Smoke Ventilation of Common Access Areas of Flats and Maisonettes Appendix B – Froude Number Scale-Modelling of Smoke Management in a Corridor and Stair using Natural Ventilation and Mechanical Exhaust

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Introduction

As full-scale experiments can be very costly, and analytical solutions not possible, the well established technique of physical, reduced-scale modelling has been used for many years to study smoke movement and control in buildings. The basic principle of reduced-scale modelling is to build a scale model of the geometry and undertake experiments such that various dimensionless numbers, or groups, are preserved at reduced- and full-scales so that the results at reduced-scale can be extrapolated to full-scale. It has found widespread application in wind tunnel studies of the build environment and for vehicle aerodynamics, as well as other application such as smoke movement.

Results from a series of experiments using a 1/5-th scale physical model of a fire compartment, corridor and stairwell were undertaken in parallel to the review (Appendix A), the numerical simulations (Appendices C,D,E and F) and the analytical study of corridor smoke movement (Appendix H). Measures studied included natural smoke venting through external wall vents and smoke shafts and mechanical smoke extraction from the corridor. The rig was adapted from the one used in the previous study of the smoke ventilation of firefighting shafts [Harrison & Miles, 2002].

Physical modelling and scaling relationships

The main physical processes associated with smoke movement can be described by an equation of state and conservation equations for mass, momentum and energy. These can be expressed in terms of dimensionless variables for position, velocity, pressure, density, temperature etc, e.g. dimensionless position (distance), $\hat{x}$, is defined as *x/l*, where *x* is the position at the real-life (full) scale and *l* is a characteristic length (the scale factor). Rewriting the equation of state and conservation equations in terms of the dimensionless variables yields a new set of equations, with nine dimensionless variables and nine, additional, dimensionless groups (or numbers). In order to exactly scale results from reduced-scale to full-scale it would be necessary to preserve all the dimensionless numbers. In practice this is not possible, and so for a given type of experiment it is necessary to preserve those groups which are most important. Details of the formulation of the dimensionless form of the governing equations and the associated dimensionless variables and groups may be found elsewhere, see, for example, [Klote & Milke, 2002].

For smoke movement applications, Froude modelling is often used. Here the Froude number, F_r, is preserved at both reduced- and full-scales, and is defined as,

$$F_r = \frac{U^2}{gl} \tag{B1}$$

where *U* is the characteristic velocity and *g* the acceleration due to gravity. With Froude modelling the Reynolds number (another dimensionless group) is not preserved, which is a reasonable approximation provided the flow is turbulent at both scales. Furthermore, three heat transfer dimensionless groups are also not preserved, which means that heat transfer to the solid boundaries at full-scale cannot be derived from the reduced-scale experiments.

Froude modelling allows position (distance) (*x*), time (*t*), velocity (*u*), temperature (*T*), convective heat release rate ($\dot{Q}_c$), mass flow ($\dot{m}$), volume flow ($\dot{V}$) and pressure difference (Δp) to be translated (scaled) from the reduced-scale experiment to full-scale according to the following scaling relations, where $L=(l_{full}/l_{mod})$ is the ratio of length scale at full and model scales and the subscripts *full* and *mod* refer to full and modelled (reduced) scale respectively,

$$x_{full} = x_{\mathrm{mod}} L \tag{B2}$$

$$t_{full} = t_{\mathrm{mod}} L^{1/2} \tag{B3}$$

$$u_{full} = u_{\mathrm{mod}} L^{1/2} \tag{B4}$$

$$T_{full} = T_{\mathrm{mod}} \tag{B5}$$

$$\dot{Q}_{c,full} = \dot{Q}_{c,\mathrm{mod}} L^{5/2} \qquad \text{(B6)}$$

$$\dot{m}_{full} = \dot{m}_{\mathrm{mod}} L^{5/2} \qquad \text{(B7)}$$

$$\dot{V}_{full} = \dot{V}_{\mathrm{mod}} L^{5/2} \qquad \text{(B8)}$$

$$\Delta p_{full} = \Delta p_{\mathrm{mod}} L \qquad \text{(B9)}$$

Provided the flow in the model is, to a good approximation, fully turbulent and that heat looses to the boundaries are only a secondary mechanism, then the results from the 1/5-th scale experiments can be translated to full-scale by the above relationships. Furthermore, the important parameters required in the design and analysis of the various smoke management schemes are all included in the list above.

While the dimensionless heat transfer groups are not preserved in Froude modelling, some processes can nonetheless be partly preserved. If the solid surfaces are considered to be semi-infinite, then the thermal inertia can be scaled as follows,

$$(k\rho c)_{full} = (k\rho c)_{\mathrm{mod}} L^{0.9} \qquad \text{(B10)}$$

where k,ρ,c are the thermal conductivity, density and specific heat of the solid material respectively.

Description of the 1/5-th scale rig

The model, representing a six-storey building containing a fire compartment (representing a dwelling), a lobby or corridor and a stairwell, consisted essentially of steel frames with ceramic fibre, plywood and Perspex sheets attached.

It was designed to meet established scaling principles, effectively modified Froude Number scaling, requiring that the equivalent flows are fully turbulent at both full- and model-scale. This required that the significant flows should have Reynolds numbers $\geq$ 3000. Dimensional relationships between fluid dynamic variables can be derived from first principles. These relationships can be simplified by holding one of the variables constant, to then derive the so-called scaling laws, described above. For the current study it was appropriate to keep the temperature equal at both full- and model-scale.

The physical modelling study examined four geometric scenarios, namely:

(1) corridor,

(2) corridor and stairwell,

(3) lobby and stairwell,

(4) compartment opening directly onto stairwell.

Each scenario included an adjoining fire compartment, in which a methylated spirits fire was located. The fuel was supplied at a controlled rate via a calibrated flow meter, and burned in a 0.2 m by 0.2 m (at model scale) tray. A single fire size was used, representing in 0.18 MW at full-scale. The above four scenarios examined in this study are shown in Figures B1,B2, B3 and B4 respectively.

Smoke management methods studied included two sizes of smoke shaft, using both mechanical and natural extraction, and different size of ventilation and inlet openings.

The main parameters monitored were buoyant layer depth, visibility, gas temperature and velocity. Visual measurements using artificial smoke were also carried out. Each experiment, or run, was conducted for 10 minutes to ensure that a steady state condition had been reached, after which time the measurements were taken.

Following a short description of the instrumentation and main measurement parameters, some specific information about the runs performed with the four scenarios is provided below in separate sections. This is then followed by a section discussing the overall findings from the physical modelling study.

Instrumentation

Table B1 lists the instruments used in this study. The model was instrumented throughout with thermocouples, carbon dioxide sample probes and pitot tubes to obtain temperatures, visibility and velocity measurements respectively at the specific locations shown in Figures B1 to B4.

The carbon dioxide sample probes in the corridor were located 220 mm below the ceiling. The pitot tubes (i.e. velocity probes) were located 30 mm below the ceiling.

A total of five thermocouple columns were located within the corridor as indicated in the diagram, including one just inside the compartment door opening. Each column contained 10 chrome/alumel thermocouple junctions spaced non-linearly along the column.

The hot gases released from the fire compartment were highlighted with smoke from a commercial smoke generator. The smoke was injected into the rear of the compartment in order to mix with the hot gases entering the corridor. This allowed detailed visual observations to made of the gases as they moved through the model.

It should be noted that instrument measurements, particularly of the CO_2 concentrations, were carried out separately. This was to avoid any CO_2 produced by the smoke generator interfering with the gas measurements.

Visibility

Visibility was calculated from the concentration of CO_2 above ambient in the compartment and the corridor, and was defined by the following expression:

$$V_c = 1.44D^{-0.76} \qquad \text{(B11)}$$

Where:
$D = (D_c C_c T_f) / (C_f T_c)$
C is the carbon dioxide concentration above ambient
T is the absolute temperature in ^{O}K
D is the optical density
D_c is taken to be a worse case optical density taken to be 10

Subscripts:
c indicates a variable in the corridor
f indicates a variable in the fire compartment

Note that the CO_2 concentration measured in the compartment was taken just below the ceiling before it entered the corridor.

The CO_2 in the corridor was measured at 220 mm below the ceiling (i.e. 1.1m at full-scale). It follows that the visibility values shown in the result table are for that depth below the corridor ceiling.

Buoyant gas layer depth

This is the depth of an equivalent homogeneous layer having a temperature equal to the maximum temperature in the real layer (as defined from the thermocouple column) and exerting the same buoyant pressure on the ceiling as the real layer.

Physical modelling of Scenario 1 - corridor only

Model details

The modelled geometry consisted of a compartment opening onto the side of the corridor at one end, as shown in Figure B1. The corridor had the provision for openings at both ends, corresponding to full-scale dimensions of up to 1.5 m wide by 2 m high. The corridor was, at full-scale, 17.5 m long, 2.2 m high and 2.1 m in wide. The compartment door opening onto the corridor corresponded to a 'door gap' opening of 200 mm at full-scale.

Two sizes of smoke shaft, with full-scale cross-sectional areas of 1.5 m^2 and 3 m^2, were positioned at either one or both ends of the corridor.

Scenario 1 - initial study

Note that in Table B2, Runs (test numbers) 1 to 15, referred to below, correspond to the information in the tables in an earlier progress report [Miles, 2004d].

A finding from this initial study was that for this configuration an average visibility of about 2.4 m was achieved with both vents open directly to the outside. Closure of either vent caused a reduction in visibility as expected. The lowest visibility was achieved when it was the remote vent that was closed, which reduced the visibility to 0.28 m (Run 3).

Attaching a smoke shaft to the remote vent did not improve the visibility (which was achieved in the vent only case in Run 1). The optimum visibility inside the corridor, when using a smoke shaft at the remote end of the corridor, was achieved when the inlet to the shaft was open, producing a visibility of 1.25 m (Run 4) and 1.43 m (Run 6) for the 1.5 m^2 and 3 m^2 shafts respectively.

Attaching shafts to the near vent end (i.e. at compartment end) produced a higher level of visibility, and was achieved with the shaft inlet closed. Values of 2.55 m (Run 9) and 5.22 m (Run 11) were recorded for the 1.5 m^2 and 3 m^2 shafts respectively. In both cases the buoyant layer depth was reduced to about 0.4 m.

Attaching a shaft to both ends of the corridor produced at best a visibility of about 1 m. This was recorded in Run 15 using the 3 m^2 shafts with their inlets closed.

Overall the best conditions in this first part of this study were achieved in Run 11 with the 3 m^2 shaft attached to the near vent end with its inlet closed.

It should be noted that at the near end the gases will be hotter and will preferentially vent out of the near vent, given the proximity of the vent from the compartment door.

It follows that by attaching a shaft at this end will vent the gases more effectively as demonstrated in Runs 9 and 11. Closing the shaft inlets allowed the make up air to enter via the remote vent improving conditions generally within the corridor.

Scenario 1 – further study

In the initial set of Runs, reported above, it was found that attaching a 3 m^2 smoke shaft (with its inlet closed) to the near vent end of the corridor produce the optimum visibility of about 5 m within the corridor. The remote vent in this case was open to the outside to supply make up air to the corridor. This may prove impracticable and may be a problem if this remote vent is subject to adverse wind effects, in which case the smoke may possibly mix down into the lower level of the corridor and thus lowering visibility even further.

Table B4 shows the Runs (numbers 16 to 36) which were carried out to investigate whether conditions within the corridor for Scenario 1 could be further improved. In this part of the study alterations to the vent sizes and the addition of an inlet into the side of the corridor (Figure B1) were examined. In addition, a shaft with a cross sectional area of 1.5 m^2 was equipped with a mechanical fan to determine the effects of powered extraction from the corridor.

In the initial study of Scenario 1 it was found that the lower section of the vents (Figure B5a) at the ends of the corridor were causing the incoming air to interfere with the outgoing gas layer. To minimise this effect the lower section of the vents were removed so that the vents extended to the full height of the corridor as shown in Figure B5b. It was also found that additional make up air was necessary at low level to improve visibility conditions within the corridor at low level. This inlet measured 0.5 m in height and 0.75 m in width (full-scale) and was located at the side of the corridor as shown in Figure B1.

Run 16 examined the effect of these extended vents at both ends of the corridor. It can be seen from the results that a visibility in excess of 100 m was achieved as a result of this change to the vent size.

Run 36 and 17 examined the effect of closing of the top section of upper near vent, leaving a 0.5 m lower opening as shown in Figure B5e. This was carried out in order to transform this near vent into an inlet only. Run 17 demonstrated that this reduced the visibility significantly to about 1.5 m. Opening the side inlet raised this visibility to about 5 m as demonstrated by Run 36. Run 18 was carried out to establish if the side inlet could supply sufficient replacement air on its own. Comparison between Run 36 and 18 indicates that it can not do so.

The next series of Runs (i.e. Runs 20 to 35) carried out on Scenario 1 retained the low level air inlet at the near end of the corridor, and examined the effect of smoke shafts (Figure B6 and B7) using natural and mechanical extraction at the remote end of the corridor (as indicated in Table B1).

Runs 20 to 21 demonstrated the effect of a 1.5 m^2 (full-scale) cross section mechanical and natural extraction shafts. It can be seen that the conditions within the corridor using either method of extraction did not significantly improve visibility conditions within the corridor.

Runs 37, 38 examined the effect of using a larger shaft having a cross sectional area of 3 m^2 (full-scale). In these Runs it was found that the full height of the remote vent was causing the gas layer to interfere with incoming air at that end which was the reason for the previous poor visibility levels achieved in the previous Runs.

As a result of the above findings, the lower section of the remote vent was sealed off leaving an effective slit vent as shown in Figure B5c. This vent measured 0.4 m high by 1.5 m in width (full-scale) located at the remote end of the corridor. This ensured that all the incoming air would come in at low level via the inlet at the side of the corridor and at the near end inlet and prevent interference with the out going layer at the remote end.

The above Runs used a 3 m^2 shaft with its base inlet open. It can be seen that a visibility level of about 94 m was achieved. Run 38 demonstrated that without the additional air coming through the side inlet, visibility is reduced to about 6m within the corridor.

The final series of Runs for this scenario (i.e. Runs 24 to 35) examined the effect of using the smaller shaft (cross sectional area 1.5 m^2). These runs followed the same procedure as for the larger shafts in Runs 37 and 38. In this case the slit vent at the remote end of the corridor was increased in depth to 0.75 m and reduced to 1m in width (full-scale) as shown in Figure B5d. This was done so as to accommodate the smaller shaft cross-section.

Runs 24,25 and 27 examined the effect of the smaller cross sectional shaft using natural extraction only. In these Runs it can be seen that for a naturally ventilated shaft the side inlet to the corridor and the bottom inlet to the shaft was necessary in order to achieve the optimum visibility of 13.4m in the corridor, as shown in Run 25.

The remaining Runs, i.e. 31 to 35, examined the same set up as above but using powered extraction as shown in Figure B8. The purpose of these Runs was to determine what extraction rate would achieve the optimum visibility within the corridor. It can be seen from Table B5 that Run 28 obtained the optimum visibility of about 13 m using an extraction rate of 1.43 ms^{-1}, which is equivalent to a volume extraction rate of 2.1 m^3s^{-1} for this size of shaft.

Runs 33 and 35 further demonstrated that without make up air conditions within the corridor worsen as indicated by the visibility and buoyant layer depth.

Physical modelling of Scenario 2 - corridor and stairwell

Model details

In this scenario the corridor used in Scenario 1 was connected to a five storey stairwell as shown in Figures B2 and B6. The stairwell measured approximately 17 m in height at full-scale and was 10 m wide by 2.5 m in depth. A ventilation opening was provided at the top, with an area of 1 m^2 at full-scale. The stairwell opened onto the corridor half way along the side of the corridor as shown. A door adjoining the staircase was located at first floor level and measured 0.8 m wide by 2 m in height (full-scale) and opened into the corridor as shown.

The stairwell had 5 levels, each 3 m in height, and a basement level with a door at its rear, opening out to the outside.

Experimental procedure and findings

The door opening into the stairwell was adjusted so that the gap between the edge of the door and the door frame corresponded to 200 mm at full-scale. This was the same gap that had been set between the fire compartment and corridor at the near end of the corridor.

The aim of this next series of Runs was to use the ventilation and inlet arrangement which gave the optimum conditions within the corridor and determine what effect these would have on the conditions within the stairwell.

Figure B8 shows model set up with a powered shaft attached to the remote end of the corridor. Figures B9 and B10 demonstrate the smoke flow behaviour that was observed in some of the Runs.

It was shown in Scenario 1 that a slit vent at the remote end of the corridor, and with the large smoke shaft (3 m^2) attached (i.e. Run 37), produced excellent visibility conditions within the corridor. Runs 39 to 42 examined this set up in this scenario. In Run 39 the stairwell basement door was closed and the stairwell vent open.

It can be seen from Table B7 that the visibility in the corridor reached 6 m with poor visibility levels produced in the stairwell. This was to be expected given that the basement door was closed preventing replacement air entering the stairwell.

Run 40 has demonstrated that by opening the basement door conditions improve significantly in the corridor and the basement and 1st floor levels of the stairwell. However, visibility on the other stairwell levels was about 2 m.

Run 41 demonstrated that closing the base inlet to the bottom of the smoke shaft reduced visibility generally. Run 42 showed that closing the side inlet to the corridor reduces conditions in the corridor but improves conditions in the basement and 1st floor level of the stairwell. This behaviour is due to the stairwell pulling more makeup air through the basement door since it is unable to draw air through the corridor. This is further indicated by the direction of flow shown in Table B7.

The next set of Runs examined the effect of using the smaller shaft (i.e. 1.5 m^2) attached to the remote end of the corridor. In these Runs the remote end vent extended the full height of the corridor as used in earlier Runs (e.g. Run 16).

It can be seen that by closing of the inlets to the corridor, conditions on all levels in the stairwell were very much improved. However this was to the detriment of conditions within the corridor. The direction of the flow of gases into the stairwell was reversed as shown in the Table B7 showing that the smoke was mainly contained within the corridor for these Runs.

Runs 46 to 53 repeated the set up which produced good conditions within the corridor in Scenario 1 using natural and powered 1.5 m^2 smoke shafts, again using slot a vent described in Figure B4d at the remote end of the corridor and a bottom inlet at the near end of the corridor.

Run 46 demonstrated that using a natural shaft, conditions within the corridor reach a mean visibility of 5.5 m, with 20 m visibility achieved in the basement and 1st floor of the stairwell. However conditions in the rest of the stairwell were not so good.

A number of extraction rates were examined using a powered extract shaft. It can be seen that a careful balancing act is required to achieve good conditions in both the stairwell and the corridor.

Runs 51 and 52 demonstrated that to achieve good conditions in the entire stairwell, conditions in the corridor are by contrast relatively poor (visibility levels of about 2 to 3 m being achieved). Closing the inlet to the shaft caused the stairwell to pull makeup air through the basement door which ensured clear conditions in the stairwell. Velocity measurements made just inside the stairwell door opening indicated a reverse in gas flow i.e. not into the stairwell. This accounts for the poor visibility in the corridor.

The optimum conditions in both the stairwell and the corridor were achieved in Run 53 where a mean visibility level of 13 m was achieved in the corridor, 100 m in the basement and 1st floor levels of the stairwell and about 6 m in the rest of the stairwell. This was achieved by closing the inlet to the shaft and providing top and bottom vents and inlets in the corridor with additional air via the side inlet to the corridor.

Runs 55 to 58 were carried out to provide a base line and demonstrate what the conditions are likely to be in the stairwell if there is no form of ventilation in the corridor. It can be seen from Table B7 that as one would expect visibility levels in both the corridor and stairwell were poor with the exception in Run 55 where the basement door and stairwell vent were open. This demonstrates the effectiveness of having the basement door and vent open in the stairwell.

Temperatures recorded within the stairwell were between 2 to 3 ºC above ambient for Runs 39 to 53. Runs 55 to 58 recorded temperatures of between 3 to 9 ºC.

Physical modelling of Scenario 3 - lobby and stairwell

Model details

In this scenario a lobby is located between the fire room and a 5 level stairwell identical to that used in Scenario 2 described above (see Figure B11). A 1 m^2 openable vent is located in the side wall of the stairwell on the 1st floor level. The lobby is 2.1m wide x 2.2 m in height. The fire compartment opened onto the lobby as shown in Figure B3. A door opened onto the stairwell as shown, having the same dimensions as before with both doors open by the same amount as before i.e. 200 mm gap.

Experimental procedure and findings

Table B8 describes the conditions studied in this scenario. The aim of these Runs was to establish the best conditions for both the lobby and stairwell, primarily in terms of visibility.

The ventilation arrangements that produced the optimum conditions in the last two scenarios were applied to this scenario.

Runs 61 and 62 examined the effect of top and bottom ventilation in the side end walls of the lobby as shown in Figure B3. The stairwell basement door and top level vent were open. Run 61 demonstrated that for this configuration conditions in both the lobby and the second through top levels in the stairwell were poor. On the basement and 1st floor of the stairwell a visibility of about 11m was found.

Run 62 examined the effect of opening the 1m^2 vent on the 1st floor. Table B9 shows that there is an improvement in the corridor raising the visibility to about 6m and the basement and 1st floor level to about 27 m. However visibility levels within 2nd to top levels of the stairwell were still poor.

Runs 63 and 64 used a 1.5 m^2 smoke shaft which was attached to the near vent side of the lobby.

Closing the base inlet to the shaft produced excellent visibility conditions on all the stairwell levels. However, visibility levels in the corridor were poor. This had also been demonstrated in Scenario 2 (i.e. Runs 51 and 52).

Opening the inlet to the shaft improved visibility within the lobby to about 6 m. However, poor visibility then resulted in the stairwell with the exception of the basement and 1st floor levels, where a visibility of about 26 m was attained.

Runs 67 and 68 used the same smoke shaft (1.5 m^2), now having an extract fan fitted. The same procedure was repeated. Broadly, the same results were obtained with slightly higher visibility levels being achieved in the stairwell in Run 67, which had the shaft inlet closed.

It should be noted that further Runs were carried to examine the effect of higher extraction rates. However it was found that this process only made conditions worse in the lobby.

Further studies were also carried out to establish having a vent on the other side of the lobby instead of a low level inlet thus creating a cross ventilated lobby. A 1.5 m^2 powered smoke shaft was then located over one of the vents in order to generate cross ventilation. A number of extraction rates were examined with little if any improvement to visibility levels in the lobby.

Temperatures recorded within the stairwell were about 2 to 3 ºC above ambient.

Physical modelling of Scenario 4 - fire compartment opening onto stairwell

Model details

The geometry is the same as that used in Scenario 3 but with the side openings of the lobby closed. The fire door has been fully opened in order to study the effect of a fire compartment opening directly onto a stairwell as illustrated in Figure B4.

Experimental procedure and findings

Table B10 describes the conditions studied in this final scenario.

Run 70 examined the effect of having the top floor ceiling vent and basement door open. The effect of opening a side wall vent on the 1st floor was examined by Run 71.

Run 70 demonstrated that for this configuration visibility conditions within the top four floors was very poor with a mean visibility of 0.36m being achieved. Visibility on 1st and basement levels reached an average value of about 18 m.

Rum 71 demonstrated that by opening a 1 m^2 (full-scale) vent on the first floor level caused the visibility within the stairwell to drop overall, with about 11 m visibility achieved on the basement and 1st floor level. Conditions within the upper floors were still poor with an average visibility of 0.24 m being achieved.

Mean gas temperatures of about 6 to 9 ºC were recorded within the stairwell for these Runs.

Discussion of physical scale modelling results

Scenario 1 (corridor only)

The best conditions within the corridor were achieved in Runs 16,37,25 and 28 .In all cases visibilities in excess of 10 m were achieved.

Run 16 had external wall vents at both ends, 1 m in width at full-scale, spanning the full height of the corridor. In this Run makeup air was able enter at low level allowing an undisturbed gas layer to leave the corridor. This set up however would be susceptible to adverse wind effects.

In the other Runs (37,25 and 28) smoke shafts were used. The ventilation was provided via an upper level vent at one end of the corridor with make up air supplied through a low level inlet (1 m x 0.5 m) at the other end of the corridor. In all cases additional air was necessary via a low level side inlet (1 m x 0.5 m). The base inlets to the shafts in each case were open.

In Run 37 the upper ventilation opening was provided by a slit measuring 0.24 m x 1.5 m at full scale. The large smoke shaft was used, with cross sectional area of 3 m^2. Attaching the shaft over the vent achieved an optimum visibility 94 m in the corridor. The high visibility level was due possibly to the layer occupying a wider reservoir and thus encouraging a lower region free from smoke.

Runs 25 and 28 used shafts having cross sectional areas of 1.5m^2, and were naturally and mechanically ventilated respectively. The ventilation openings in the corridor for these Runs were 1m wide x 0.75 m high. Visibility levels of about 13 m were achieved in both these Runs. However it is important that for the powered shaft the velocity used is not too high. In this scenario a velocity of 1.43 ms^{-1} was found to produce optimum conditions in the corridor.

Figure B15 shows the configuration used in this particular scenario which produced optimum conditions within the corridor.

Scenario 2 (corridor and stair)

In this scenario the Run which produced the optimum conditions in the corridor and stairwell used the same principle used in Scenario 1 with regards to the ventilation conditions within the corridor. In this case it was Run 53 , which used a 1.5 m^2 powered shaft with its inlet closed.

Again a number of velocities were examined. A velocity in the shaft of 0.85 ms^{-1} produced the best conditions in both the corridor (visibility =13 m), stairwell basement and 1st floor (visibility > 100m) and rest of stairwell (visibility = 6 m). It should be noted that 6m was the optimum visibility that could be achieved for this scenario.

It should be noted furthermore that if conditions in the corridor are not important then excellent conditions can be achieved in the entire stairwell by raising the extraction rate of the shaft to greater 1.34ms^{-1} as demonstrated in Run 51 and 52. Visibilities in excess of 100m were achieved. This level of visibility was achieved due to the corridor being depressurised and hence preventing any hot gases entering the stairwell as indicated in the gas flow direction in Table B7.

Figures B12,13 and 14 illustrate the typical temperature profiles recorded in different locations within the model.

Figure B16 shows the configuration used in this particular scenario that produced optimum conditions in both the stairwell and corridor.

Scenario 3 (lobby and stair)

The same principle as used in the previous scenarios was applied here. However visibility levels of 10 m were not simultaneously achieved in both the corridor and the stairwell.

Run 64 produced the optimum visibilities, which were 6 m in the lobby, 26 m in the basement and 1st floor levels of the stairwell and about 2 m in the rest of the stairwell. This Run used a 1.5 m^2 naturally ventilated shaft. Upper vents and a lower inlet, as used in scenarios 1 and 2, were provided in the lobby.

It should be noted that a powered shaft was investigated, but that the visibility within the lobby became poorer as the extraction rate was increased (see Table B9).

Figure B17 shows the configuration used in this scenario that produced optimum conditions in both the lobby and stairwell.

Scenario 4 (stair only)

Results of this scenario are shown in Table B11. They demonstrate that only the basement and 1st floor levels of the stairwell remained relatively clear of smoke, with mean visibility measurements of 11 m and 18 m being recorded. Introducing additional ventilation on the 1st level of the stairwell caused conditions to worsen as shown in Run 71.

Measurements of air velocity through the basement door dropped by over 50% when the 1st floor vent was open in Run 71. This reduced the degree of the purging taking place within the basement and 1st floor levels (observed in Run 70) and hence a caused a reduction in visibility as shown in Table B11. This may also explain the slightly lower mean gas temperature recorded in Run 70.

Figure B18 shows the configuration used in this scenario that produced optimum conditions within the stairwell.

Optimum visibility for all scenarios

Table B12 lists the Runs that gave optimum visibility measurements, from the perspective of maintaining conditions inside both the corridor and the stairwell, for each of the scenarios studied. It can be seen that in all scenarios visibility values above 10 m could be achieved in the corridor and also the basement and 1st floor levels of the stairwell where it was included. Visibility values of 6 m, 2 m and 0.4 m on the other stairwell levels were achieved in Scenarios 2,3 and 4 respectively. An optimum visibility of 6 m was achieved in the lobby of Scenario 3.

Concluding comments from the physical modelling study

This study has demonstrated that if exposed to smoke from a dwelling fire for more than a short time, conditions inside an adjoining corridor are likely to deteriorate unless special smoke ventilation provisions are made. In the study it was shown that by venting smoke at high level, and providing replacement fresh air at one or more low level locations, a reasonably smoke free lower zone could be maintained within the corridor. This was achieved either by having full-height external wall vents at both ends, or by locating a smoke shaft at one end and low level replacement air vents at the side and opposite end of the corridor. Natural or mechanical shafts were shown to be effective. There was a marginal improvement, in the case of naturally ventilated shafts, if the base of the shaft was open.

When considering the smoke control within both the corridor and an adjoining stair, the matter was more complicated. While natural and mechanical smoke ventilation schemes could be implemented to maintain reasonable conditions within the lower zone of the corridor, smoke then generally also entered the stair. Good protection to the stair could be achieved by naturally or mechanically ventilated smoke shafts, but generally at the expense of poor conditions inside the corridor, where any stratification was lost. By a judicial selection of ventilation rate, and adequate provision of replacement air at low level to the corridor, a mechanical smoke shaft could achieve reasonable conditions inside both the corridor and stair. However, then setting the ventilation rate too low resulted in worse conditions inside the stair, and setting it too high deteriorated conditions inside the corridor.

In respect to protecting the stair from ingress of smoke, a closed base (chimney) naturally ventilated smoke shaft was preferential to an open base shaft.

To improve conditions inside a stair that is exposed to smoke, it was found that providing ventilation openings at the base and head of the stair helped, providing a flow of fresh air to disperse the smoke.

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Table B1 Instrumentation used in physical modelling study

Channel No.	Location	Distance below celing	Channel No.	Location	Distance below celing
1	Fire room opening	0.01	42	Corridor Nr	0.01
2	Fire room opening	0.03	43	Corridor Nr	0.03
3	Fire room opening	0.05	44	Corridor Nr	0.05
4	Fire room opening	0.08	45	Corridor Nr	0.08
5	Fire room opening	0.11	46	Corridor Nr	0.11
6	Fire room opening	0.16	47	Corridor Nr	0.16
7	Fire room opening	0.21	48	Corridor Nr	0.21
8	Fire room opening	0.26	49	Corridor Nr	0.26
9	Fire room opening	0.31	50	Corridor Nr	0.31
10	Fire room opening	0.39	51	Corridor Nr	0.43
11	Centre of lobby	0.01	52	Stair (2) door	0.01
12	Centre of lobby	0.03	53	Stair (2) door	0.02
13	Centre of lobby	0.05	54	Stair (2) door	0.04
14	Centre of lobby	0.08	55	Stair (2) door	0.07
15	Centre of lobby	0.11	56	Stair (2) door	0.1
16	Centre of lobby	0.16	57	Stair (2) door	0.15
17	Centre of lobby	0.21	58	Stair (2) door	0.19
18	Centre of lobby	0.26	59	Stair (2) door	0.25
19	Centre of lobby	0.36	60	Stair (2) door	0.35
20	Centre of lobby	0.43	61	Stair (2) door	0.38
21	Stairwell 1 door opening	0.01	62	Corridor R	0.01
22	Stairwell 1 door opening	0.03	63	Corridor R	0.03
23	Stairwell 1 door opening	0.05	64	Corridor R	0.05
24	Stairwell 1 door opening	0.08	65	Corridor R	0.08
25	Stairwell 1 door opening	0.11	66	Corridor R	0.11
26	Stairwell 1 door opening	0.16	67	Corridor R	0.16
27	Stairwell 1 door opening	0.21	68	Corridor R	0.21
28	Stairwell 1 door opening	0.26	69	Corridor R	0.26
29	Stairwell 1 door opening	0.31	70	Corridor R	0.31
30	Stairwell 1 door opening	0.39	71	Corridor R	0.43
31	Stairwell (1)	0.01	72	Vent R	0.02
32	Stairwell (1)	0.36	73	Vent Nr	0.02
33	Stairwell (1)	0.71	74	Mid cor.	0.21
34	Stairwell (1)	1.06	78	Fire room	0.02
35	Stairwell (1)	1.41	79	Room probe	0.02
36	Stairwell (1)	1.76	80	Ambient	
37	Stairwell (1)	2.11	81	Stair (2) 5th	0.3
38	Stairwell (1)	2.46	82	Stair (2) 4th	0.3
39	Stairwell (1)	2.81	83	Stair (2) 3rd	0.3
40	Stairwell (1)	3.16	84	Stair (2) 2nd	0.3
41	Stairwell (1)	3.46	85	Stair (2) 1st	0.3
			86	Stair (2) Base	0.3
			101	F R CO_2	0.02
			102	Cor/Lob/St CO_2	0.21
			103	F R Vel.	0.02
			104	Cor N Vel.	0.02
			105	Cor R Vel.	0.02
			106	Stair (2) Vel.	0.02
			107	Stair (2)Delta P	0.21

Note that all distances are at model scale

Table B2 **Procedure table for physical modelling Scenario 1 - initial study**

Test (run) no.		Vents remote	Vents near	Shaft size	Shaft remote	Shaft near	Shaft base inlet remote	Shaft base inlet near
1		Y	Y	N/A	N/A	N/A	N/A	N/A
2		Y	N	N/A	N/A	N/A	N/A	N/A
3		N	Y	N/A	N/A	N/A	N/A	N/A
4		Y	Y	S	Y	N/A	Y	N/A
5		Y	Y	S	Y	N/A	N	N/A
6		Y	Y	L	Y	N/A	Y	N/A
7		Y	Y	L	Y	N/A	N	N/A
8		Y	Y	S	N/A	Y	N/A	Y
9		Y	Y	S	N/A	Y	N/A	N
10		Y	Y	L	N/A	Y	N/A	Y
11		Y	Y	L	N/A	Y	N/A	N
12		Y	Y	S	Y	Y	Y	Y
13		Y	Y	S	Y	Y	N	N
14		Y	Y	L	Y	Y	Y	Y
15		Y	Y	L	Y	Y	N	N

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Table B3 Results for physical modelling Scenario 1 - initial study

Run No.		Fire compartment opening				Mean values in corridor			
		Temp. (^{O}C)	Layer (m)	Velocity (m/s)		Temp. (^{O}C)	Buoyant Layer (m)	Visibility (m)	Velocity (m/s)
1		155.04	1.10	4.11		48.94	0.64	2.43	0.53
2		164.87	1.34	4.33		64.35	0.86	0.76	0.72
3		165.44	1.32	4.35		53.66	0.80	0.28	0.32
4		161.85	1.35	4.20		55.84	0.81	1.26	0.81
5		155.47	1.31	4.10		53.05	1.13	0.62	1.02
6		168.19	1.38	4.35		56.46	0.78	1.44	0.78
7		157.84	1.29	4.09		52.21	1.13	0.60	0.77
8		147.49	1.30	3.94		46.31	0.59	0.92	1.23
9		158.61	1.29	4.12		52.59	0.41	2.55	0.84
10		153.41	1.30	4.04		50.12	0.60	0.83	0.77
11		140.90	1.23	3.71		41.91	0.42	5.22	1.88
12		153.12	1.22	4.01		49.56	0.56	0.60	0.46
13		132.74	1.11	3.55		40.17	0.61	0.68	0.51
14		163.23	1.23	4.27		57.44	0.60	0.51	0.86
15		136.98	1.19	3.59		39.95	0.54	0.99	1.51

Note that all dimensions and results have been scaled to full scale

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Table B4 **Procedure table for physical modelling Scenario 1 - further study**

Test No.		Model set up: Vent remote	Inlet near	Inlet side	Shaft size	Shaft used?	Shaft inlet open?
16		Y	Y	N	N/A	N/A	N/A
36		Y	Bottom	Y	N/A	N/A	N/A
17		Y	Bottom	N	N/A	N/A	N/A
18		Y	N	Y	N/A	N/A	N/A
20		Y	Bottom	N	S	Y	Y
21		Y	Bottom	N	S(mech)	Y	Y
37		Slit	Bottom	Y	L	Y	Y
38		Slit	Bottom	N	L	Y	Y
25		Top	Bottom	Y	S	Y	Y
24		Top	Bottom	N	S	Y	Y
27		Top	Bottom	Y	S	Y	N
31		Top	Bottom	Y	S (mech)	Y	Y
28		Top	Bottom	Y	S (mech)	Y	Y
29		Top	Bottom	Y	S (mech)	Y	Y
34		Top	Bottom	Y	S (mech)	Y	Y
32		Top	Bottom	Y	S (mech)	Y	Y
30		Top	Bottom	Y	S (mech)	Y	Y
33		Top	Bottom	N	S (mech)	Y	Y
35		Top	Bottom	Y	S (mech)	Y	N

Table B5 Results for physical modelling Scenario 1 - further study

	Fire compartment			Mean values in corridor				Shaft
Test No.	Temp. (°C)	B Layer (m)	Velocity (m/s)	Temp. (°C)	B Layer (m)	Visibility (m)	Velocity (m/s)	Velocity (m/s)
16	155.13	1.29	4.21	49.27	0.60	>100	1.19	N/A
36	178.30	1.30	4.53	68.34	0.75	4.73	2.50	N/A
17	168.13	1.32	4.42	64.13	0.78	1.54	2.46	N/A
18	164.06	1.31	4.32	62.37	0.78	1.86	2.73	N/A
20	176.14	1.39	4.45	70.16	0.96	1.65	3.42	2.16
21	146.73	1.25	3.83	57.09	0.98	1.07	2.67	2.79
37	178.44	1.30	4.53	68.51	0.72	93.97	2.41	1.72
38	159.82	1.29	4.16	59.32	0.67	5.87	2.28	1.78
26	171.95	1.33	4.32	63.53	0.68	6.60	2.83	0.92
25	177.99	1.31	4.42	66.34	0.69	13.40	3.04	1.87
24	173.05	1.34	4.34	64.76	0.71	6.33	2.90	1.82
27	158.29	1.33	4.09	58.96	0.74	3.11	3.21	0.99
31	168.63	1.28	4.35	65.03	0.82	1.49	2.46	0.95
28	170.68	1.30	4.33	64.26	0.70	12.99	2.75	1.43
29	167.07	1.29	NM	62.31	0.68	5.41	NM	1.78
34	159.07	1.28	4.19	59.43	0.71	11.85	2.62	1.99
32	172.29	1.31	4.36	64.95	0.72	4.83	3.25	2.72
30	170.35	1.32	4.37	65.29	0.69	7.21	2.88	2.23
33	174.39	1.34	4.45	67.70	0.79	4.79	3.45	2.26
35	145.18	1.26	3.79	58.88	1.09	0.64	2.99	2.24

Note that all dimensions and results have been scaled to full scale

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Table B6 Procedure table for physical modelling Scenario 2

		Model set up							
Test No.		Vent remote	Inlet near	Inlet side	Shaft size	Shaft used?	Shaft inlet open?	Stair vent	Stair door basement
39		Slit	Bottom	Y	L	Y	Y	Y	N
40		Slit	Bottom	Y	L	Y	Y	Y	Y
41		Slit	Bottom	Y	L	Y	N	Y	Y
42		Slit	Bottom	N	L	Y	Y	Y	Y
43		Y	N	N	S	Y	Y	Y	Y
44		Y	N	N	S	Y	N	Y	Y
45		Y	N	Y	S	Y	Y	Y	Y
46		Top	Bottom	Y	S	Y	Y	Y	Y
48		Top	Bottom	Y	S(mech)	Y	Y	Y	Y
49		Top	Bottom	Y	S(mech)	Y	Y	Y	Y
50		Top	Bottom	Y	S(mech)	Y	Y	Y	Y
51		Top	Bottom	Y	S(mech)	Y	N	Y	Y
52		Top	Bottom	Y	S(mech)	Y	N	Y	Y
53		Top	Bottom	Y	S(mech)	Y	N	Y	Y
55		N	N	N	N	N	N	Y	Y
56		N	N	N	N	N	N	Y	N
57		N	N	N	N	N	N	N	Y
58		N	N	N	N	N	N	N	N

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Table B7 Results for physical modelling Scenario 2

Run No.	Fire compartment Temp. (°C)	Fire compartment Layer (m)	Fire compartment Velocity (m/s)	Mean values in corridor Temp. (°C)	Mean values in corridor B Layer (m)	Mean values in corridor Visibility (m)	Mean values in corridor Velocity (m/s)	Shaft Velocity (m/s)	Stairwell (2) Gas flow direction (IN/OUT)	Stairwell (2) Door Temp (°C)	Stairwell (2) Door Gas layer (m)	Stairwell (2) Basement & 1st Visibility (m)	Stairwell (2) 2nd to 5th Visibility (m)
39	184.88	1.34	4.27	66.86	0.61	6.00	0.93	1.42	IN	35.85	0.09	7.92	0.70
40	183.31	1.31	4.29	65.36	0.60	37.62	0.93	1.71	IN	30.66	0.10	74.18	1.91
41	177.76	1.31	4.26	66.21	0.62	4.54	0.93	0.36	OUT	28.14	0.10	10.57	2.28
42	190.90	1.35	4.37	67.14	0.61	10.51	0.83	1.62	OUT	30.92	0.10	154.44	2.01
43	189.52	1.35	4.36	76.78	0.66	0.78	0.80	2.16	OUT	31.41	0.35	69.91	13.19
44	139.46	1.18	3.38	51.88	0.67	0.74	0.69	1.43	OUT	4.18	0.74	16.02	86.45
45	175.82	1.29	4.21	72.56	0.66	1.18	0.94	2.01	OUT	33.05	0.10	148.26	57.31
46	173.70	1.30	4.05	61.37	0.60	5.45	0.93	1.75	OUT	26.88	0.11	20.27	2.35
48	168.41	1.31	4.01	59.67	0.61	8.02	0.97	2.10	OUT	24.86	0.11	22.22	3.62
49	173.60	1.29	4.14	63.29	0.65	10.01	0.92	1.67	IN	30.69	0.12	27.01	2.75
50	173.26	1.33	4.07	62.53	0.62	6.59	1.04	2.37	OUT	27.04	0.08	37.90	1.76
51	153.70	1.22	3.66	57.14	0.81	2.56	0.85	2.18	OUT	1.62	NL	100.00	100.00
52	176.86	1.27	4.05	66.21	0.71	2.78	1.00	1.34	OUT	2.72	NL	77.39	100.00
53	187.67	1.33	4.30	70.44	0.66	13.09	1.10	0.85	OUT	28.80	0.07	100.00	5.57
55	167.60	1.30	4.03	59.93	1.00	0.19	0.48	N/R	IN	33.87	0.19	68.62	0.44
56	174.05	1.31	4.14	71.28	1.20	0.25	1.83	N/R	IN	44.00	0.23	1.61	0.27
57	184.54	1.37	4.37	65.81	1.01	0.18	2.18	N/R	IN	37.12	0.19	0.19	1.57
58	187.90	1.32	4.49	64.59	0.94	0.17	0.41	N/R	IN	33.90	0.17	0.38	1.62

Note that all dimensions and results have been scaled to full scale

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Table B8 Procedure table for physical modelling Scenario 3

Test No.		Vent remote	Inlet near	Shaft size	Shaft used?	Shaft inlet open?	Stair vent	Stair door basement
		Model set up						
61		Bottom	Top	N/A	N/A	N/A	Y	Y
62		Bottom	Top	N/A	N/A	N/A	Y	Y
63		Bottom	Top	S	Y	N	Y	Y
64		Bottom	Top	S	Y	Y	Y	Y
67		Bottom	Top	S(mech)	Y	N	Y	Y
68		Bottom	Top	S(mech)	Y	Y	Y	Y

Table B9 Results for physical modelling Scenario 3

		Fire compartment				Mean values in lobby			Shaft		Staircase (1)				
											Door	Door	Basement & 1st	2nd to 5th	Stair well
Test No.		Temp. (°C)	B Layer (m)	Velocity (m/s)		Temp. (°C)	B Layer (m)	Visibility (m)	Velocity (m/s)		Temp (°C)	B layer (m)	Visibility (m)	Visibility (m)	Temp. (°C)
61		140.68	1.28	3.95		83.84	0.57	1.15	N/R		62.41	0.54	11.00	0.59	2.75
62		154.60	1.30	4.18		92.37	0.62	6.28	N/R		70.87	0.57	27.34	1.42	3.67
63		148.10	1.28	3.93		76.14	0.52	1.17	1.30		53.94	0.42	12.85	79.98	2.33
64		149.67	1.31	4.05		90.69	0.48	5.81	1.70		69.53	0.40	26.10	2.07	2.78
67		141.33	1.35	3.80		72.88	0.52	1.64	1.13		54.55	0.47	37.31	81.70	1.96
68		161.67	1.29	4.28		99.36	0.57	3.13	1.27		74.61	0.50	39.60	0.97	3.73

Note that all dimensions and results have been scaled to full scale

Table B10 **Procedure table for physical modelling Scenario 4**

		Model set up		
Test No.		Stair vent	Stair door basement	1st floor vent
70		Y	Y	N
71		Y	Y	Y

Table B11 **Results for physical modelling Scenario 4**

							Staircase (1)				
		Fire compartment					Door	Door	Basement & 1st	2nd to 5th	Stair well
Test No.		Temp. (^oC)	B Layer (m)	Velocity (m/s)			Temp (^oC)	B layer (m)	Visibility (m)	Visibility (m)	Temp. (^oC)
70		141.70	1.42	3.00			82.61	1.29	17.81	0.36	6.63
71		161.40	1.53	3.48			102.00	1.37	10.87	0.24	8.58

Note that all dimensions and results have been scaled to full scale

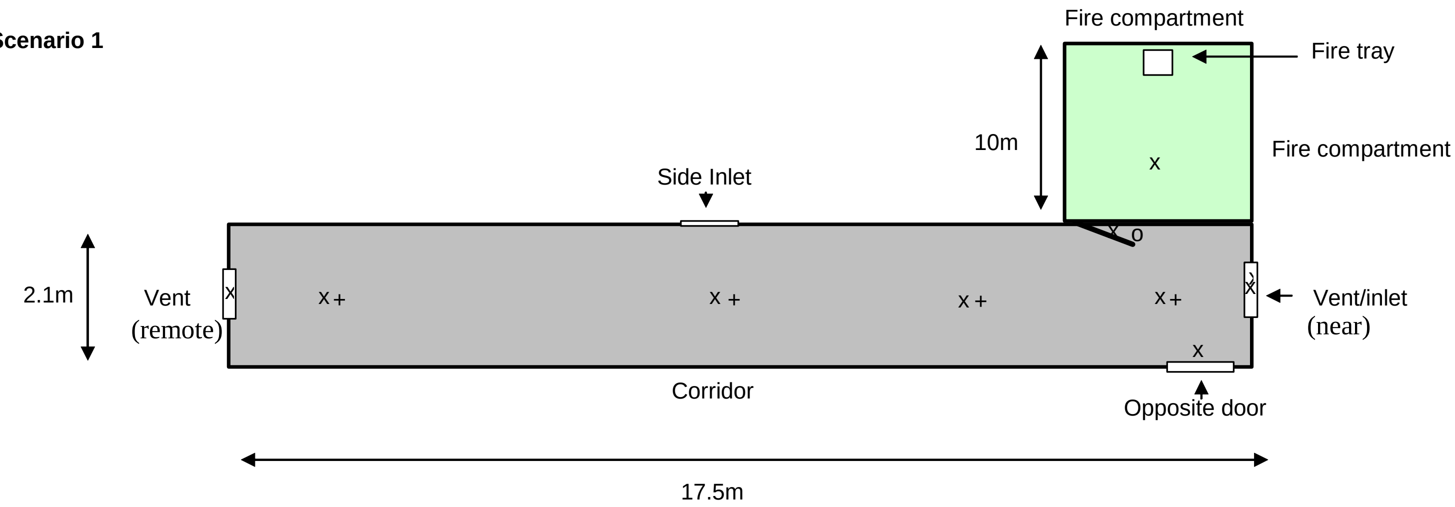
Table B12 Summary of optimum visibility results, with emphasis on corridor and stairwell combined conditions

Scenario	Run number	Optimum visibility (m)				Shaft size used	Extraction method	Shaft inlet
		Corridor	Lobby	Stairwell				
				Basement & 1st floor	2nd to 5th floors			
1	25,28*,34*,37	> 10m	N/A	N/A	N/A	1.5 and 3m^2	Powered & natural	Open
2	53	>10m	N/A	>10	5.6m	1.5m^2	Powered	Closed
3	64	N/A	5.8m	>10	2.1m	1.5m^2	Natural	Open
4	70	N/A	N/A	>10	0.4m	1.5m^2	N/A	N/A

* used powered extraction

Note that all dimensions and results have been scaled to full scale

Scenario 1



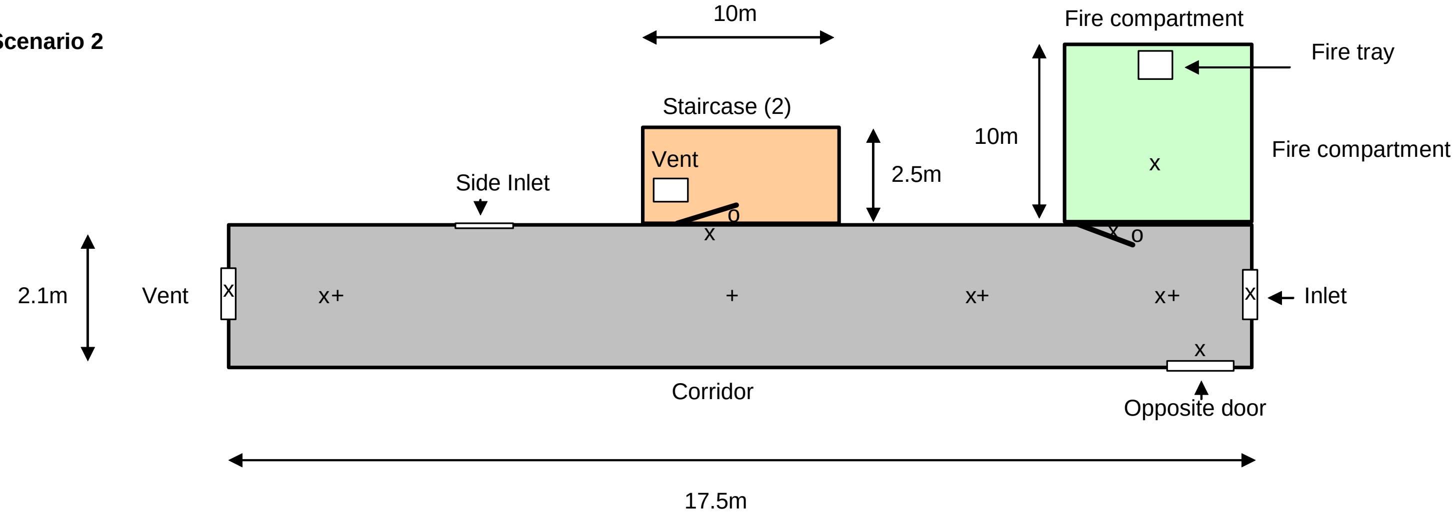
x - Thermocouple columns and junctions

+ - Carbon dioxide sampling point

o - Velocity probe

Figure B1 Corridor and fire compartment used in physical modelling Scenario 1 (full-scale dimensions shown)

Scenario 2



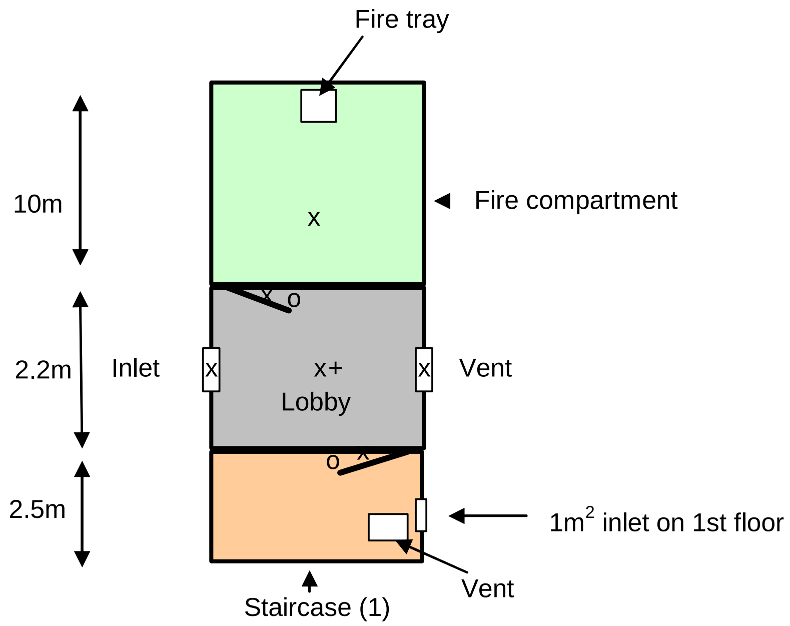
x - Thermocouple columns and junctions

+ - Carbon dioxide sampling point

o - Velocity probe

Figure B2 Stairwell attached to side of corridor used in physical modelling Scenario 2 (full-scale dimensions shown)

Scenario 3

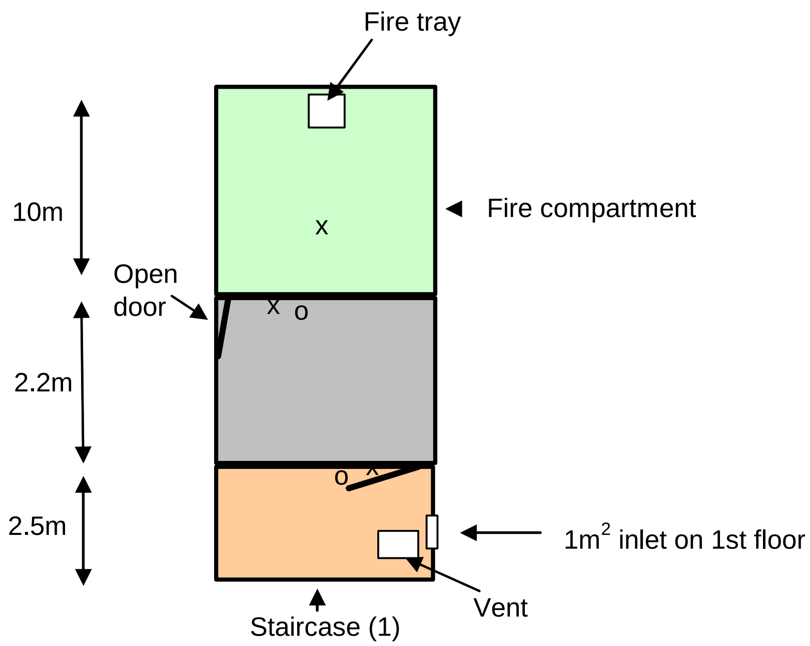


x - Thermocouple columns and junctions

+ - Carbon dioxide sampling point

o - Velocity probe

Figure B3 Lobby and staircase used in physical modelling Scenario 3 (full-scale dimensions)



x - Thermocouple columns and junctions

+ - Carbon dioxide sampling point

o - Velocity probe

Figure B4 Extended fire compartment opening onto stairwell used in physical modelling Scenario 4 (full-scale dimensions)

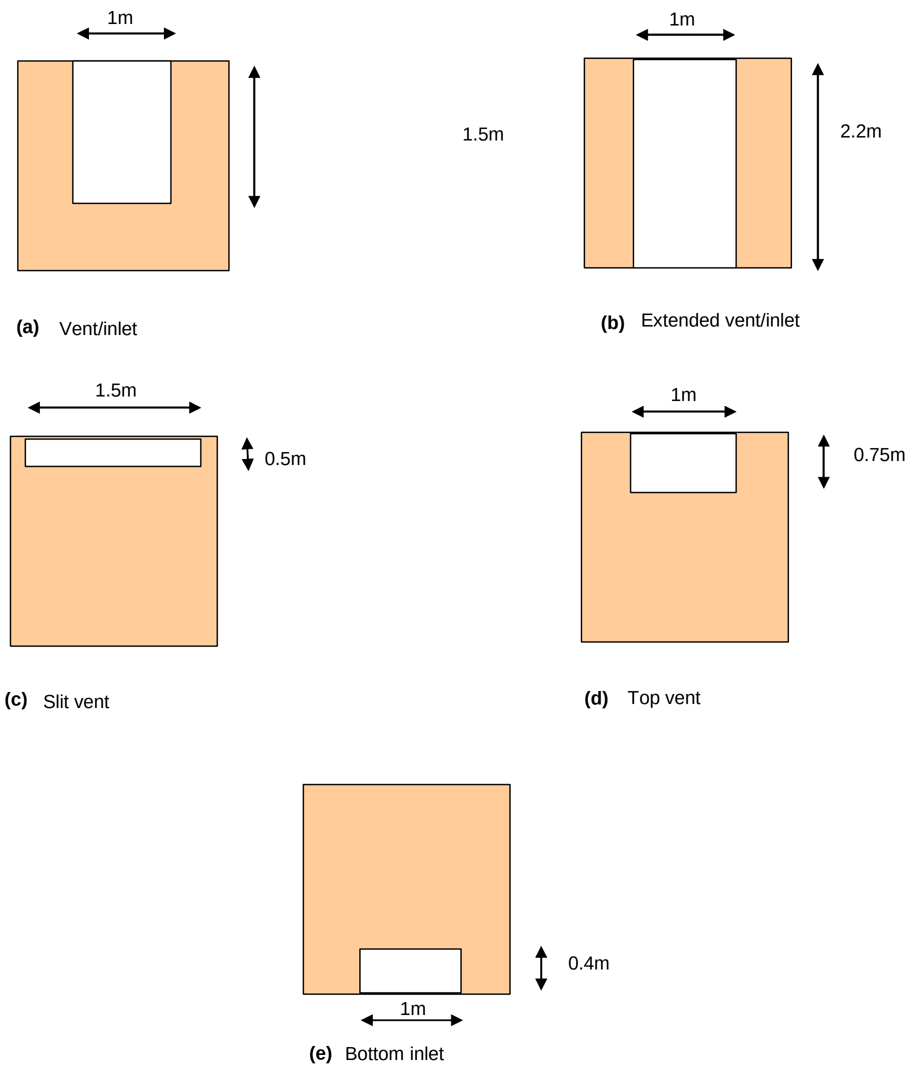


Figure B5 Types of ventilation and inlet openings used in corridor and lobby (full-scale dimensions shown)

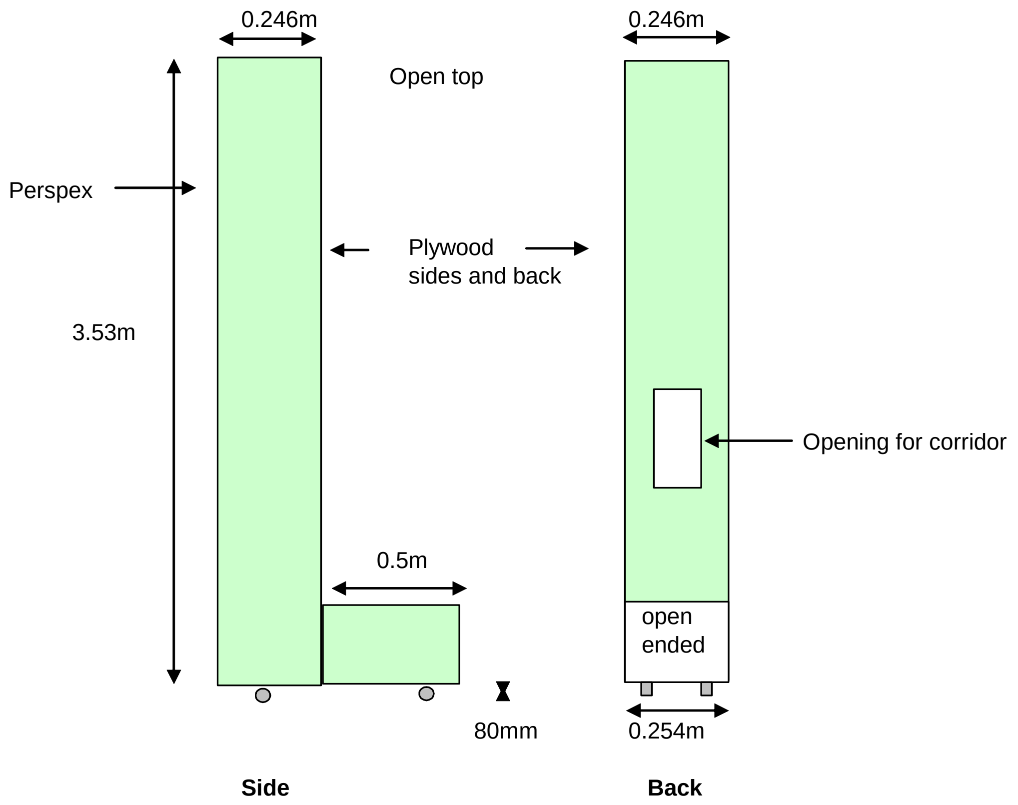


Figure B6 Example of shaft used in the study

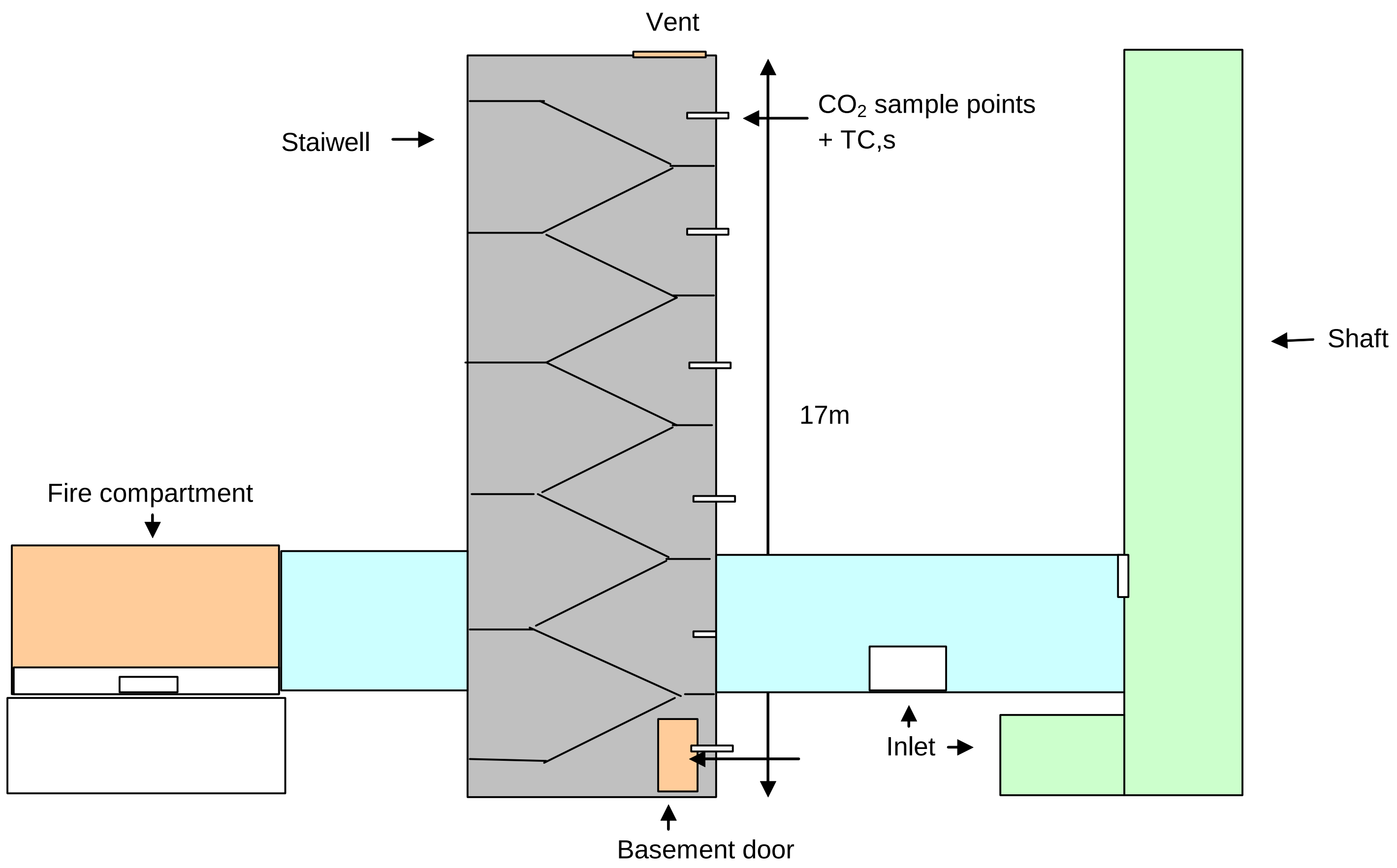


Figure B7 Elevation of physical modelling (Scenario 2)

Figure B8 Corridor with powered shaft attached at its remote end

Figure B9 Smoke flowing along corridor from fire compartment

Figure B10 Photograph showing physical modelling Scenario 1 set with smoke layer in corridor entering large shaft

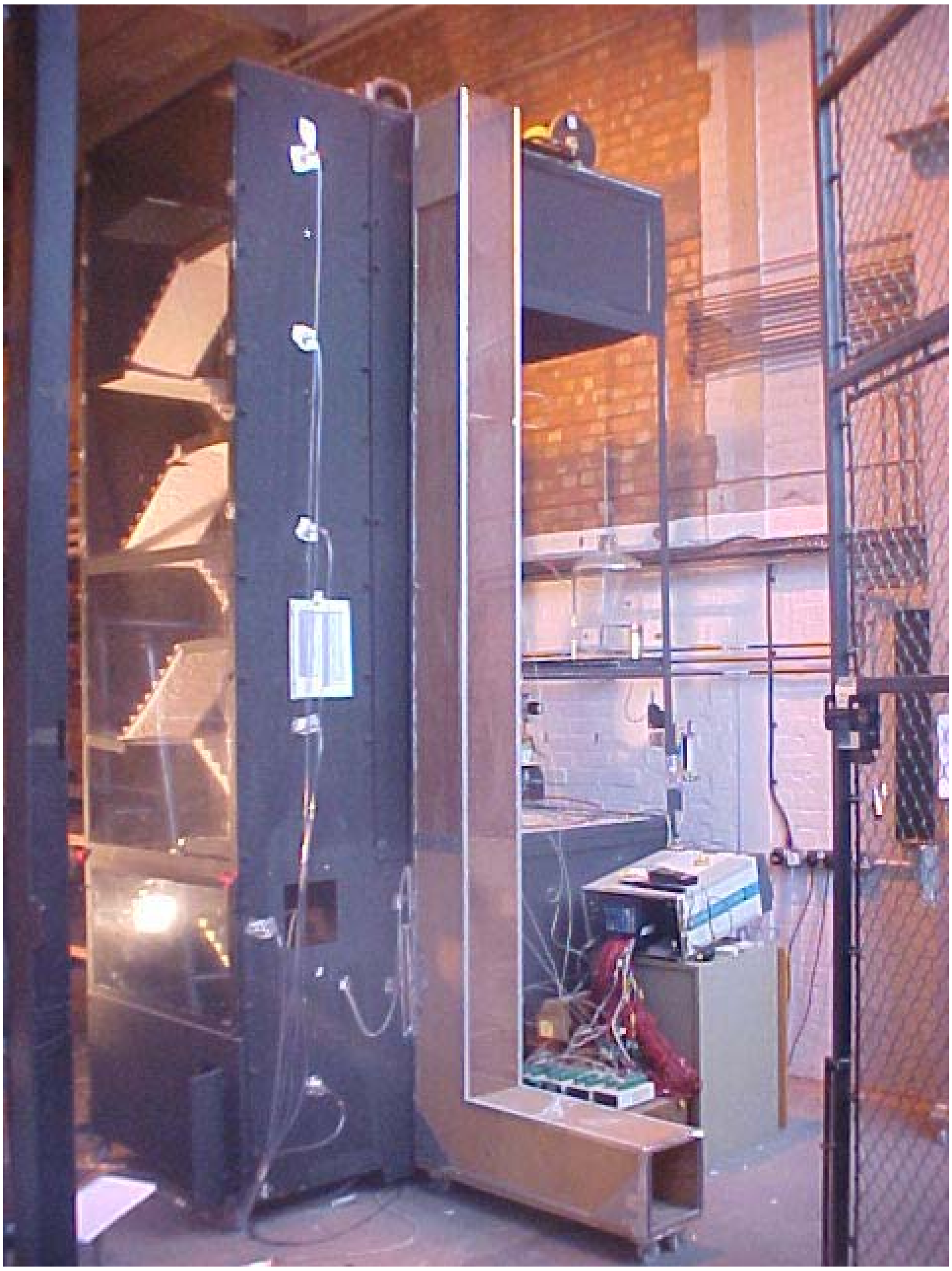


Figure B11 Photograph showing physical modelling Scenario 3 set up with shaft and staircase attached to lobby

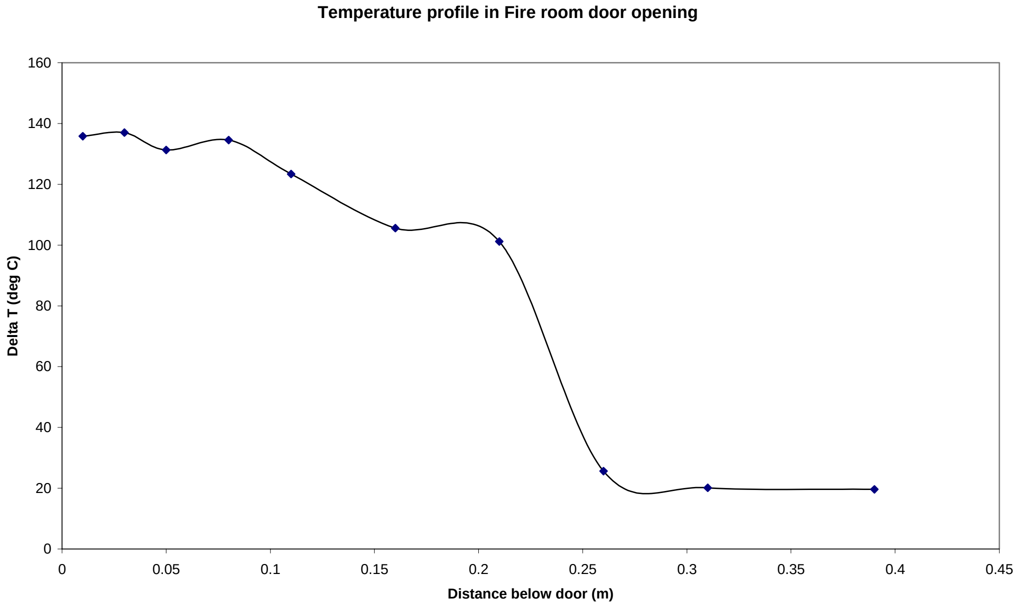


Figure B12 Typical temperature profile recorded in fire compartment door opening

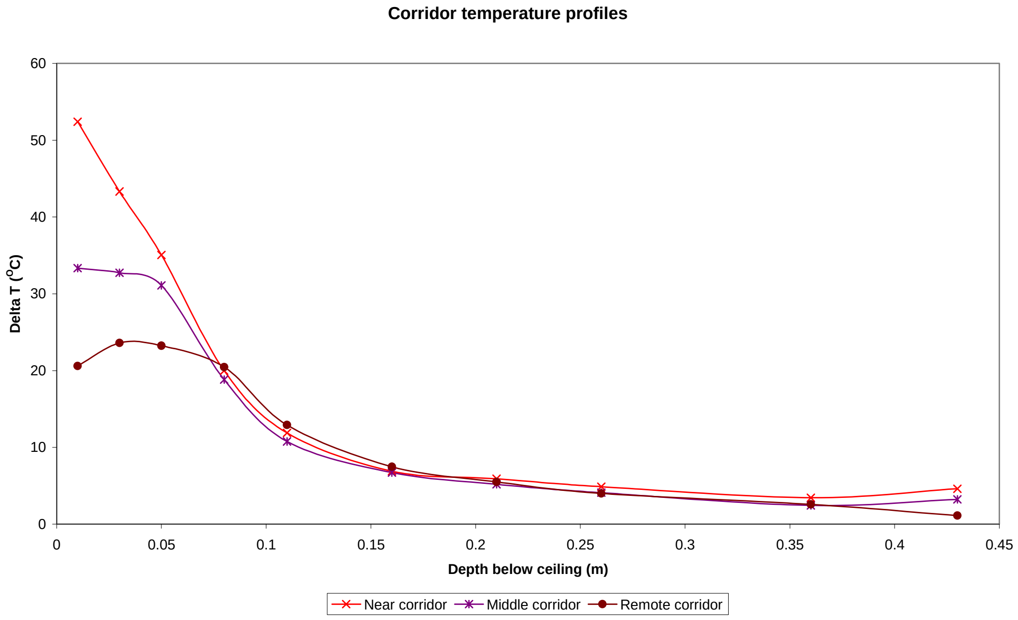


Figure B13 Typical temperature profiles recorded in corridor

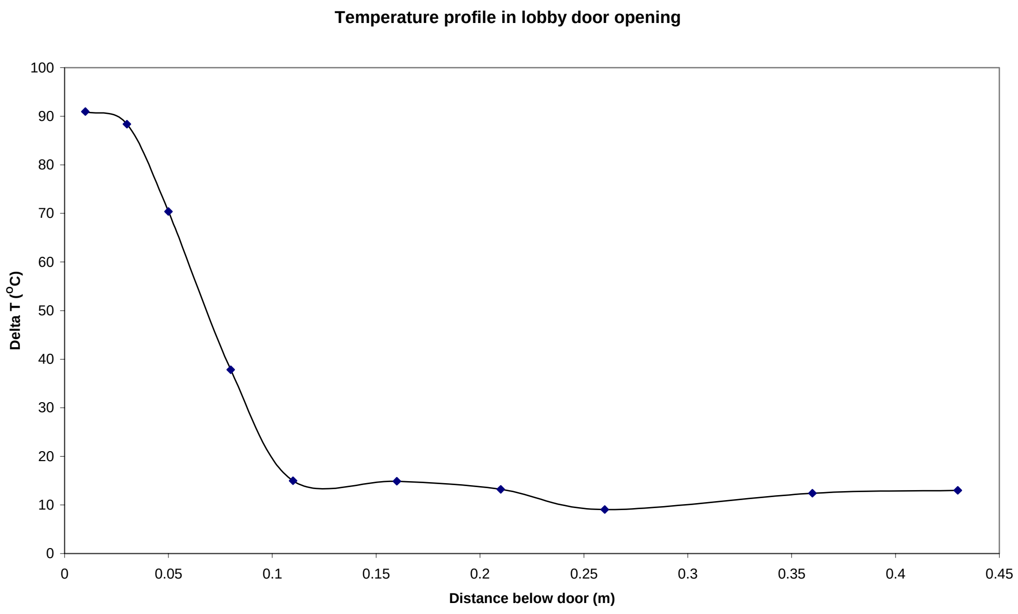


Figure B14 Typical temperature profile recorded in lobby

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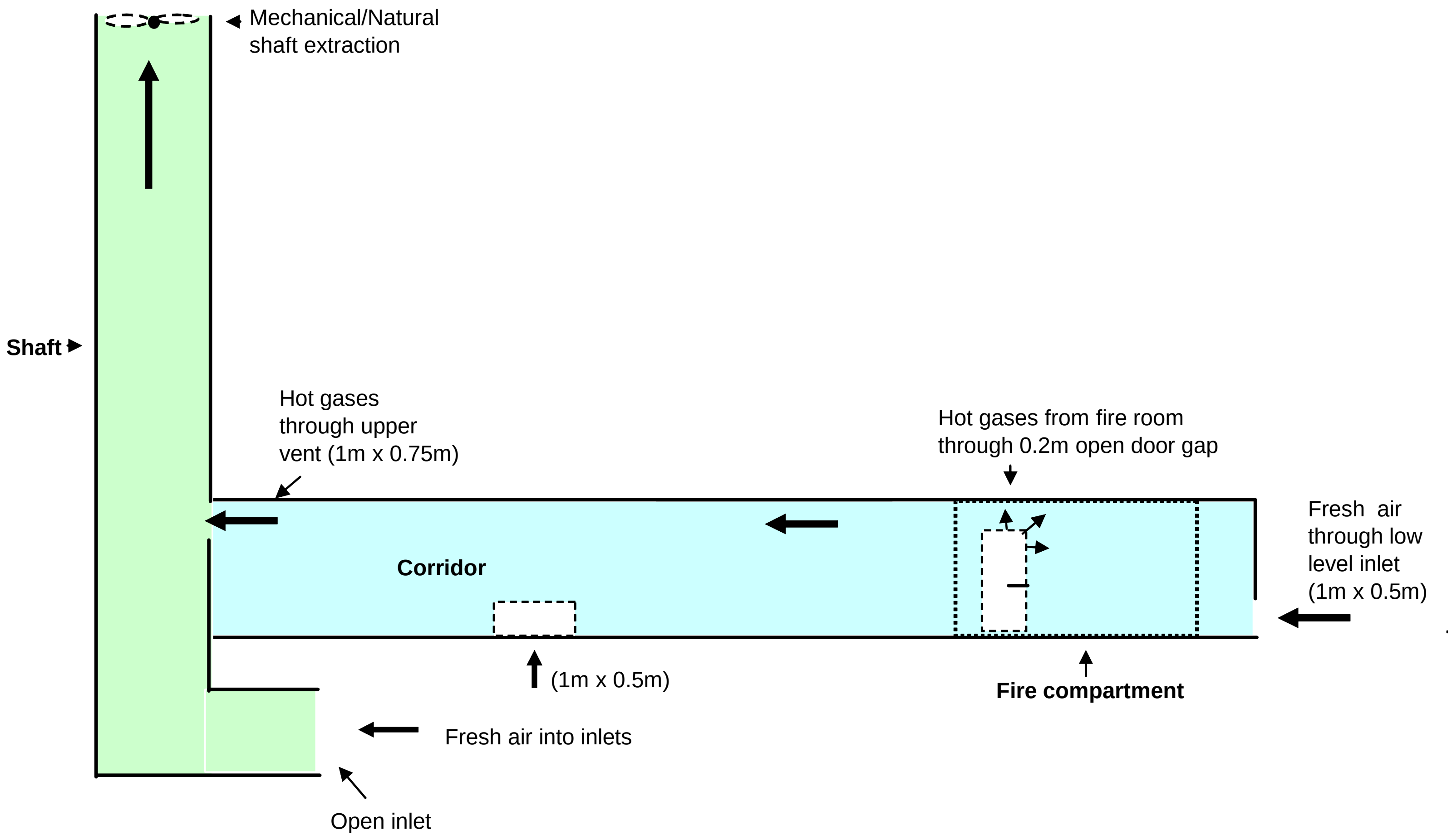

Figure B15 Elevation of configuration used in physical modelling Scenario 1 to achieve optimum conditions

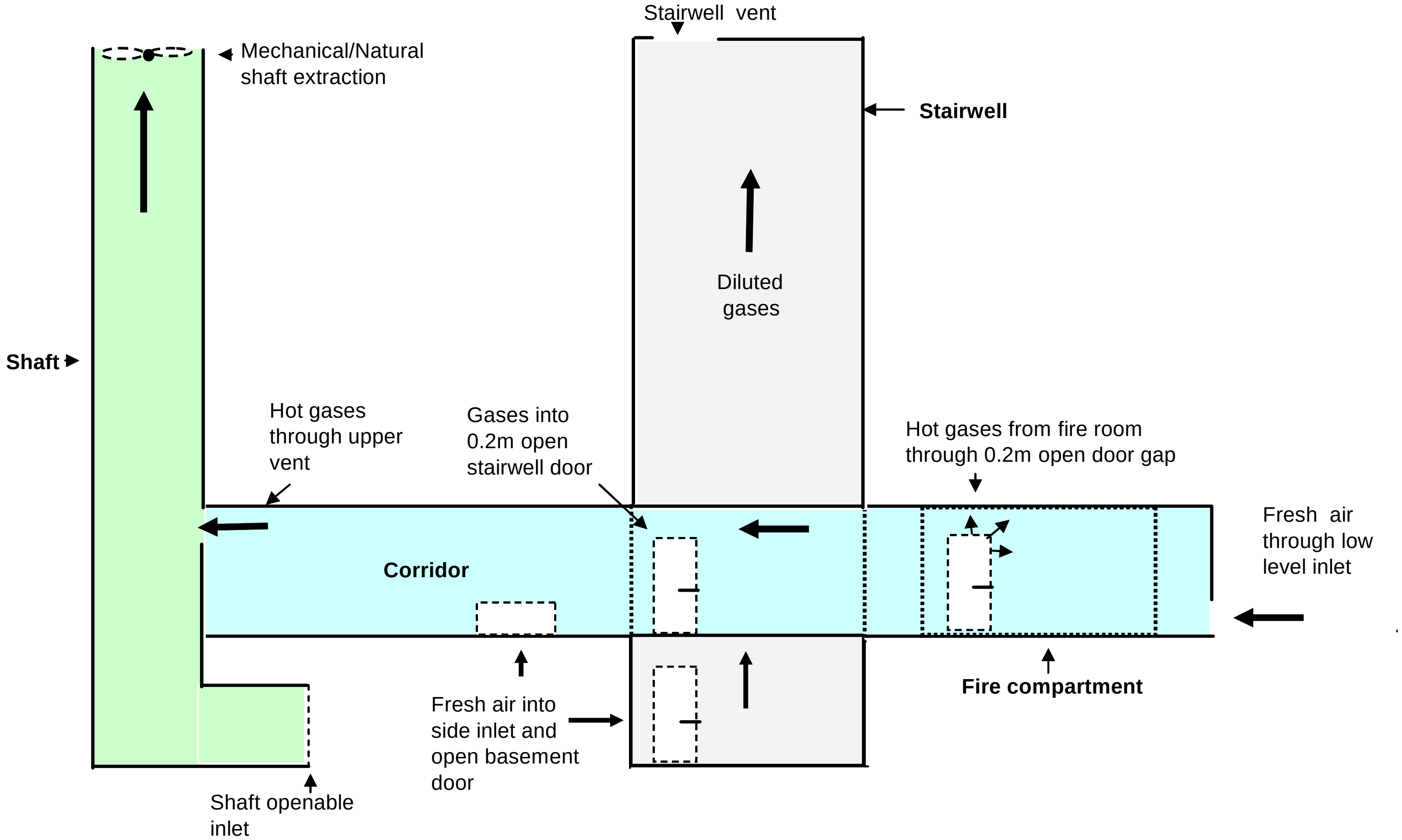

Figure B16 **Elevation of configuration used in Scenario 2 to achieve optimum conditions in model**

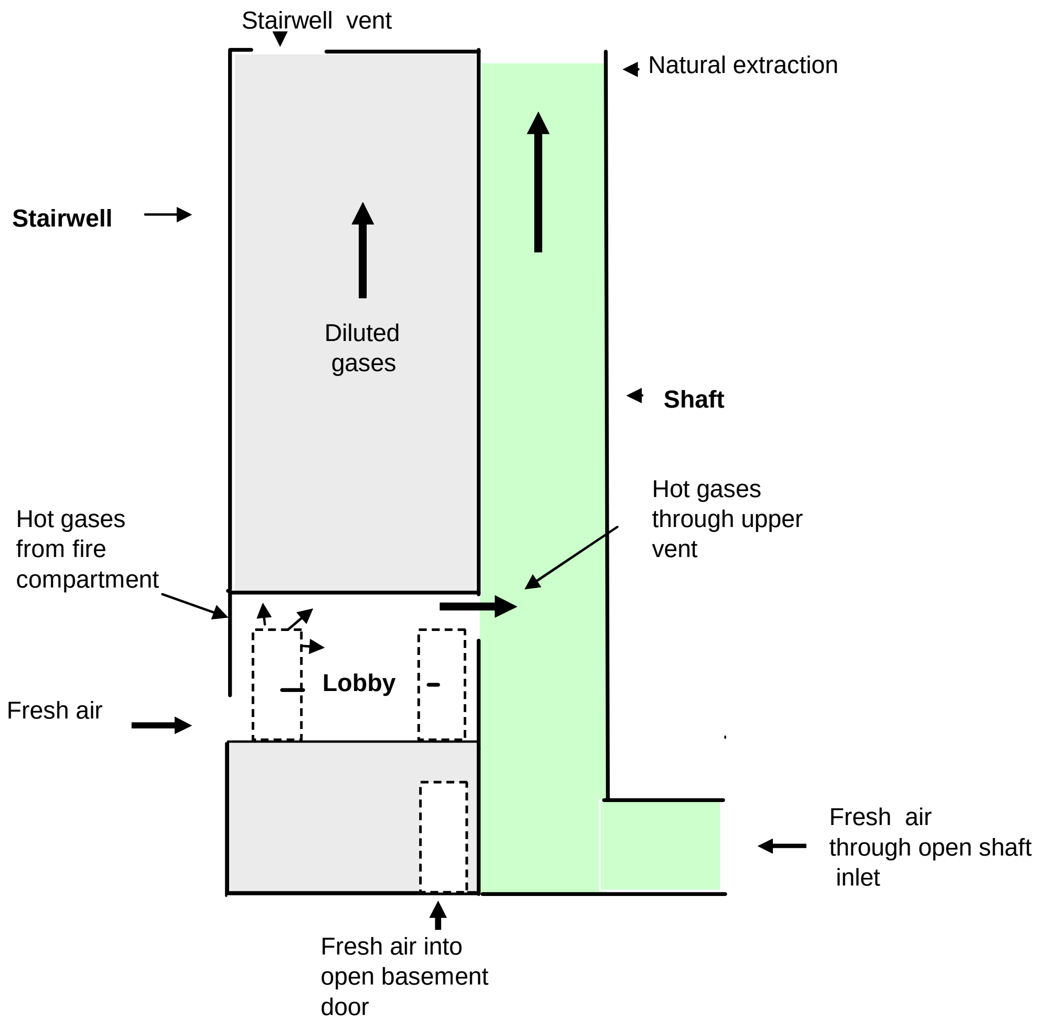

Figure B17 Elevation of configuration used in physical modelling Scenario 3 to achieve optimum conditions in model

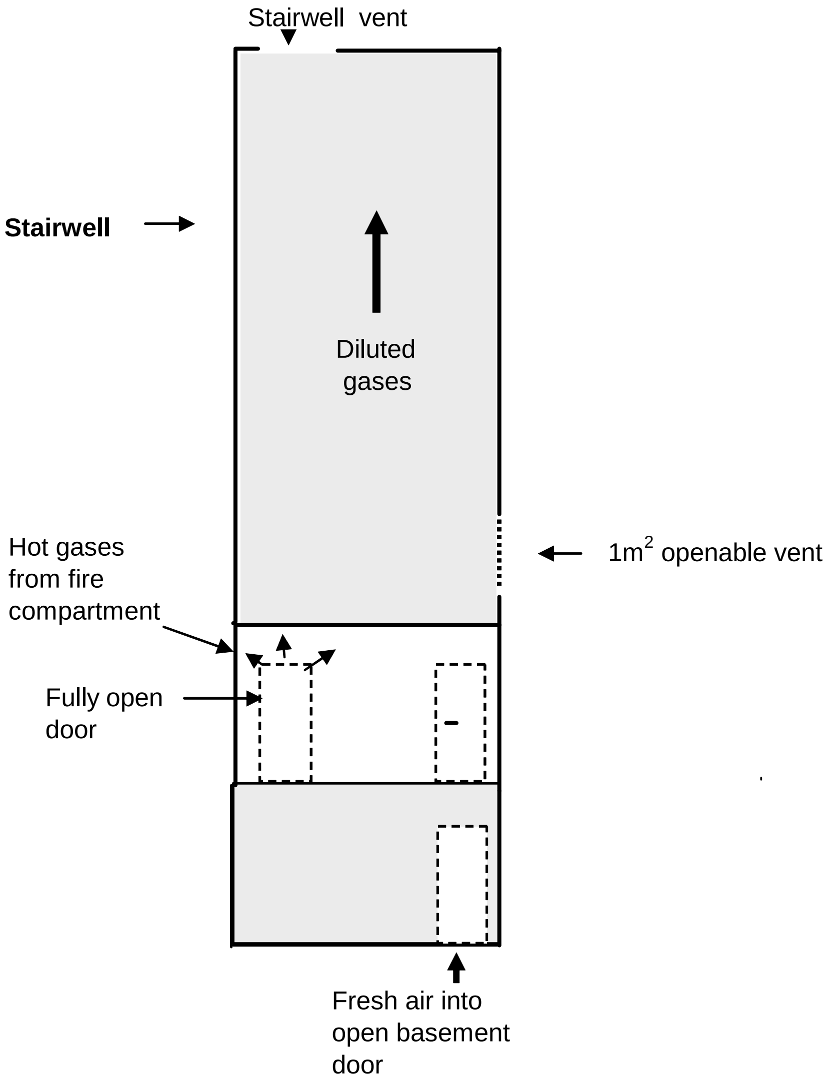

Figure B18 Elevation of configuration used in physical modelling Scenario 4 to achieve optimum conditions in model

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