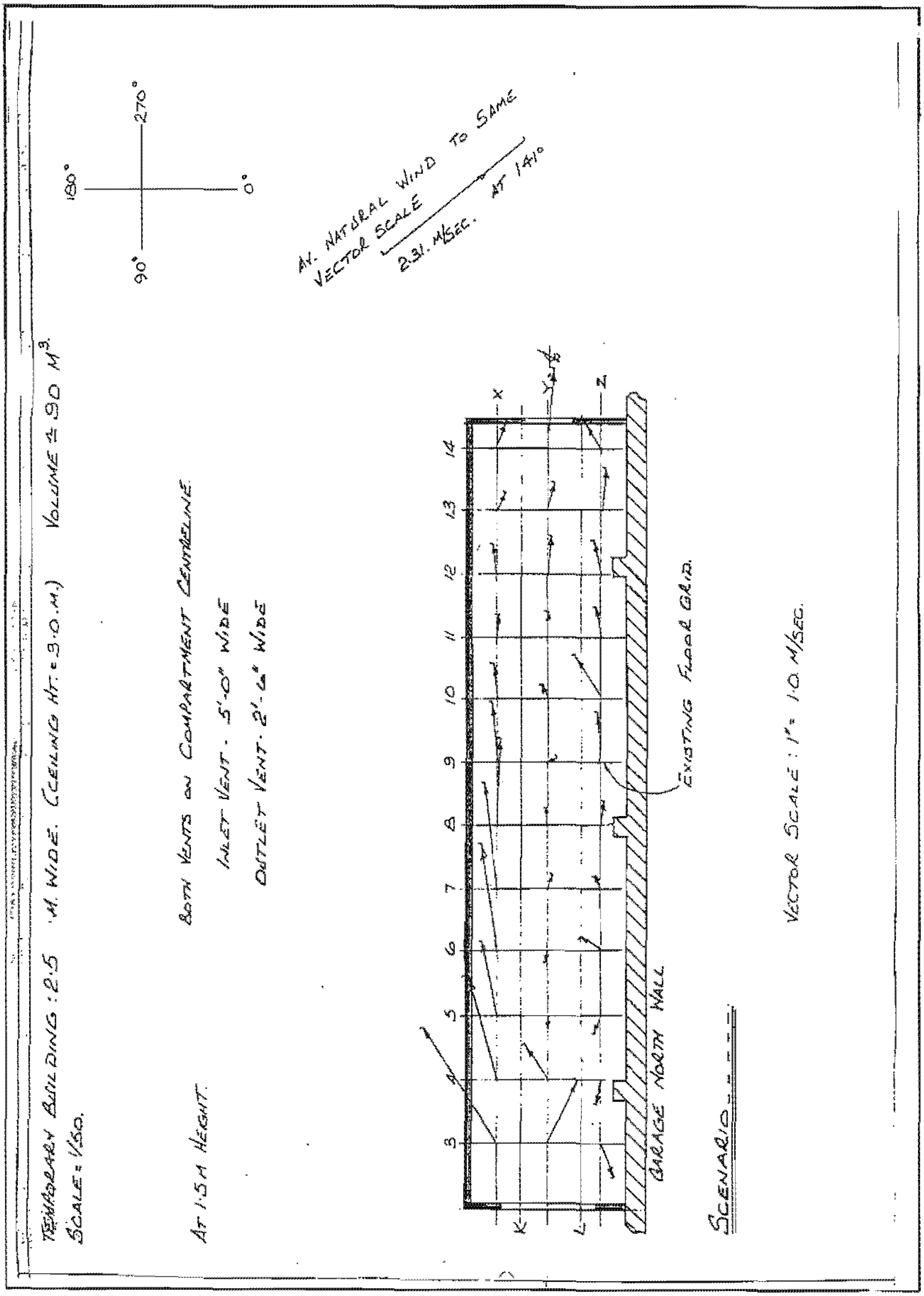


Figure 75. Airflow survey in 2.5 metres wide compartment: 5' 0" inlet – 2' 6" outlet.

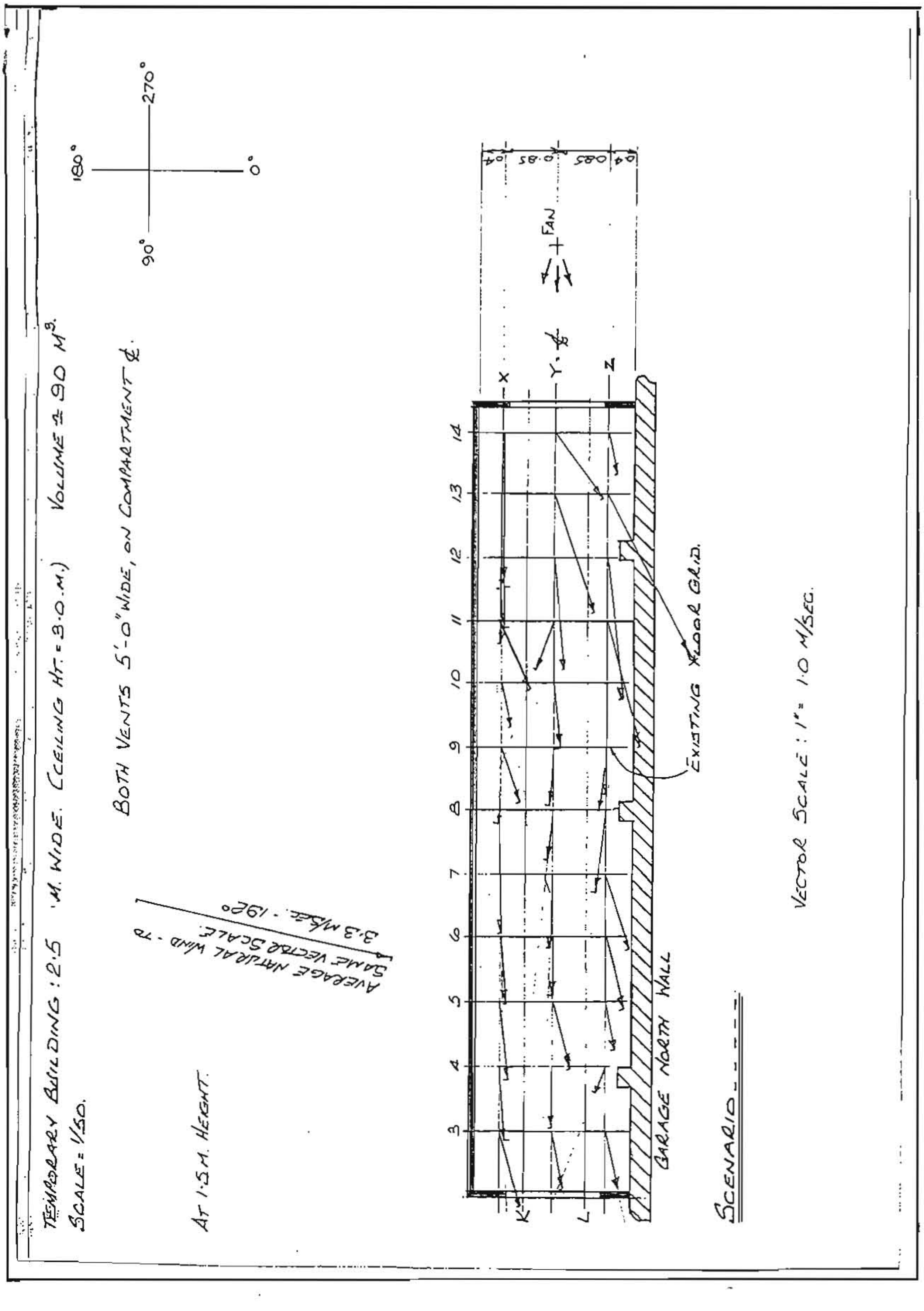


Figure 76. Airflow survey in 2.5 metres wide compartment: 5' 0" inlet 5' 0" outlet.

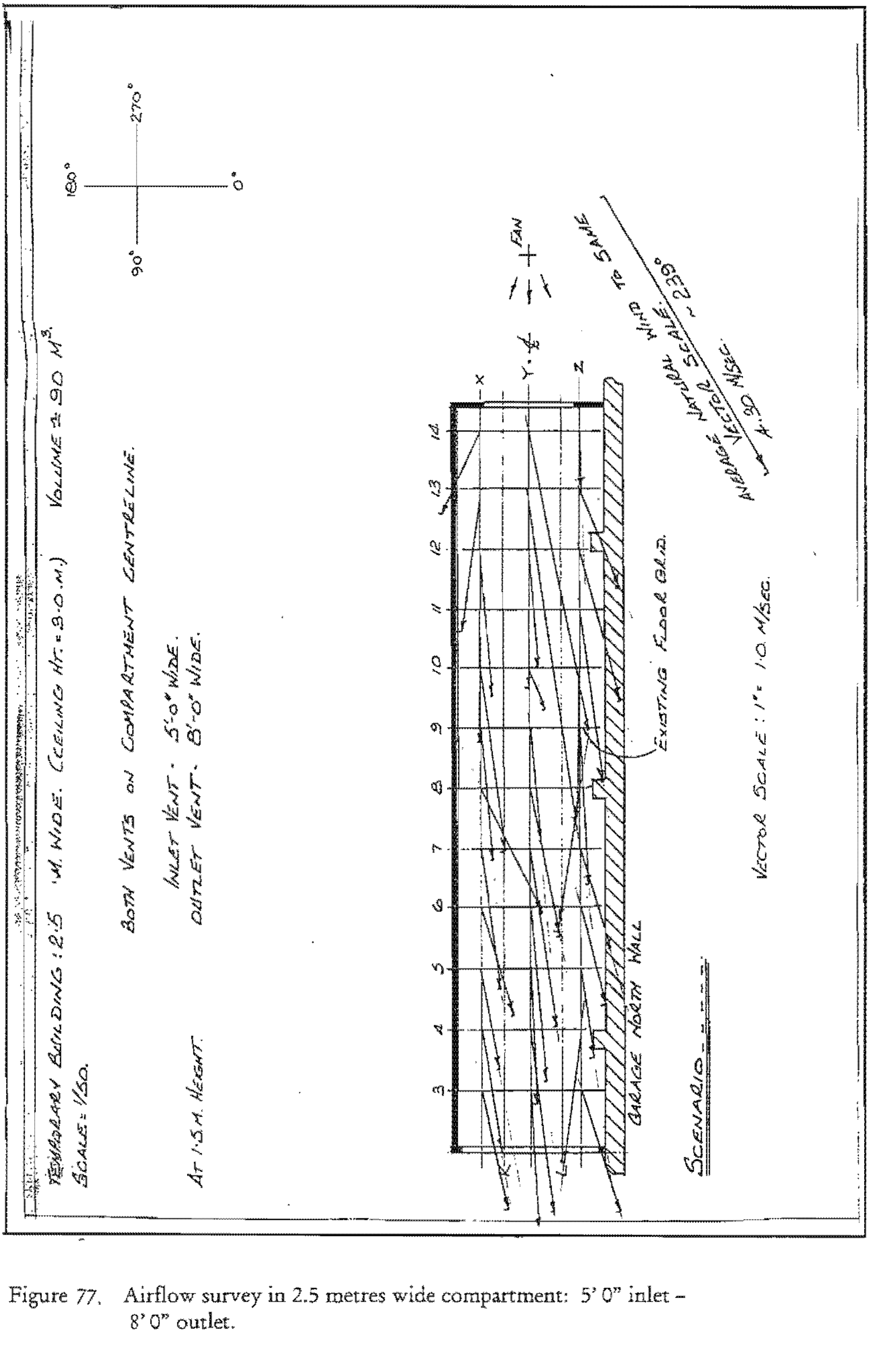


Figure 77. Airflow survey in 2.5 metres wide compartment: 5' 0" inlet – 8' 0" outlet.

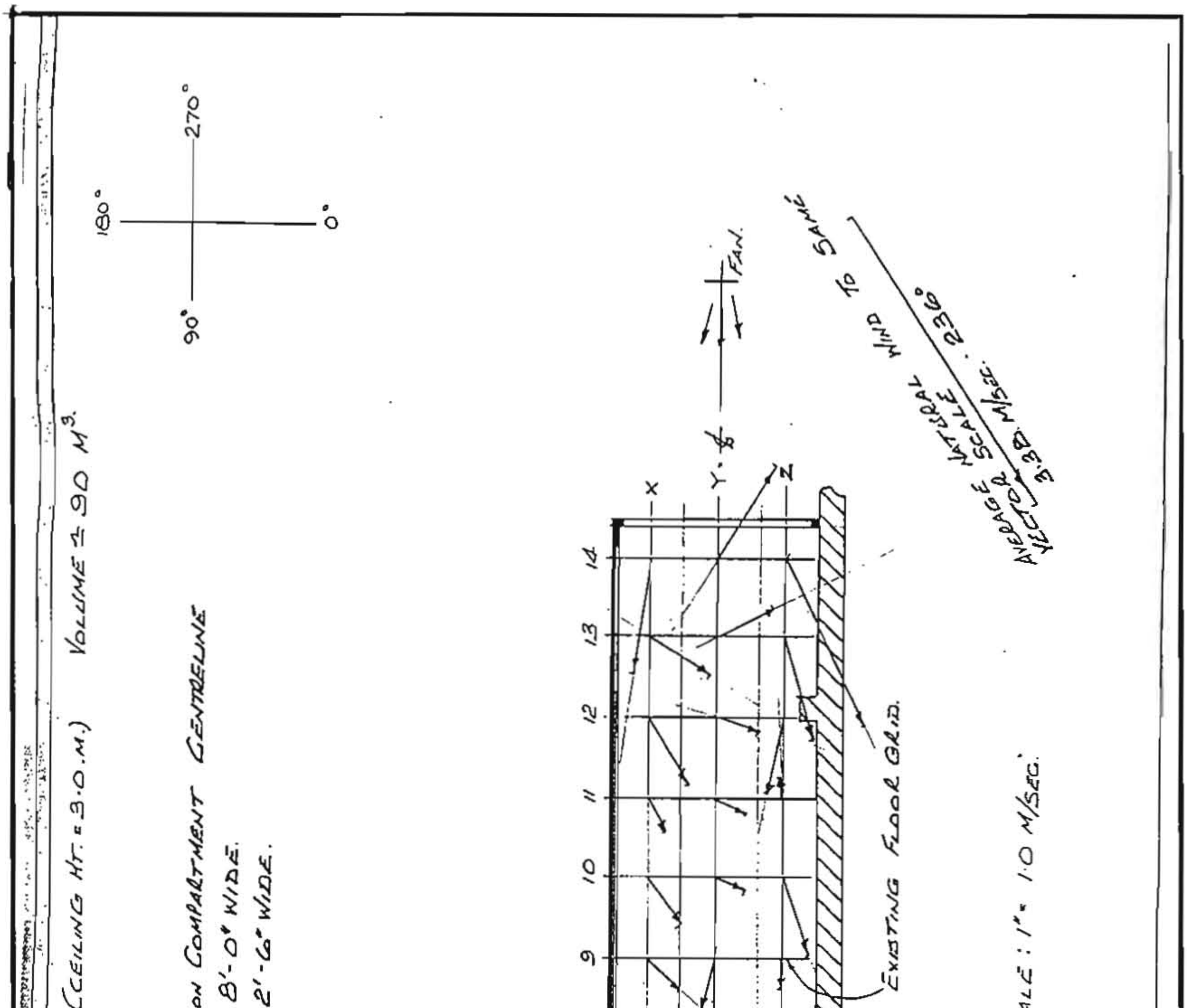


Figure 78. Airflow survey in 2.5 metres wide compartment: 8' 0" inlet – 2' 6" outlet.

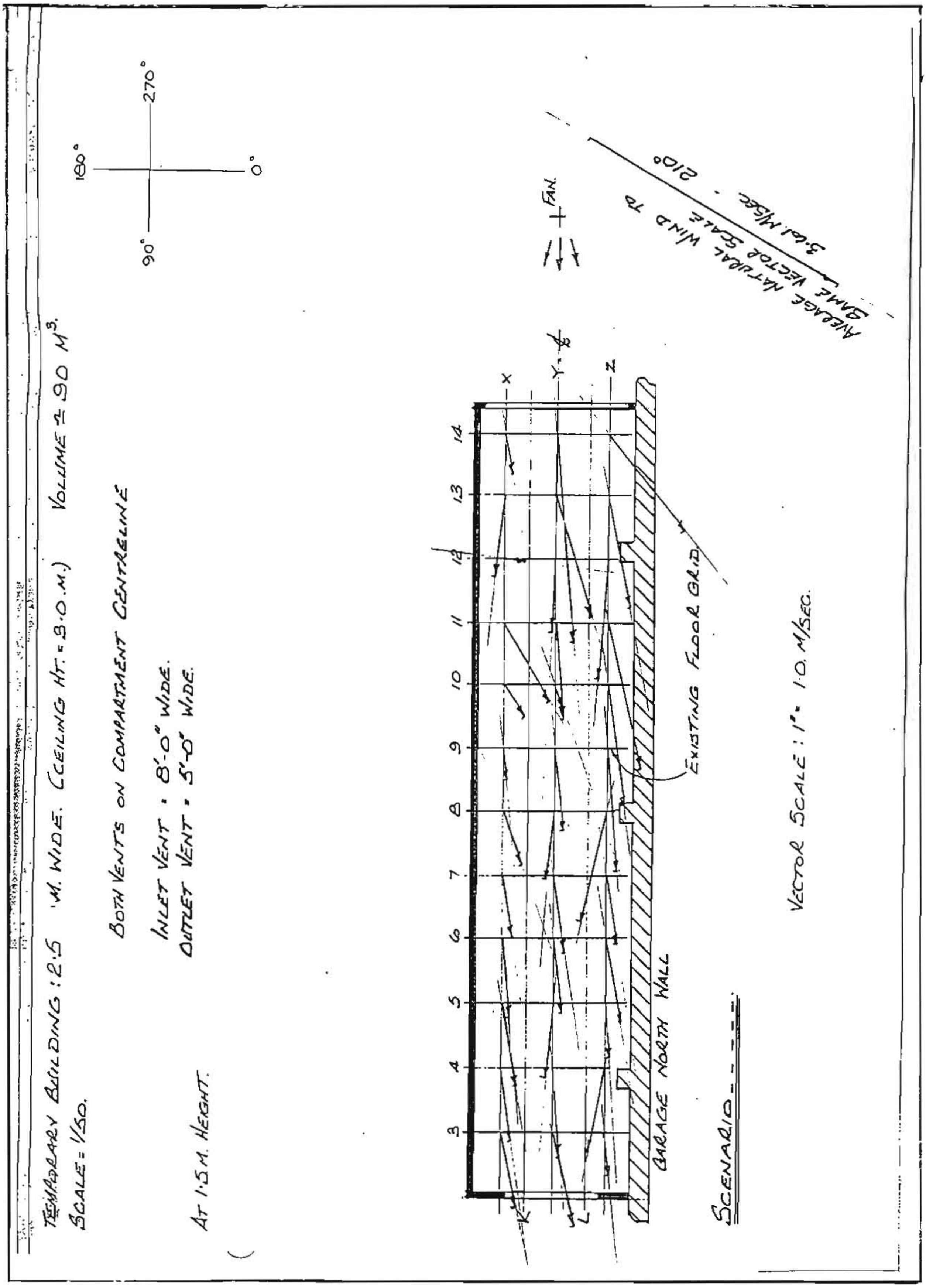


Figure 79. Airflow survey in 2.5 metres wide compartment: 8' 0" inlet – 5' 0" outlet.

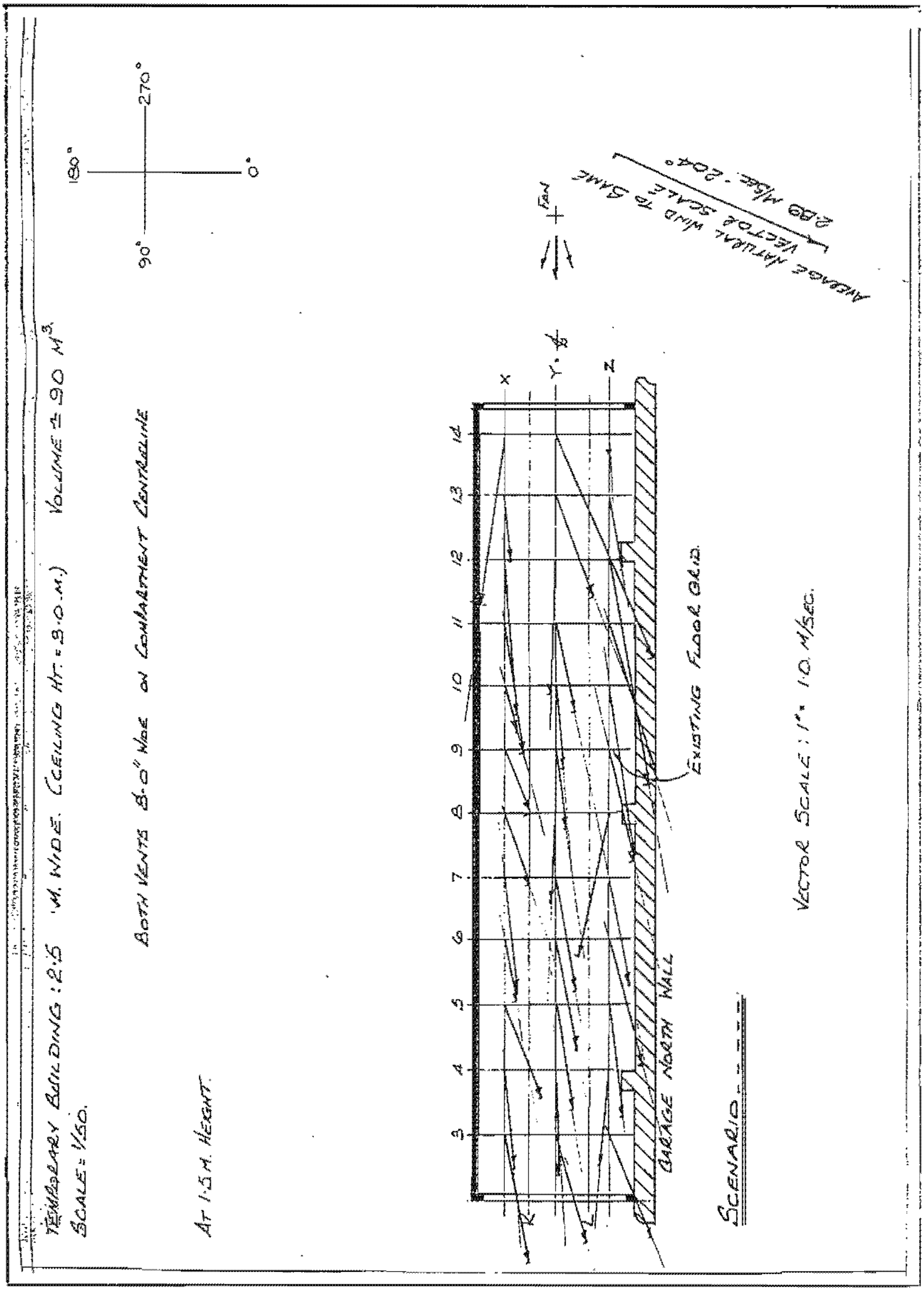


Figure 80. Airflow survey in 2.5 metres wide compartment: 8' 0" inlet – 8' 0" outlet.

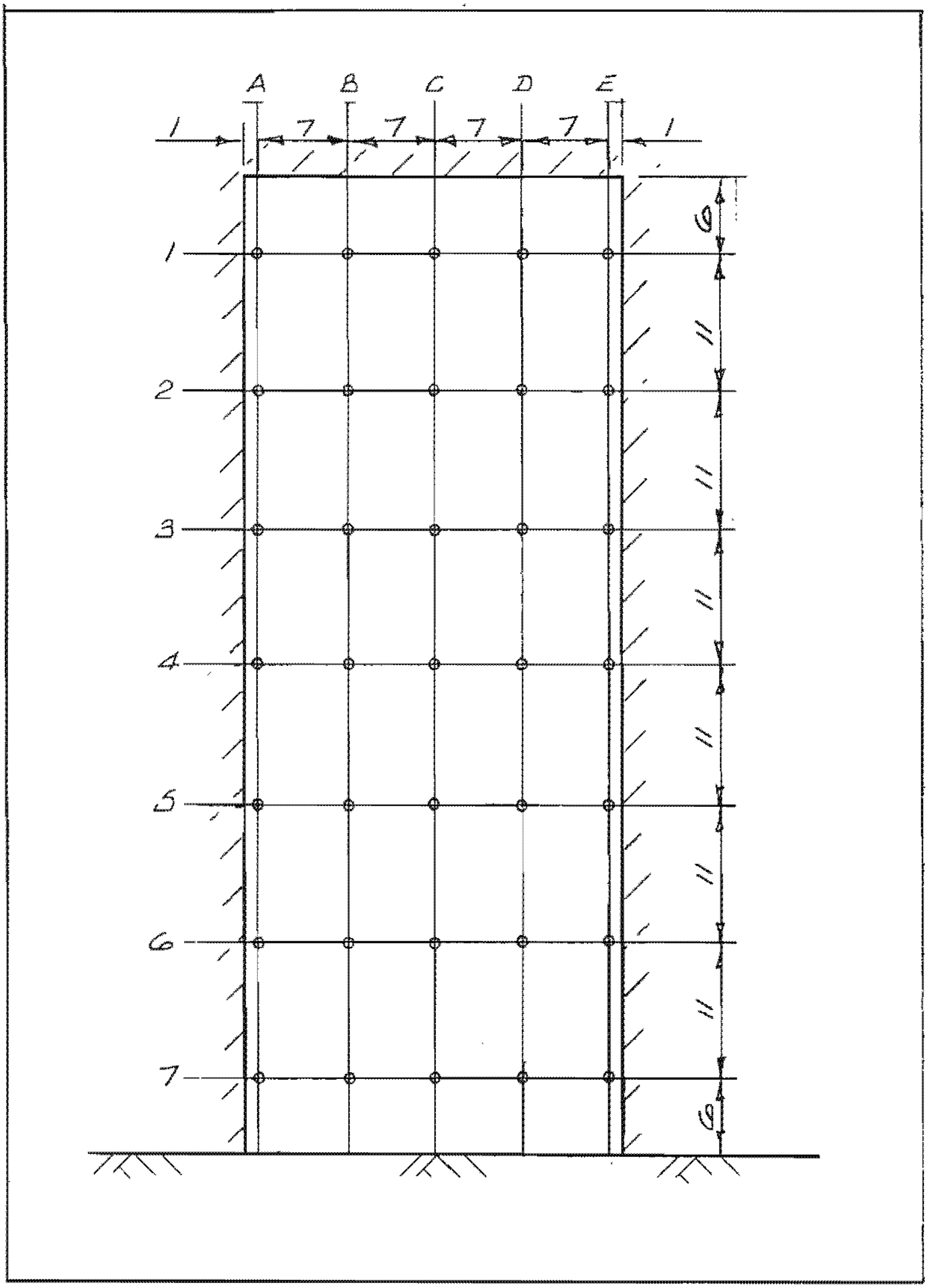


Figure 81. Grid defining the airflow sampling points in the 6' 6" x 2' 6" doorway.

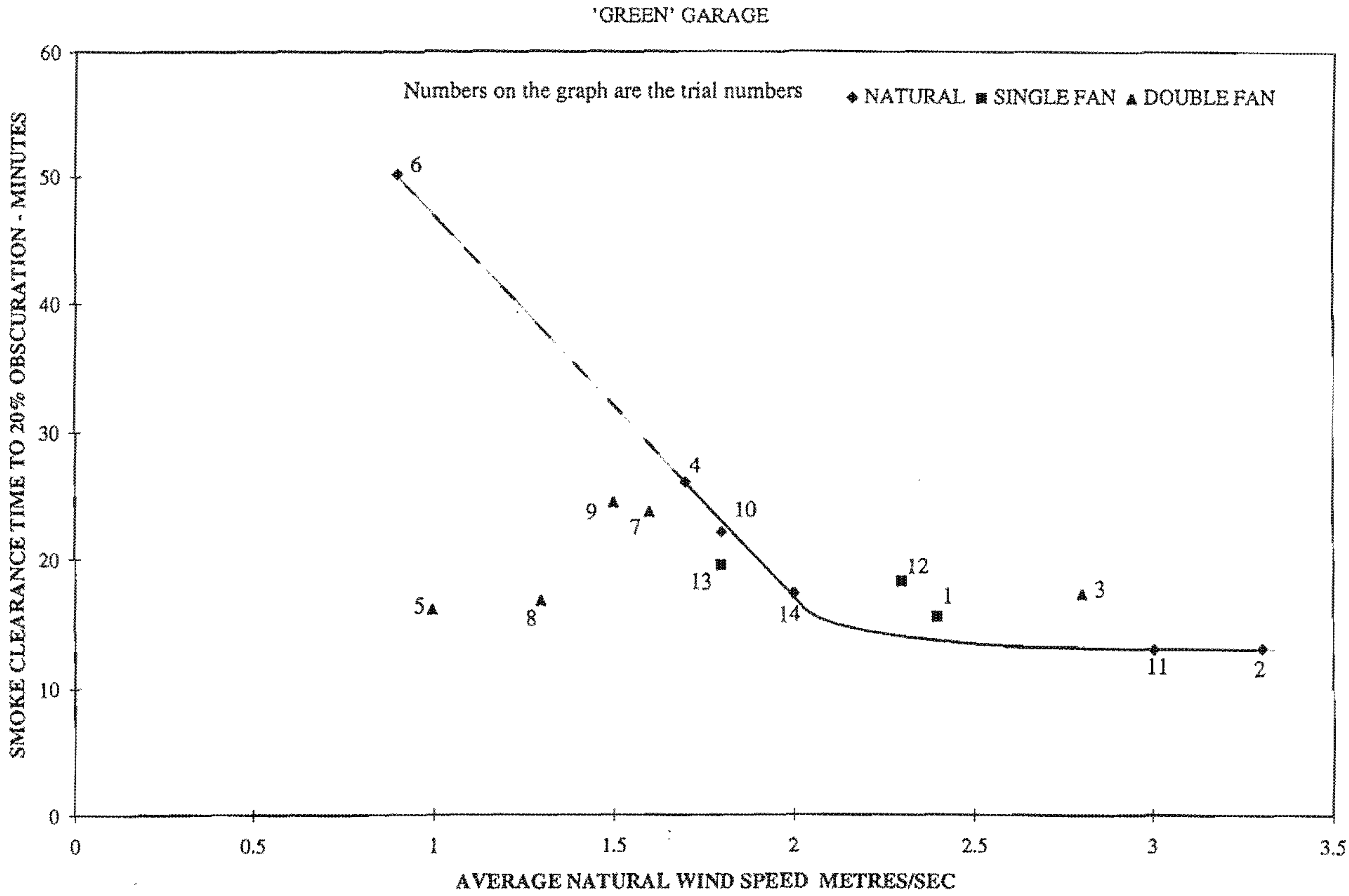


Figure 82. Smoke clearance time, to 20% obscuration Vs average natural wind speed, in the 'green' garage.

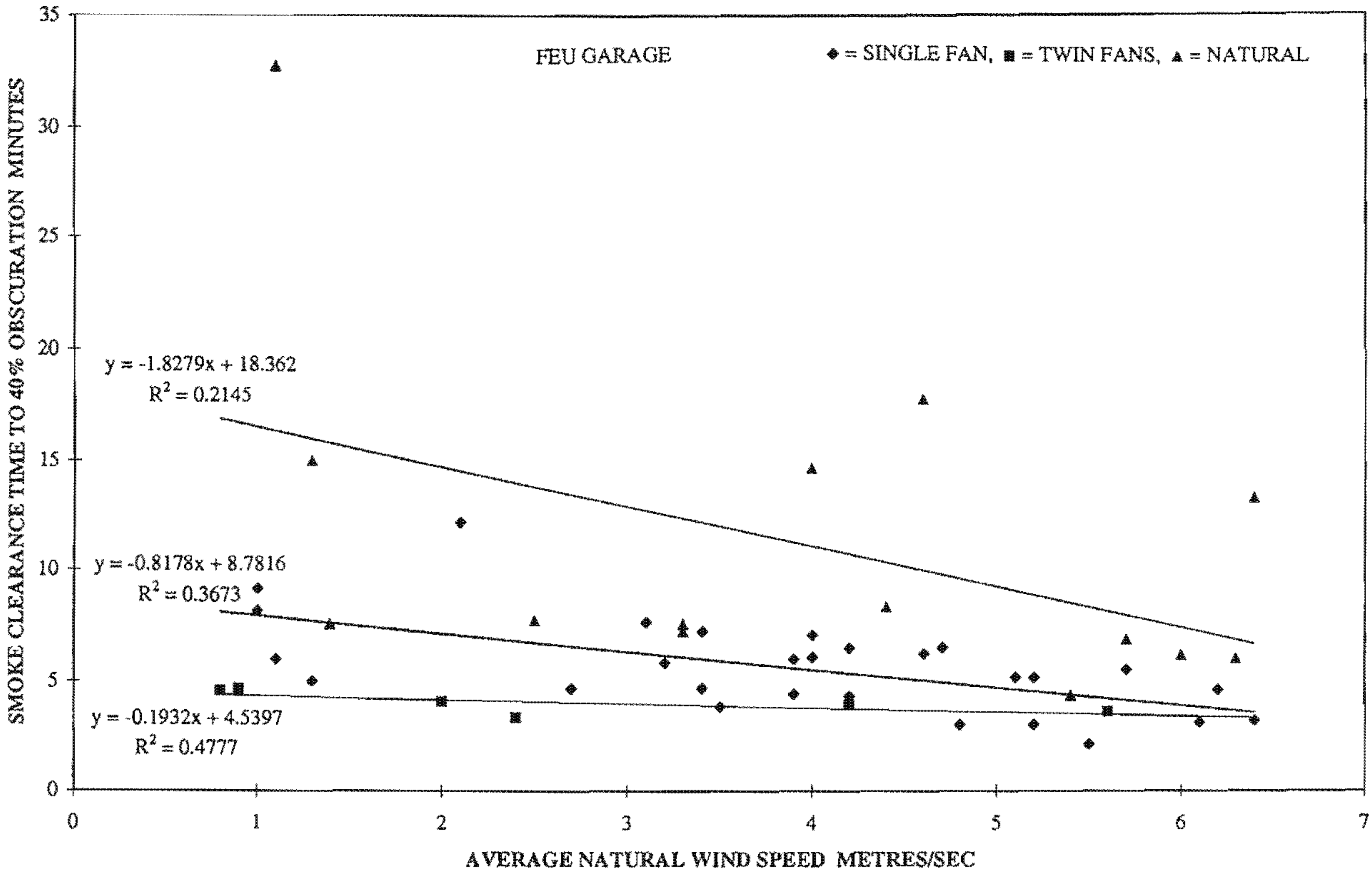


Figure 83. Smoke clearance time to 40% obscuration Vs. average natural wind speed, in the FEU garage.

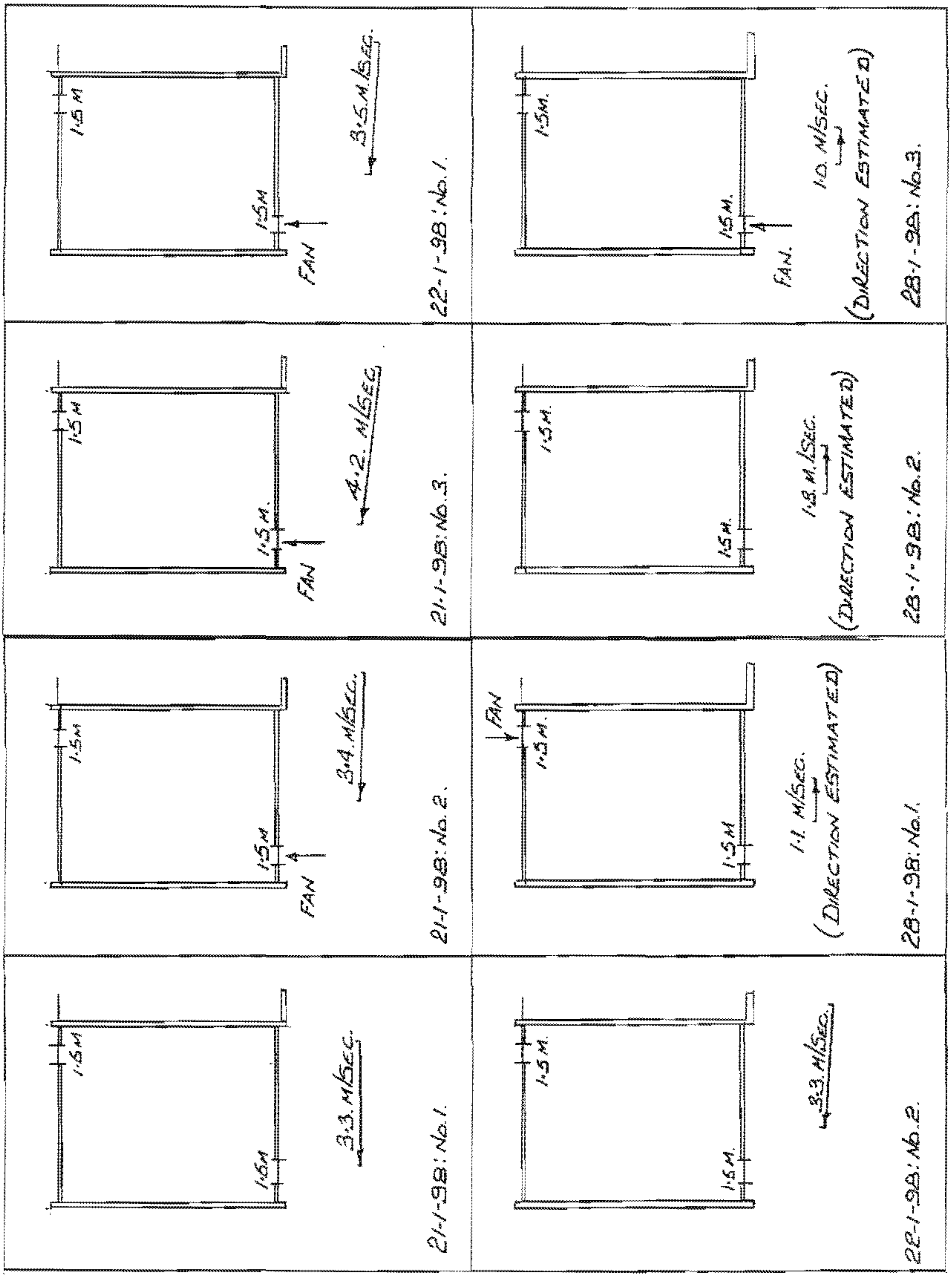


Figure 84. FEU garage trials: sketches showing sizes and orientation of vents, fan position where applicable, and average natural wind: trials 21-1-98 No1 to 28 1 98 No 3 inc.

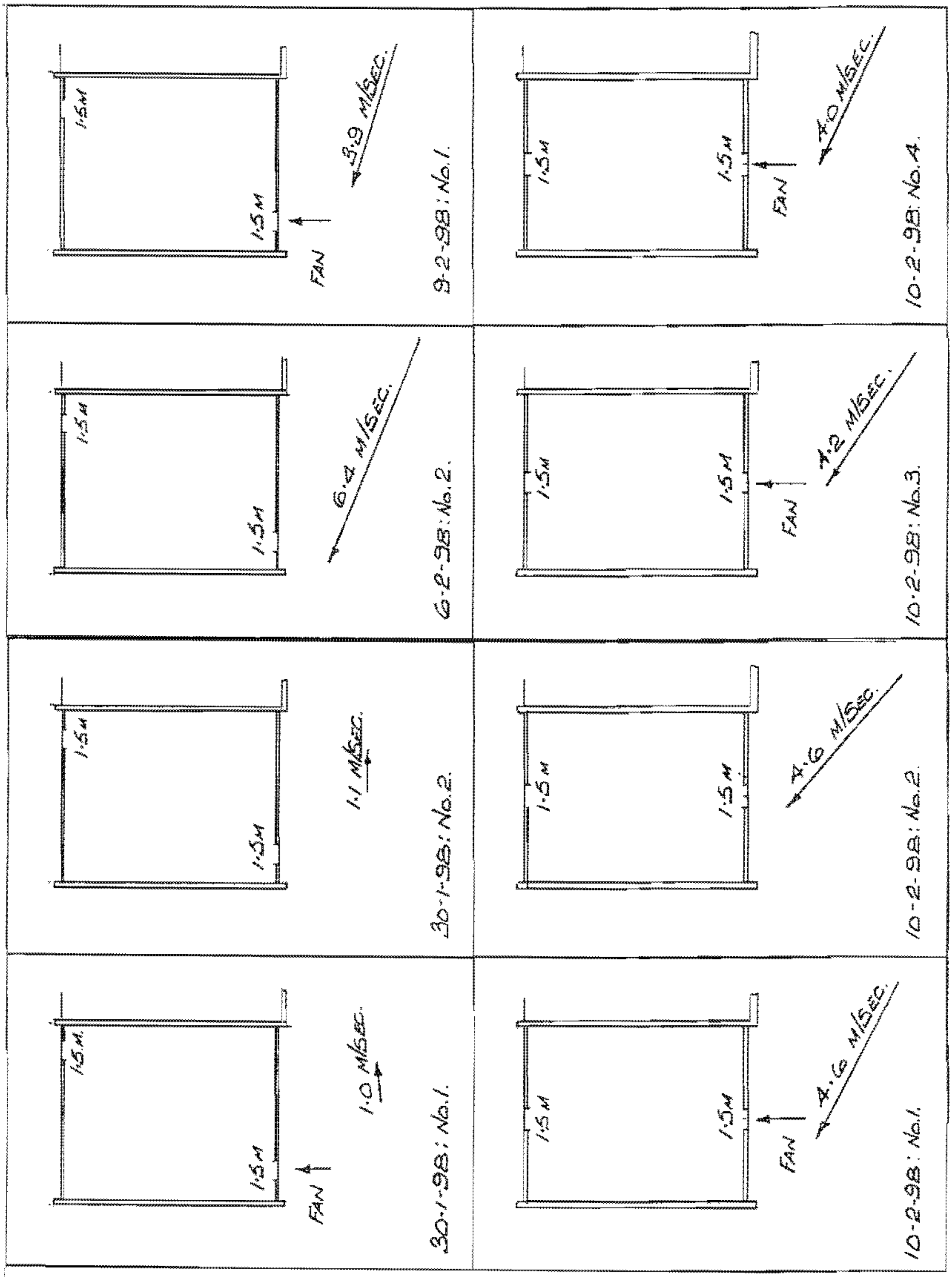


Figure 85. FEU garage trials: sketches showing sizes and orientation of vents, fan position where applicable, and average natural wind: trials 30-1-98 No1 to 10-2-98 No 4 inc.

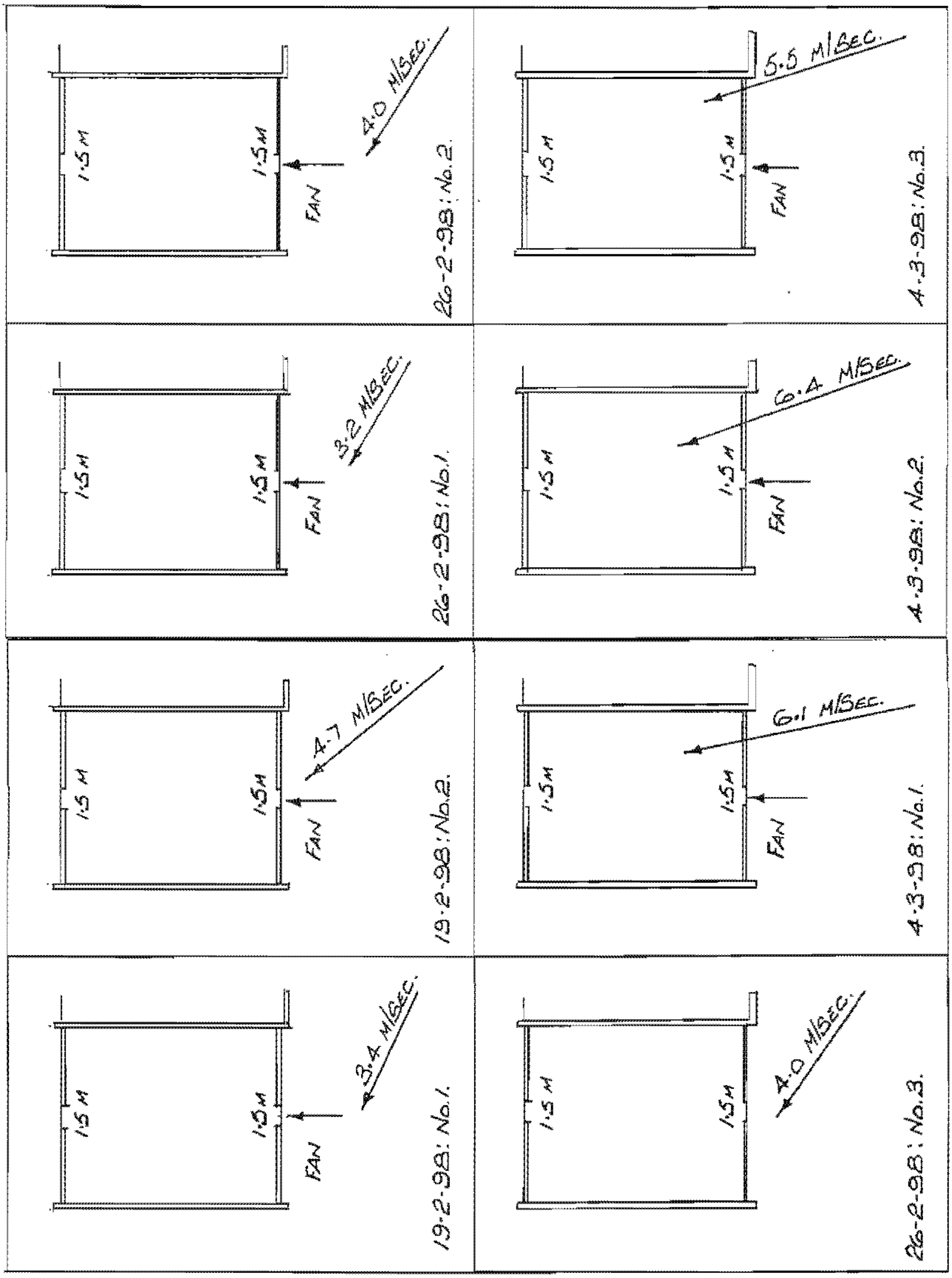


Figure 86. FEU garage trials: sketches showing size and orientation of vents, fan position where applicable, and average natural wind: trials 19-2-98 No1 to 4-3-98 No3 inc.

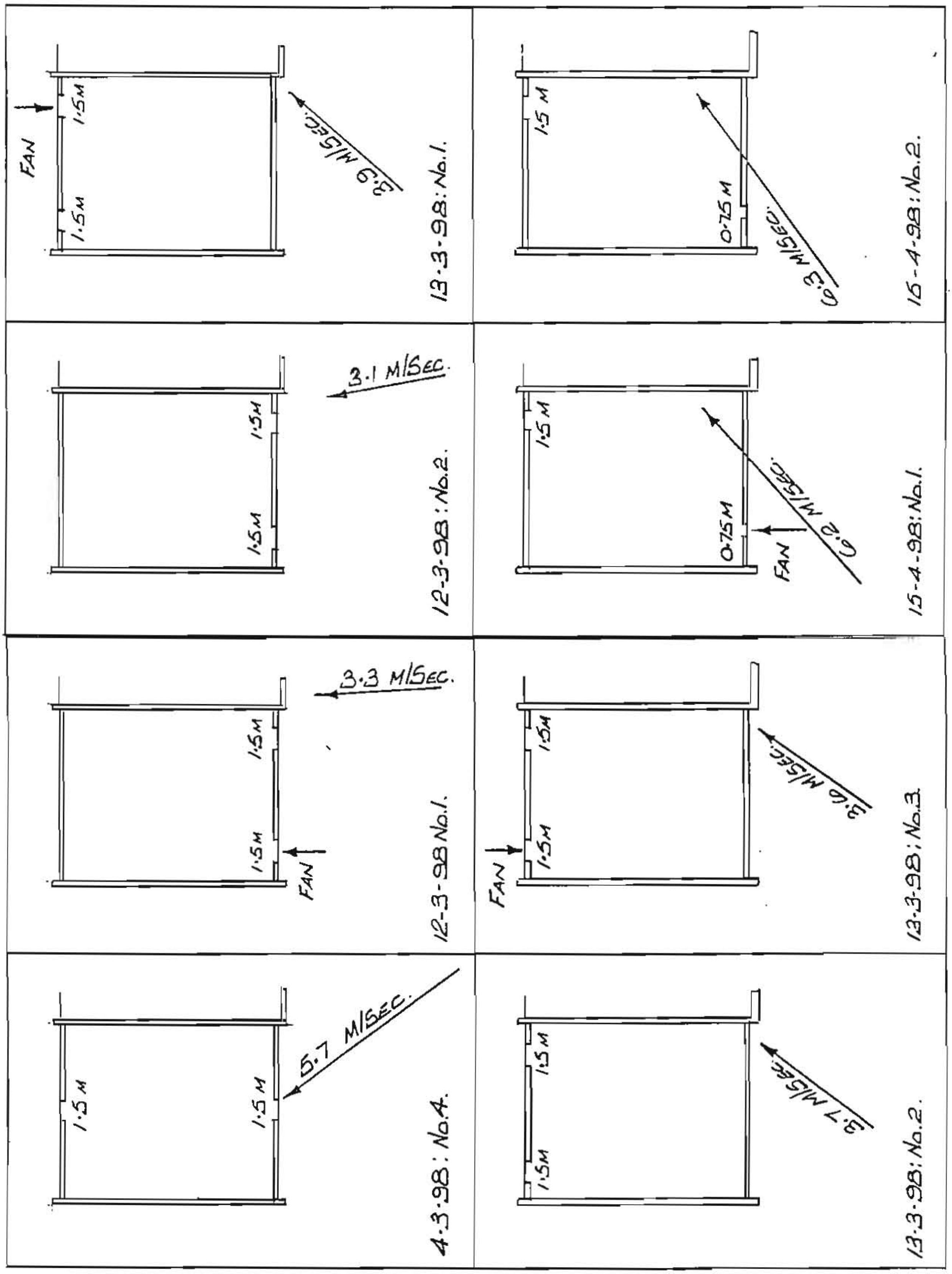


Figure 87. FEU garage trials: sketches showing sizes and orientation of vents, fan position where applicable, and average natural wind: trials 4-3-98 No 4 to 15-4-98 No 2 inc.

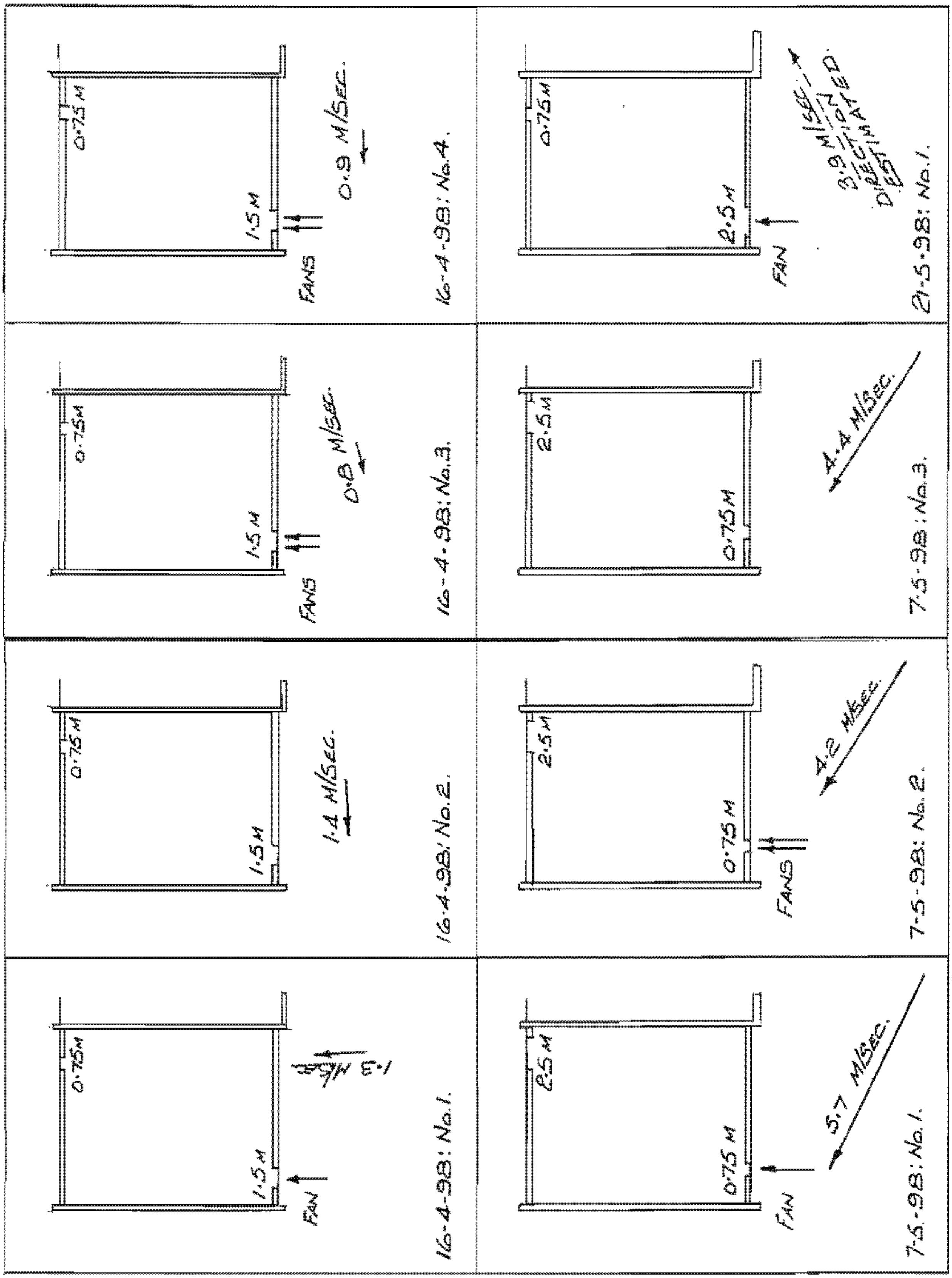


Figure 88. FEU garage trials: sketches showing sizes and orientation of vents, fan position where applicable, and average natural wind: trials 16-4–98 No1 to 21-5-98 No1 inc.

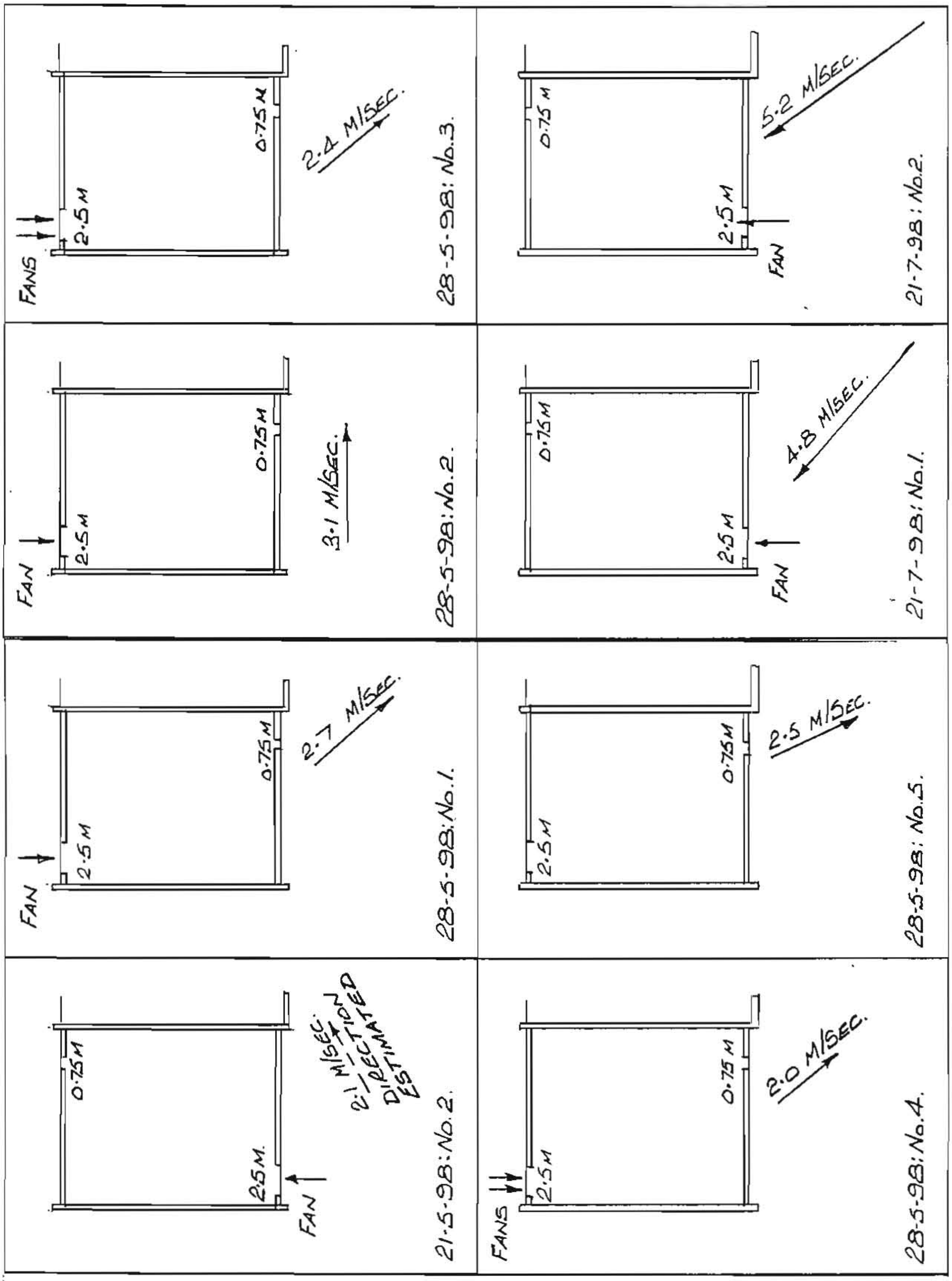


Figure 89. FEU garage trials: sketches showing sizes and orientation of vents, fan position where applicable, and average natural wind: trials 21-5-98 No 2 to 21-7-98 No 2 inc.

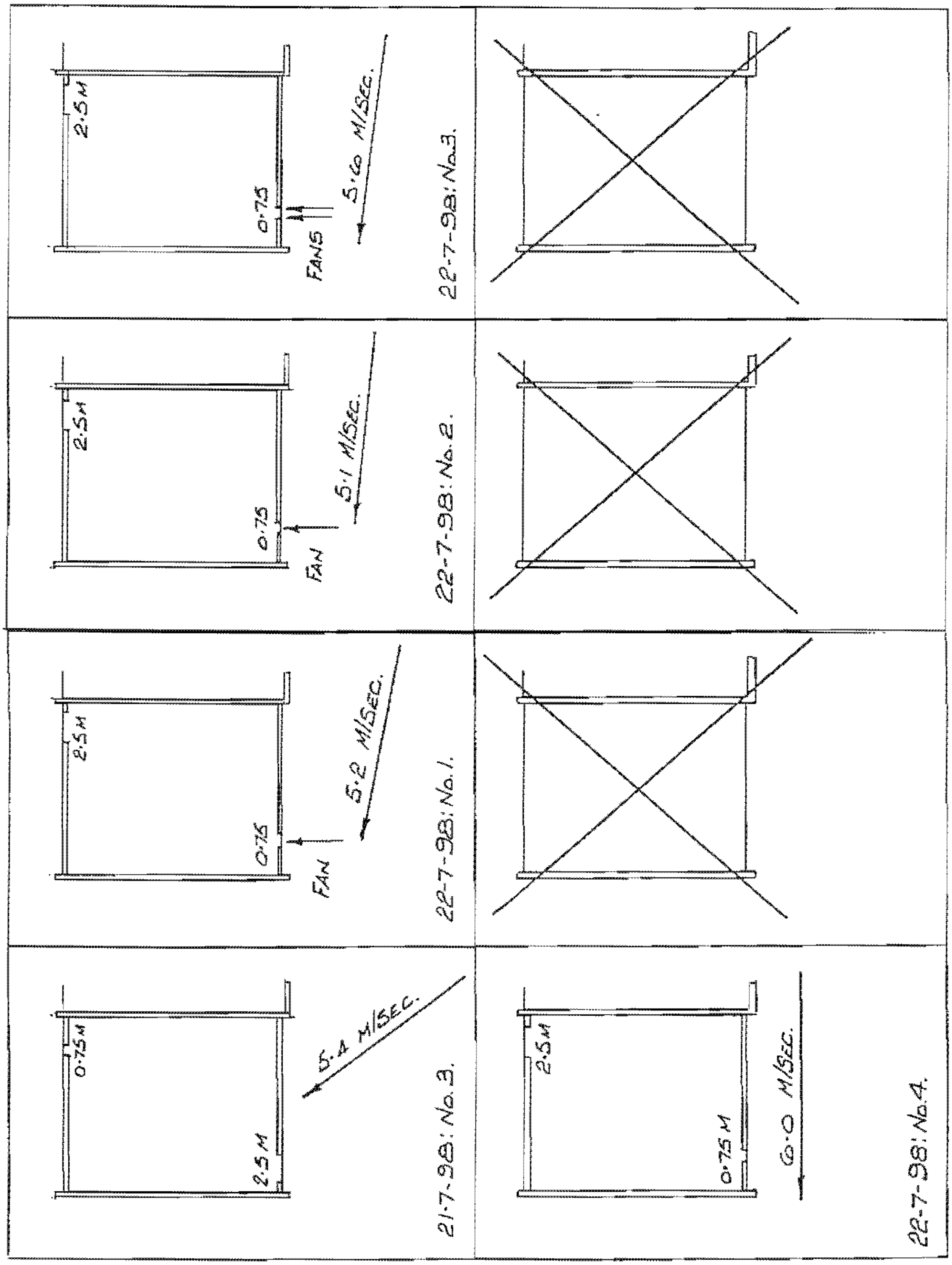


Figure 90. FEU garage trials: sketches showing sizes and orientation of vents, fan position where applicable, and average natural wind: trials 21-7-98 No 3 to 22-7-98 No 4 inc.

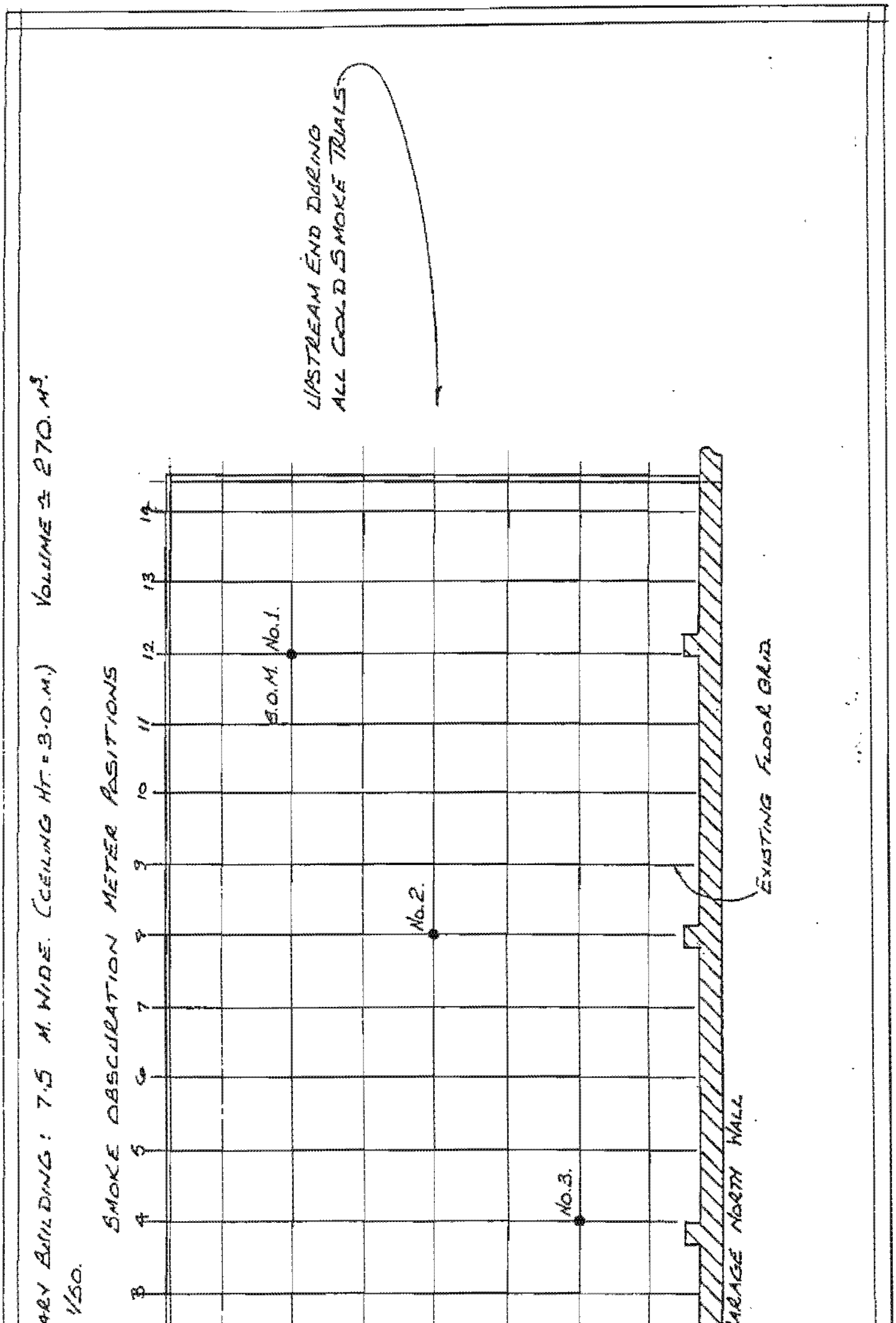


Figure 91. Positions of the smoke obscuration meters in the 7.5 metre wide compartment.

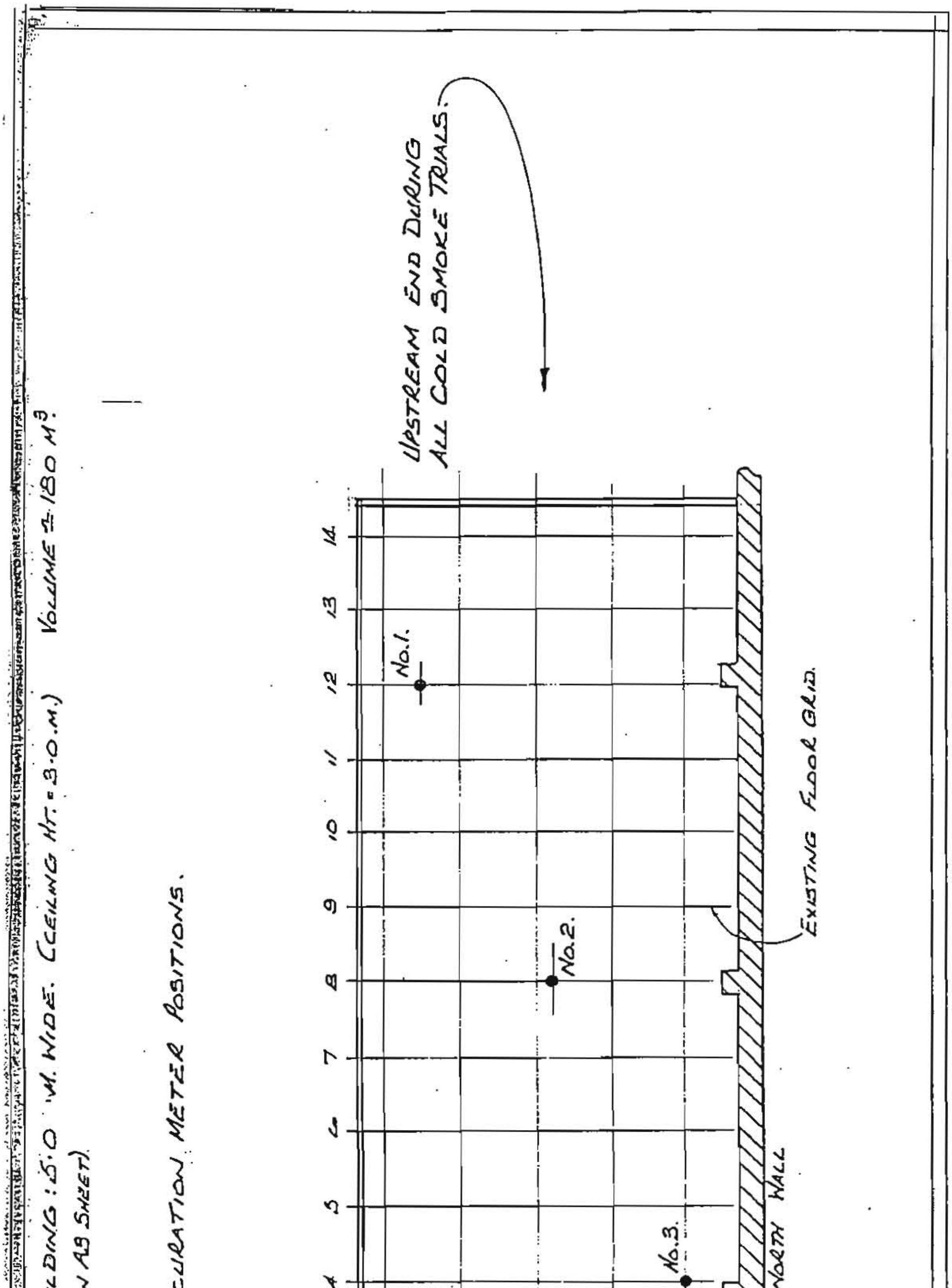


Figure 92. Positions of the smoke obscuration meters in the 5.0 metre wide compartment.

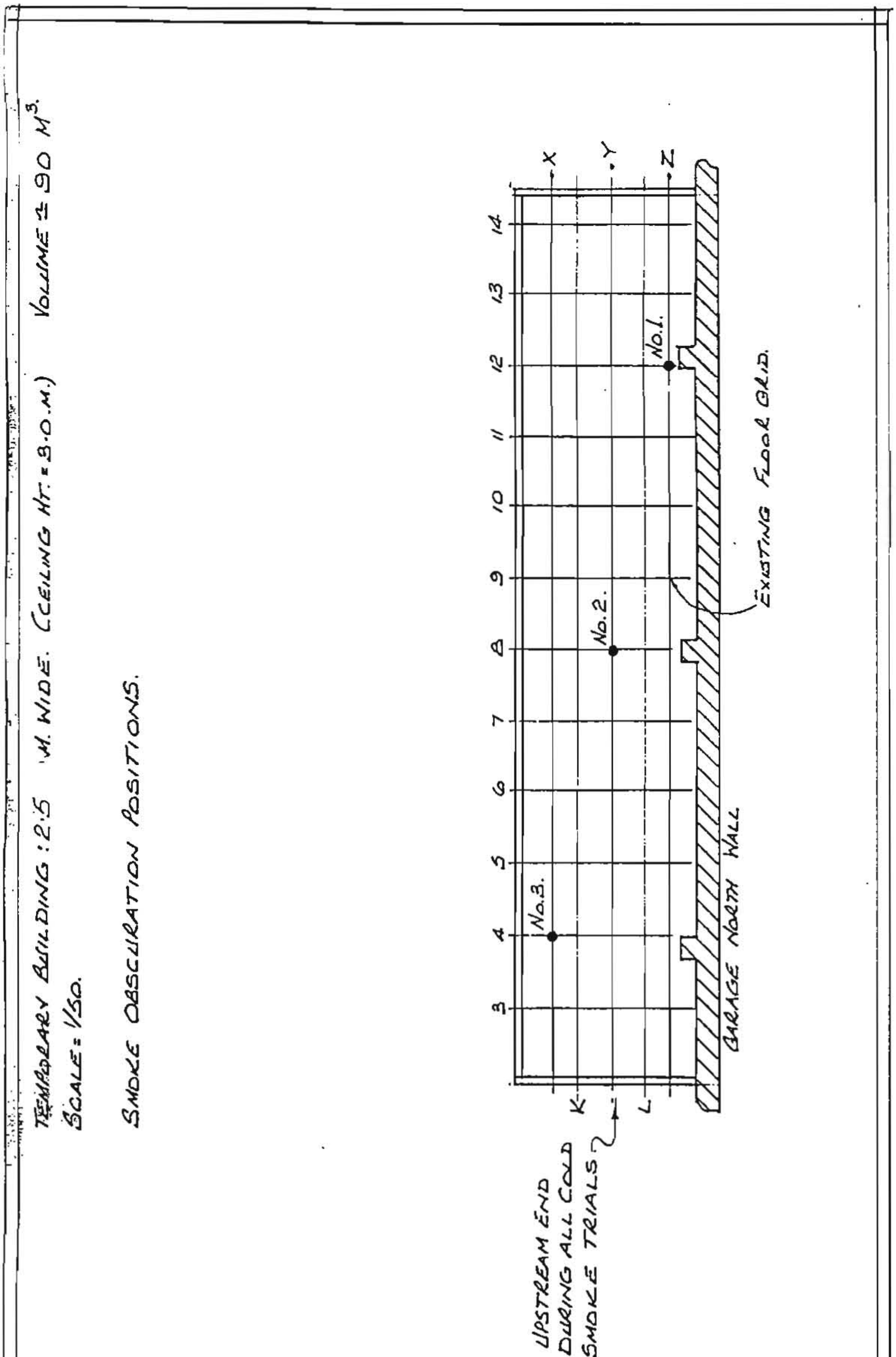


Figure 93. Positions of the smoke obscuration meters in the 2.5 metre wide compartment.

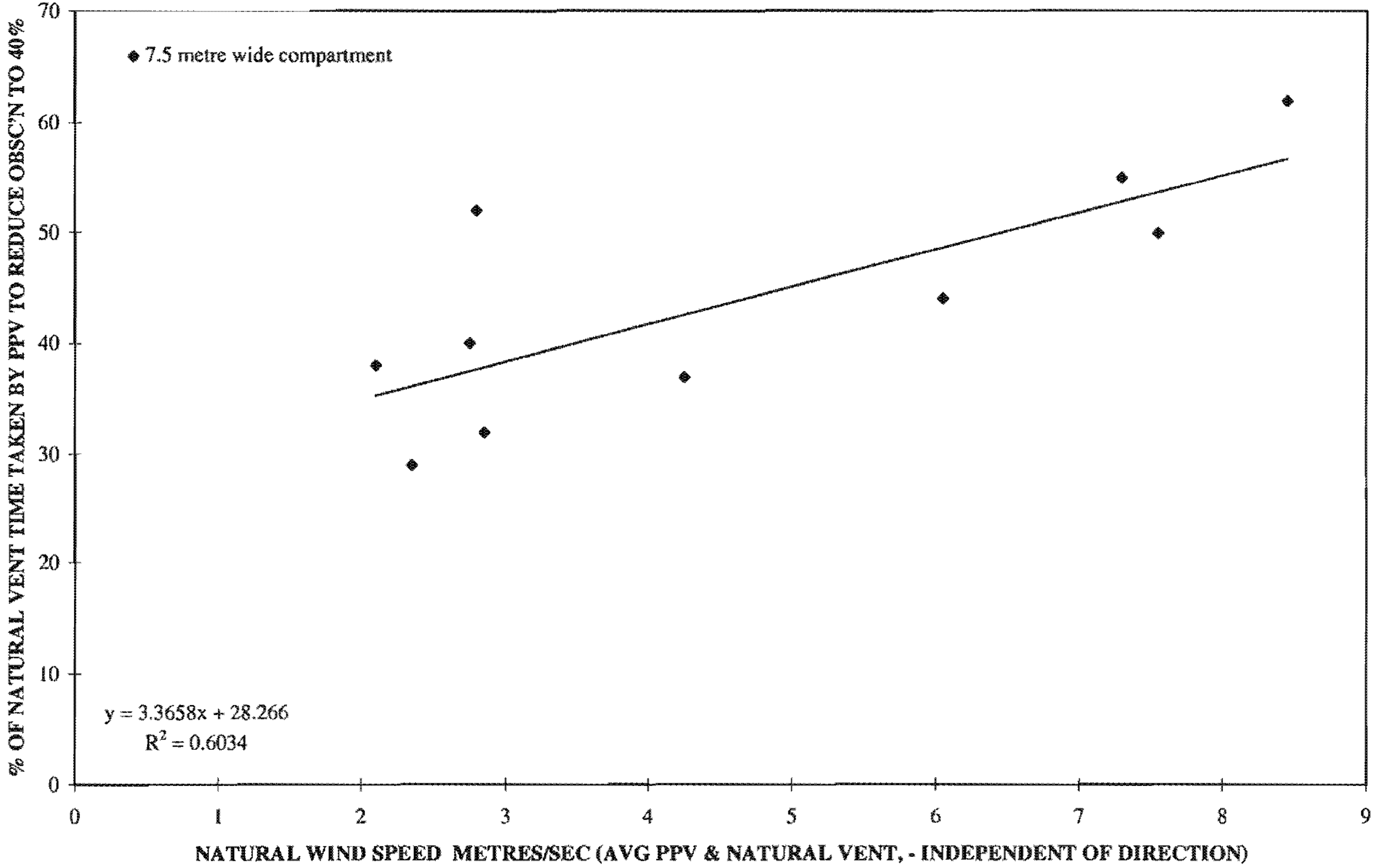


Figure 94. Percentage of natural clearance time (to 40%) taken by PPV plotted against average natural wind speed (PPV and natural ventilation) for 7.5 metres wide compartment.

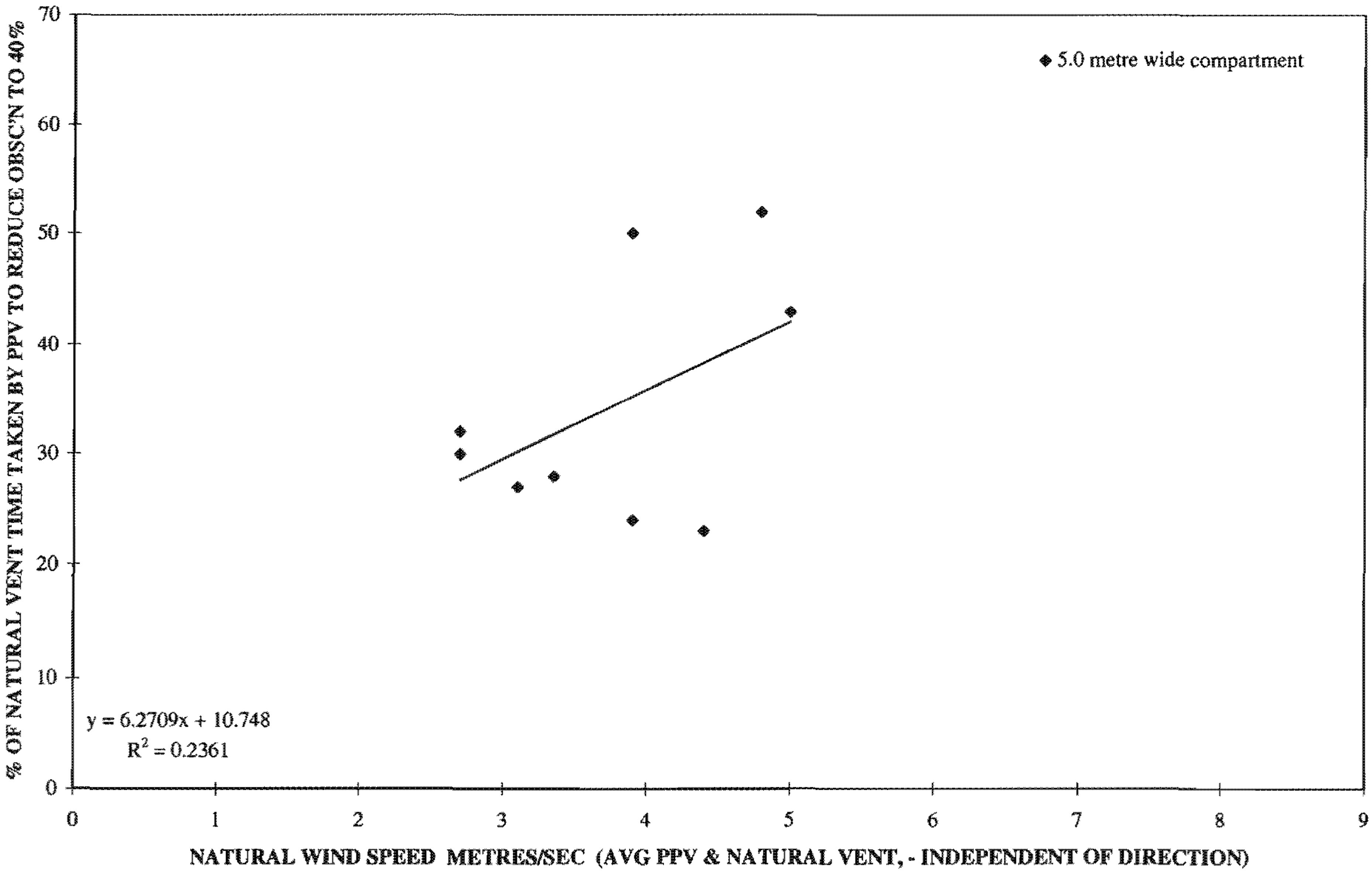


Figure 95. Percentage of natural clearance time (to 40%) taken by PPV ploted against average natural wind speed (PPV and natural ventilation) for 5.0 metres wide compartment.

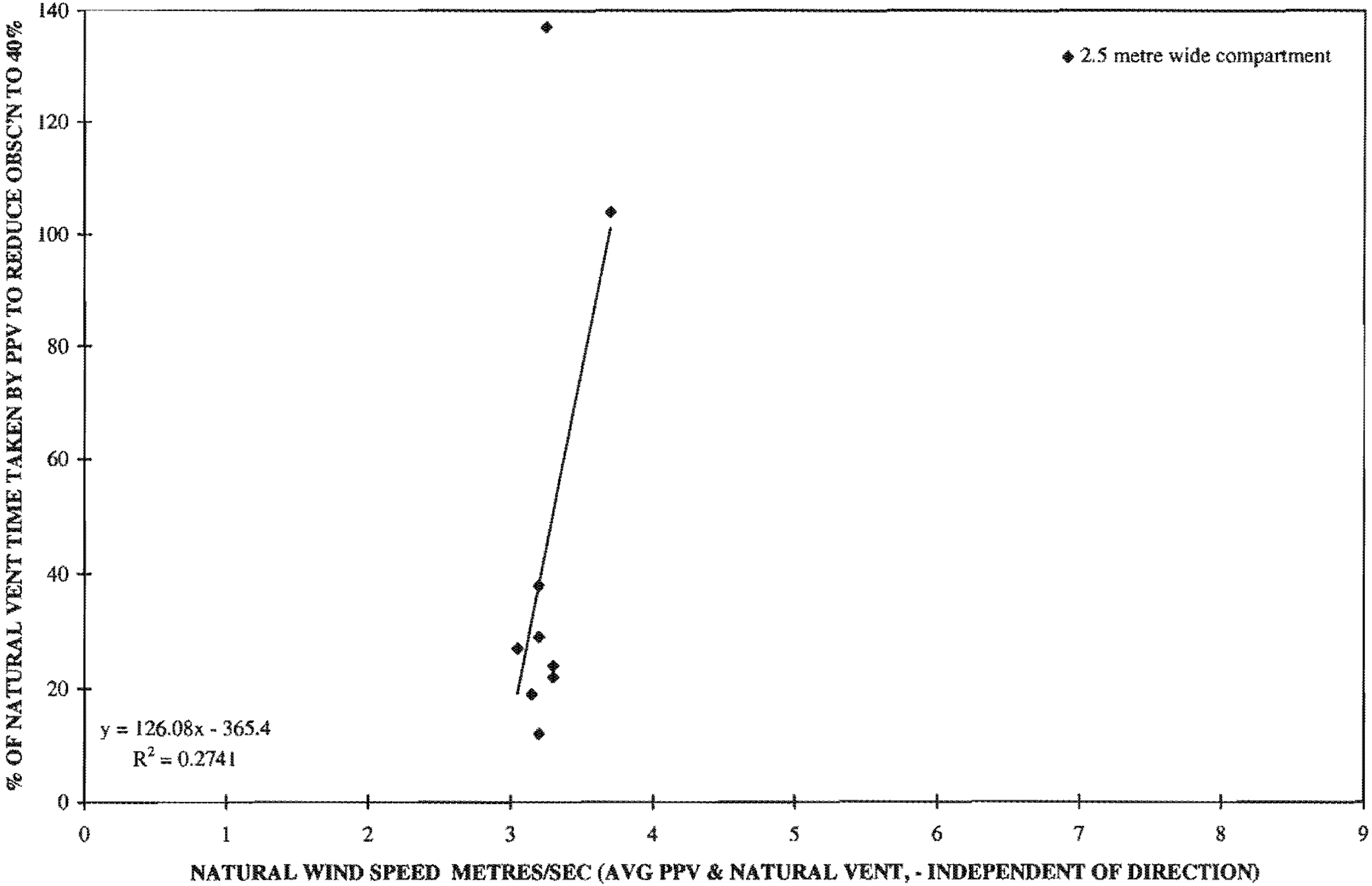


Figure 96. Percentage of natural clearance time (to 40%) taken by PPV plotted against average natural wind speed (PPV and natural ventilation) for 2.5 metres wide compartment.

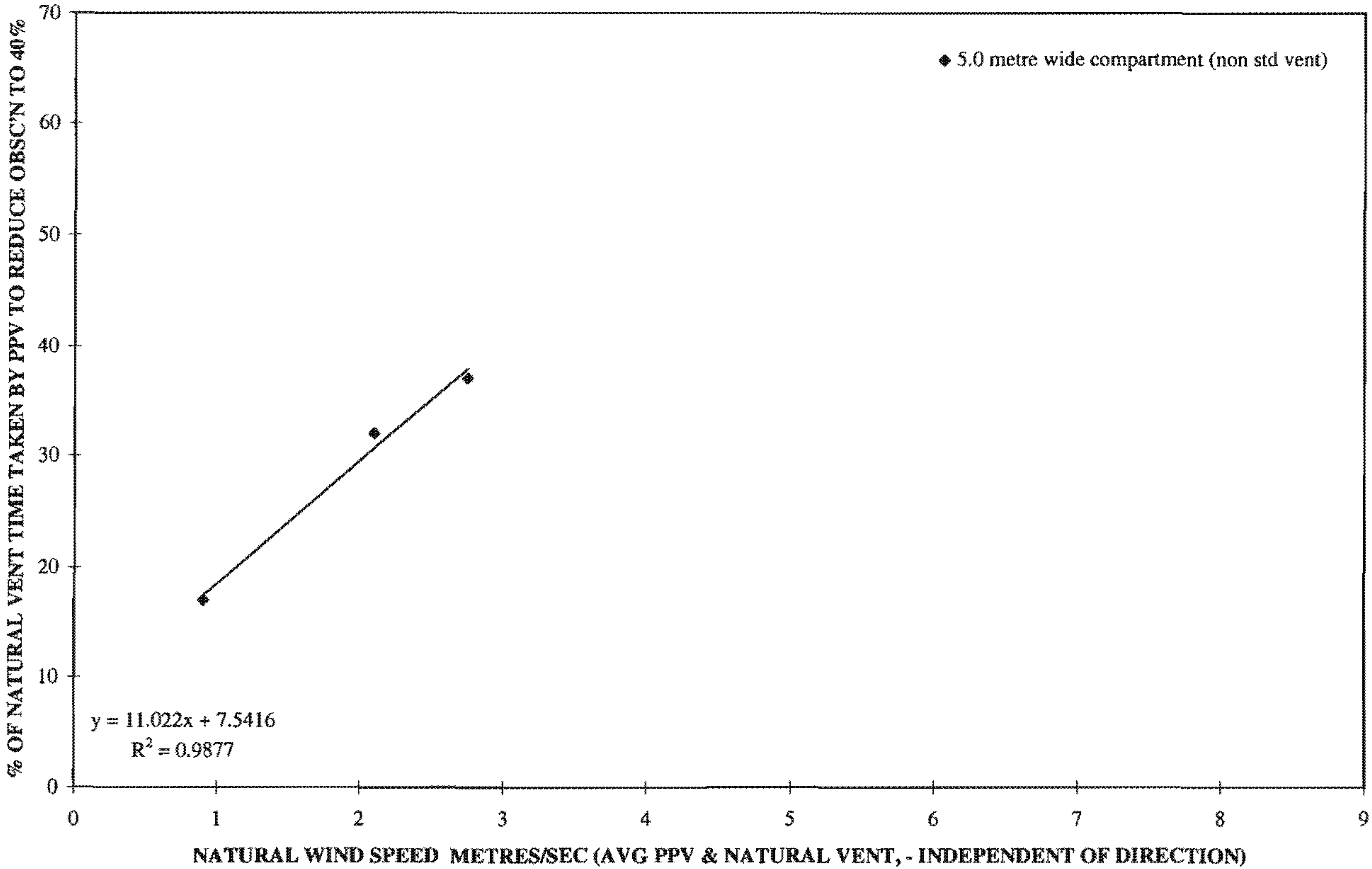


Figure 97. Percentage of natural clearance time (to 40%) taken by PPV plotted against average natural wind speed (PPV and natural ventilation) for "non-standard" vents in the 5.0 metres wide compartment.

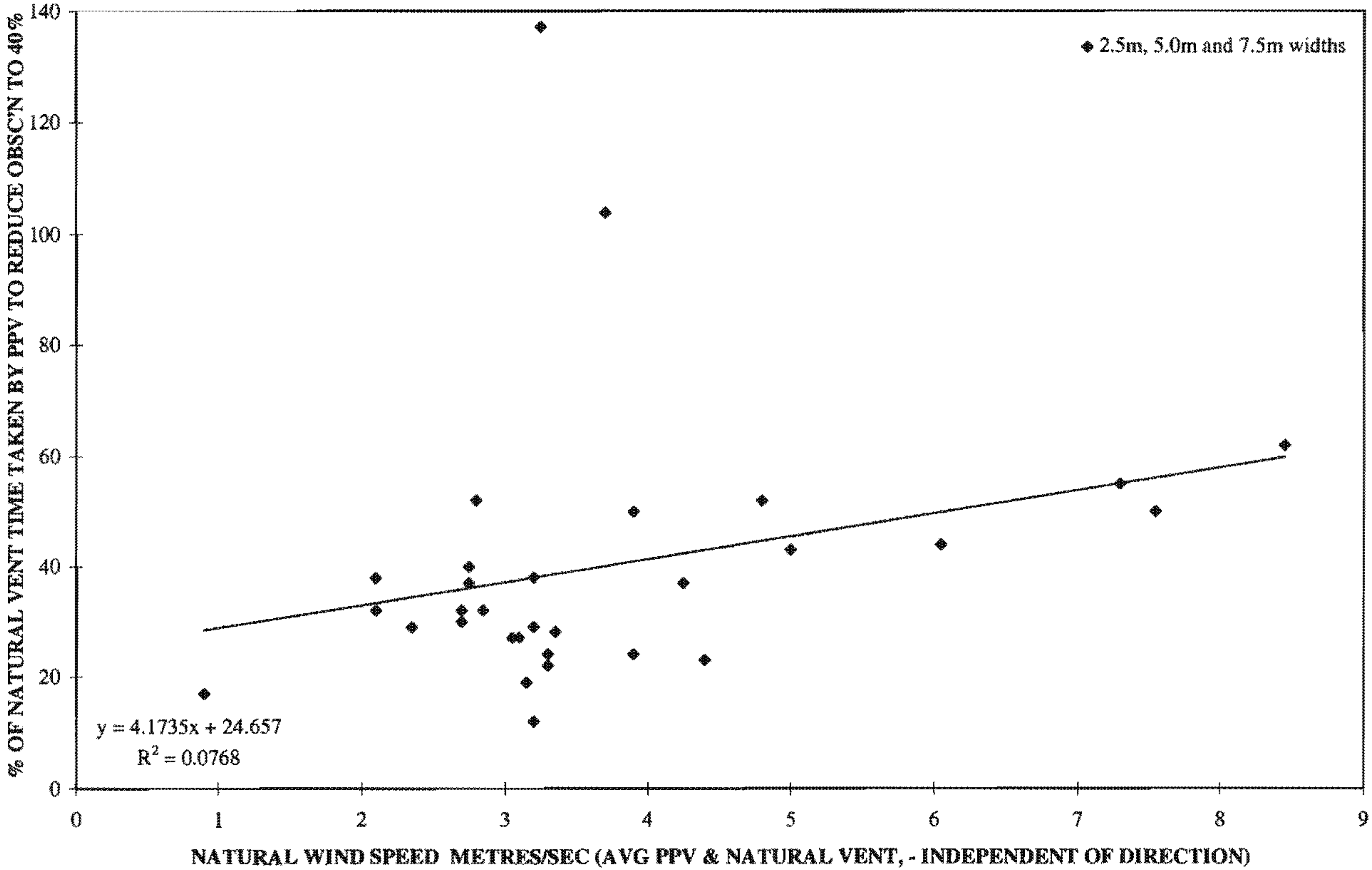


Figure 98. Overall plot of percentage natural clearance time (to 40%) taken by PPV plotted against average natural wind speed (PPV and natural ventilation) for: 7.5, 5.0 and 2.5 metres wide compartments. (Figures 109 to 112 inc. combined)

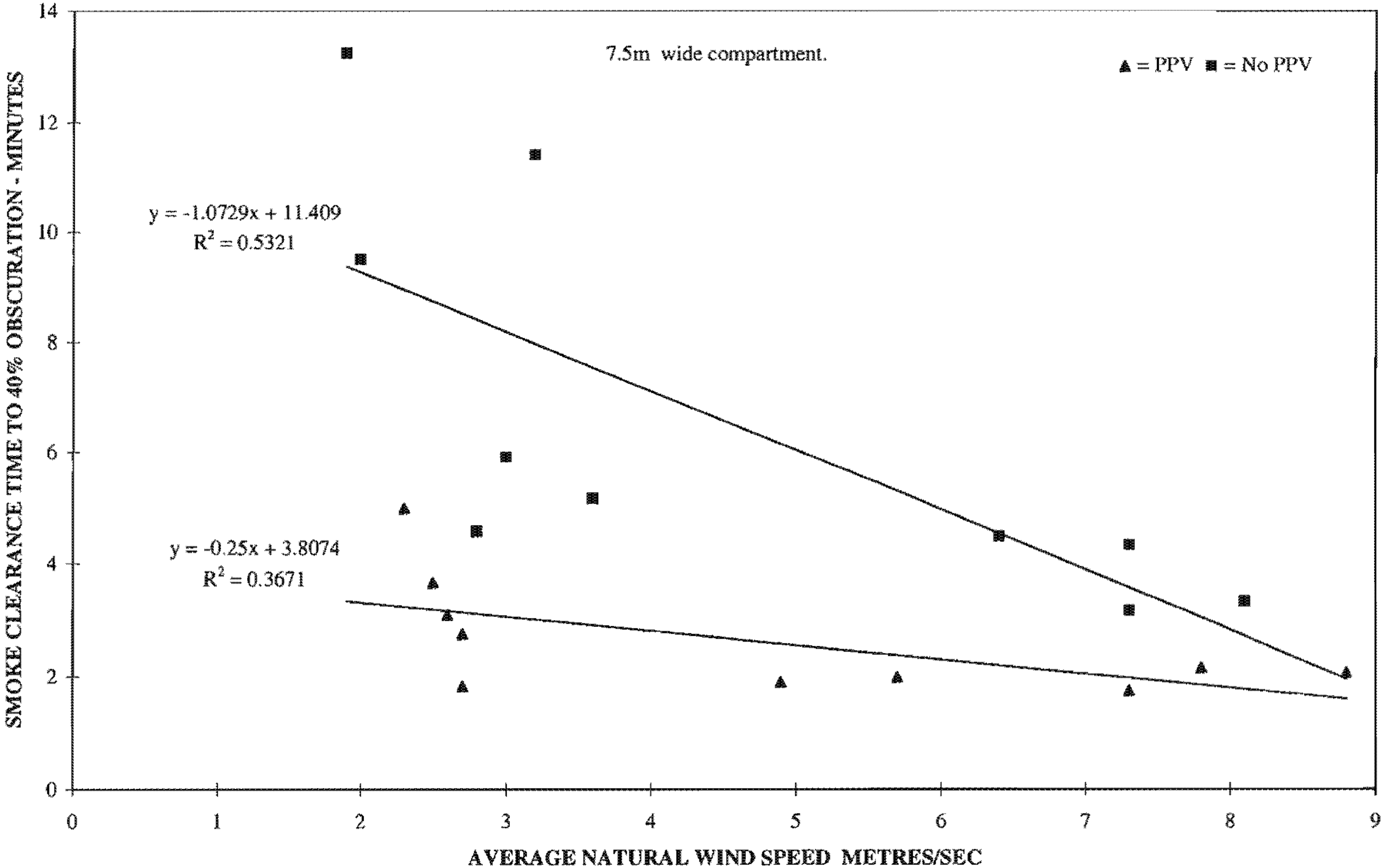


Figure 99.. Smoke clearance time (to 40% obscuration) plotted against average natural wind speed, for 7.5 metres wide compartment.

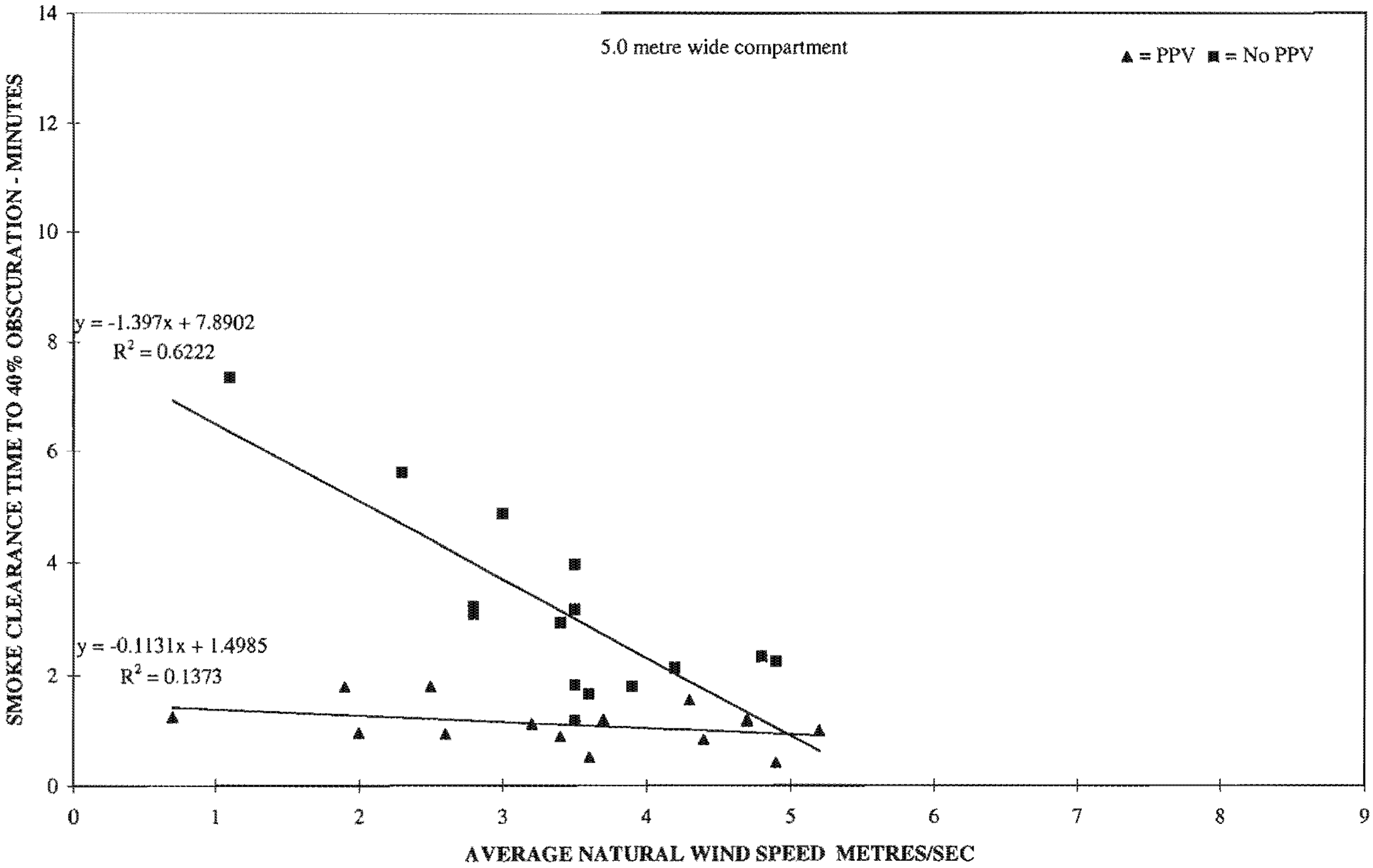


Figure 100. Smoke clearance time (to 40% obscuration) plotted against average natural wind speed, for 5.0 metres wide compartment.

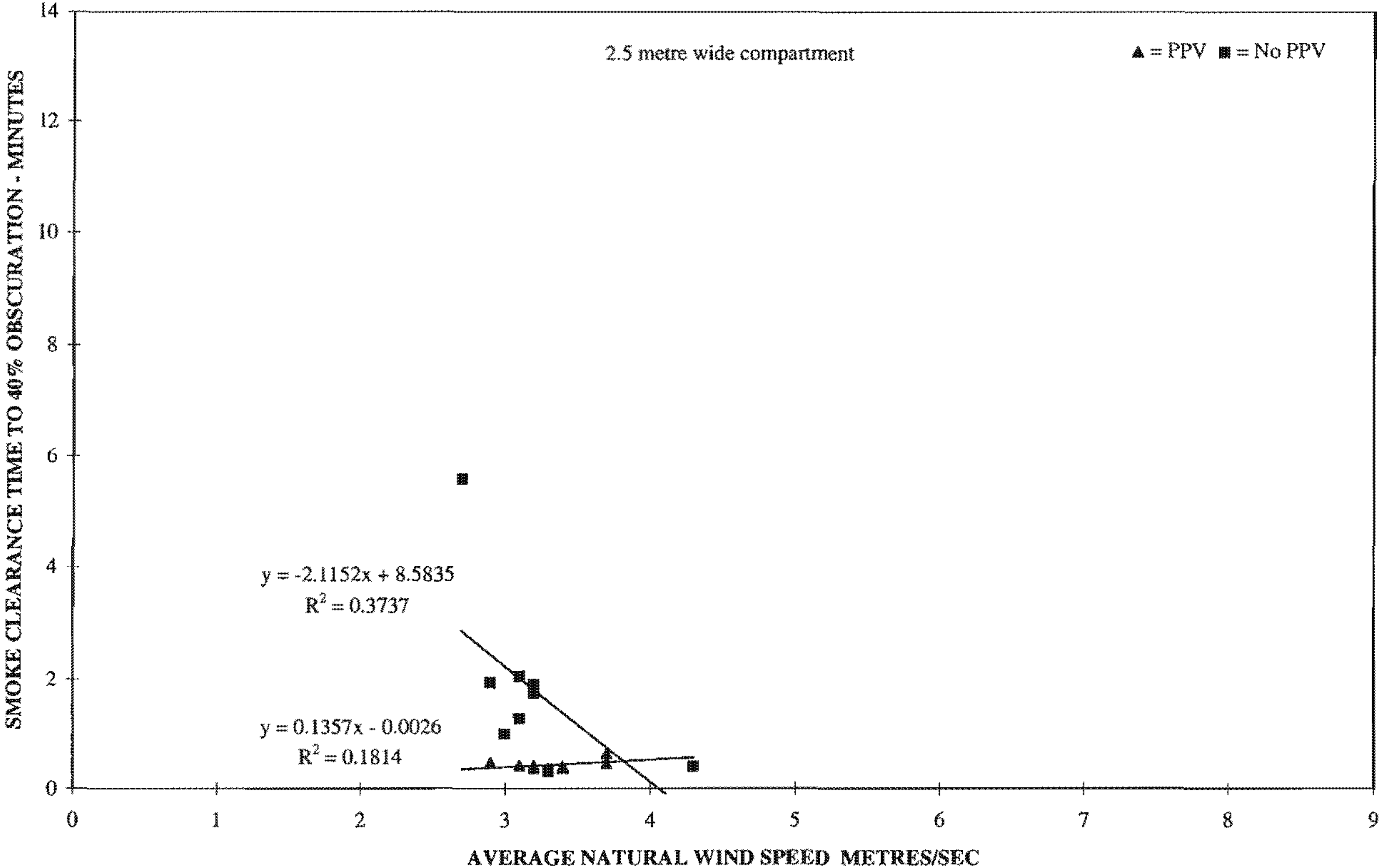


Figure 101. Smoke clearance time (to 40% obscuration) plotted against average natural wind speed, for 2.5 metres wide compartment.

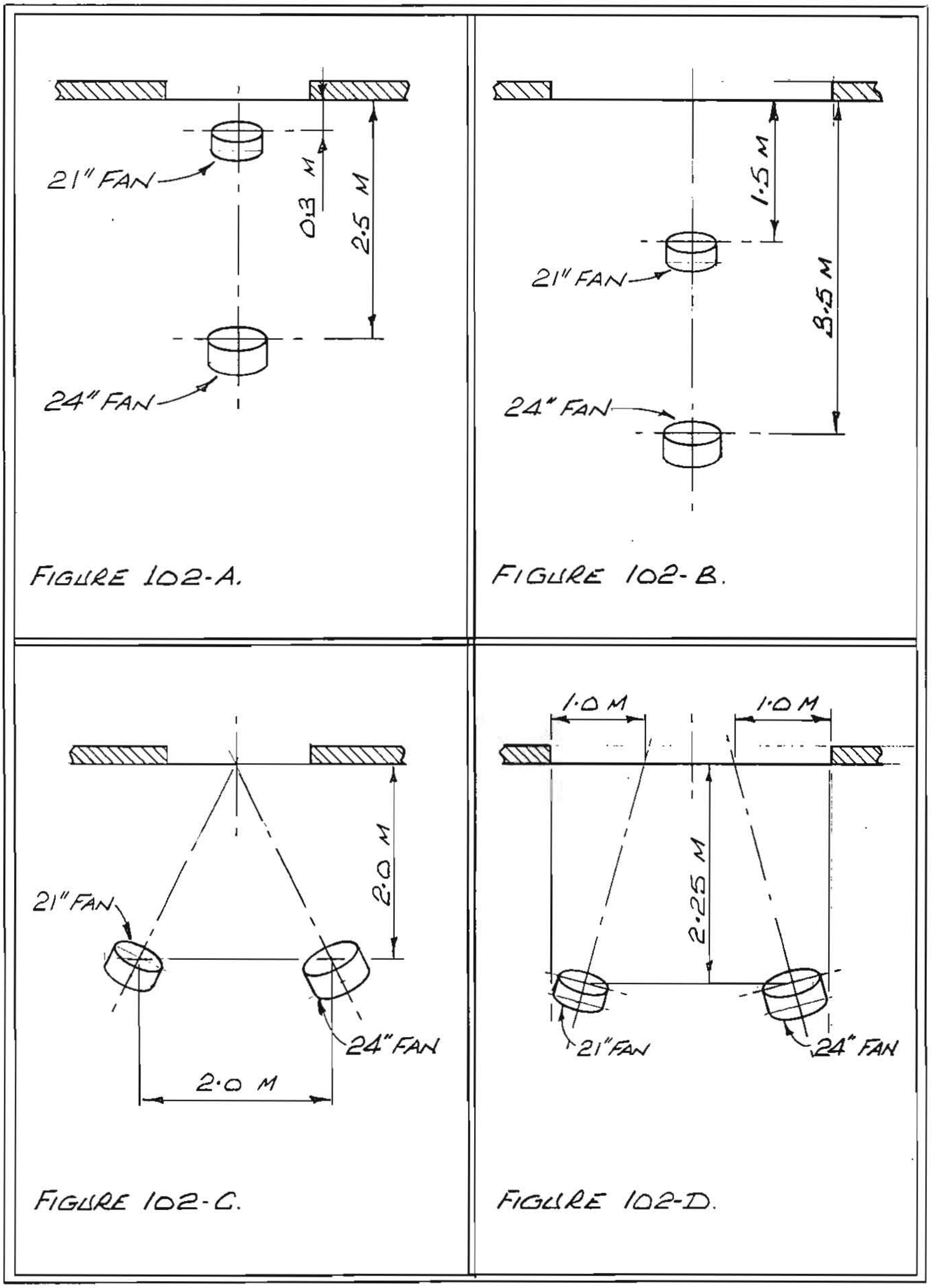


Figure 102. Orientation of fans in specific 'two – fan' trials: (read in conjunction with Table 2).